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Engineering Derivatives from Biological Systems for Advanced Aerospace Applications

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TABLE OF CONTENTS

1.0 EXECUTIVE SUMMARY 1-1

1.1 Bionics Contributions 1-1
1.2 Study Results 1-2
1.3 Conclusions 1-5

2.0 INTRODUCTION 2-1

3.0 STUDY METHODOLOGY 3-1

3.1 Literature Survey 3-1
3.2 Survey of Bionics Researchers 3-5
3.3 Bionics Workshop 3-7

4.0 HISTORY AND CONTRIBUTIONS OF BIONICS 4-1

5.0 BIONICS WORKSHOP 5-1

5.1 Opening Presentations 5-1
5.2 Working Group Results 5-3
5.3 Workshop Conclusions 5-5
5.4 Working Group Reports 5-8

6.0 BIONICS RESEARCH OPPORTUNITIES 6-1

6.1 Biological Design 6-1
6.2 Materials and Structures 6-10
6.3 Information Processing 6-19
6.4 Robotics 6-34
6.5 Life Support 6-39
6.6 Aeronautics 6-43

7.0 CONCLUSIONS AND RECOMMENDATIONS 7-1

REFERENCES A-1

APPENDICES

A. ANNOTATED BIBLIOGRAPHY A-1
B. BIONICS DIRECTORY B-1
C. WORKSHOP AGENDA AND PARTICIPANTS C-1

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LIST OF FIGURES AND TABLES

1. Figure 1.1 - History of Bionics Programs 1-3
2. Figure 2.1 - Knowledge Transfer Between Natural and Technological Systems 2-2
3. Table 3.1 - Technical Literature Databases Searched 3-2
4. Table 3.2 - Taxonomy - Natural Engineering Systems 3-4
5. Figure 3.1 - Sample Annotated Bibliography Record 3-5
6. Figure 3.2 - Sample Bionics Directory Record 3-7
7. Figure 4.1 - Outline of the Etrich Dove 4-1
8. Figure 4.2 - Line Drawing of Ribbed Structure of the Crystal Palace 4-2
9. Figure 4.3 - History of Bionics Programs 4-6
10. Figure 6.1 - Super-Large Size Passenger Plane "Megalodon" 6-3
11. Figure 6.2 - Jumbo Cargo Airfoil Similar in Concept to the B-2 Bomber 6-4
12. Figure 6.3 - Space Shuttle "Polymorph" 6-5
13. Figure 6.4 - Large Sail Yacht 6-6
14. Figure 6.5 - Cross-section of the Internal Pressure Layer of the Bio-designed Extravehicular Activity Glove 6-7
15. Figure 6.6 - Extravehicular Activity Glove "Reptus Glove" 6-8
16. Figure 6.7 - Extravehicular Activity Glove "Crusta Glove" 6-9
17. Figure 6.8 - Hierarchical Tendon Structure Showing Precison Levels of Scale 6-11
18. Figure 6.9 - Scanning Electron Micrograph of the Bessbeetle Cuticle 6-13
19. Figure 6.10 - Illustration of the Structure of the Butterfly Scale 6-15
20. Figrue 6.11 - Aztec Grating Design 6-16
21. Table 6.1 - Selected Biological Sensitivities of Animal Sensors 6-19
22. Table 6.2 - Physical Effects Detectable by Human Body Senses 6-20

23. Figure 6.12 - "Block" Diagram of the IC Base Neuromine 6-21

24. Figure 6.13 - Multiaperture Optics (MAO) Device 6-22

25. Figure 6.14 - Synthetic Analog to Human Skin 6-24

26. Figure 6.15 - Natural Olfactory Sensing Membrane and Typical Artificial Olfactory Sensing Membrane 6-26

27. Figure 6.16 - Gravity Receptors 6-33

28. Figure 6.17 - Walking Robot 6-35

29. Figure 6.18 - The Cockroach 6-36

30. Figure 6.19 - Cross-Section of an Elephant Trunk 6-38

31. Figure 6.20 - Photoconversion Processes 6-39

32. Figure 6.21 - Comparison of Deformed and Undeformed Guard Cells 6-41

33. Figure 6.22 - Short Three-Dimensional Riblets in a Staggered Array 6-44

34. Figure 6.23 - Swept-Back Wings and Fins 6-45

1.0 EXECUTIVE SUMMARY

Researchers, designers and engineers have for many years looked toward nature for design ideas and engineering principles that can be incorporated into man-made engineering systems. This concept of mimicking natural systems has been termed bionics or biomimetics. The goal of this study is to document the engineering contributions from the field of bionics and to identify opportunities for accelerated research which may provide innovative solutions, based on design principles derived from nature, to aerospace problems.

One may ask why we should expect that studying biological creatures, who are by necessity restricted to terrestrial environments, will offer any valuable insight for advanced space technology, which is inherently extraterrestrial. There are three responses to such a query.

1) Through natural selection, evolutionary pressures result in biological systems (be they structural, sensory, neural or motor) that conserve material and energy. The resulting small, lightweight, energy efficient (and frequently multifunctional) systems should be of obvious interest for aerospace designs where these are critical design parameters.

2) The performance of biological systems in robust and adaptable, and this characteristic feature is typically not environment dependent.

3) As biological research progresses, there is evidence that many basic principles are employed and adapted by many species to meet their specific functional requirements. It is these scientific principles which we seek to understand through bionics research; thus we adapt these principles to our engineering applications (even extraterrestrial) rather than mimic nature directly.

1.1 Bionics Contributions

Our study has uncovered a wealth of engineering contributions from the field of bionics. Many early flying machines were modeled after flying animals including DaVinci's designs of 1505 (bats), the Eole of 1890 (flying foxes), and the Etrich Dove of 1913. More recently, riblets and asymmetric nose cones (sharks) and leading edge combs (birds) have contributed to drag reduction, and filleted surface intersections (many fishes) have been used by the Soviets to quiet submarines.

Benefits extend beyond fluid dynamics; researchers have employed the laminated composite structure of seashells to achieve dramatic improvements in toughness of ceramic metal-matrix composites. One company, PA Technology, has adapted the non-reflective structure of the moth eye to reduce laser reflection from optical memory disks. Beginning with General Electric's adaptation of lateral inhibition (first noted in horseshoe crabs) for television and radar displays in the 1960s, research into human and animal vision has progressed, hand-in-hand, with design of machine vision and pattern recognition systems. Researchers at Caltech and elsewhere are now constructing VLSI retinas and incorporating active visual search behaviors into improved vision systems. Navy supported research into echolocation by bats and dolphin has contributed substantially to the design of sonar and radar signal processing.

Artificial neural networks and parallel processing computers have their roots in biology; yet, while powerful tools, their current capabilities are dwarfed by the complexity of processing accomplished by biological neural networks. Developers of multi-fingered robotic end-effectors have mimicked human hand motor control; while others

gained inspiration from manipulation by other species (elephant, squid, insects and crustaceans). Designers of walking machines have critically studied high speed film of the gaits of four legged mammals and six legged insects. The contributions from bionics touch almost all technical fields and extend far beyond this small sampling.

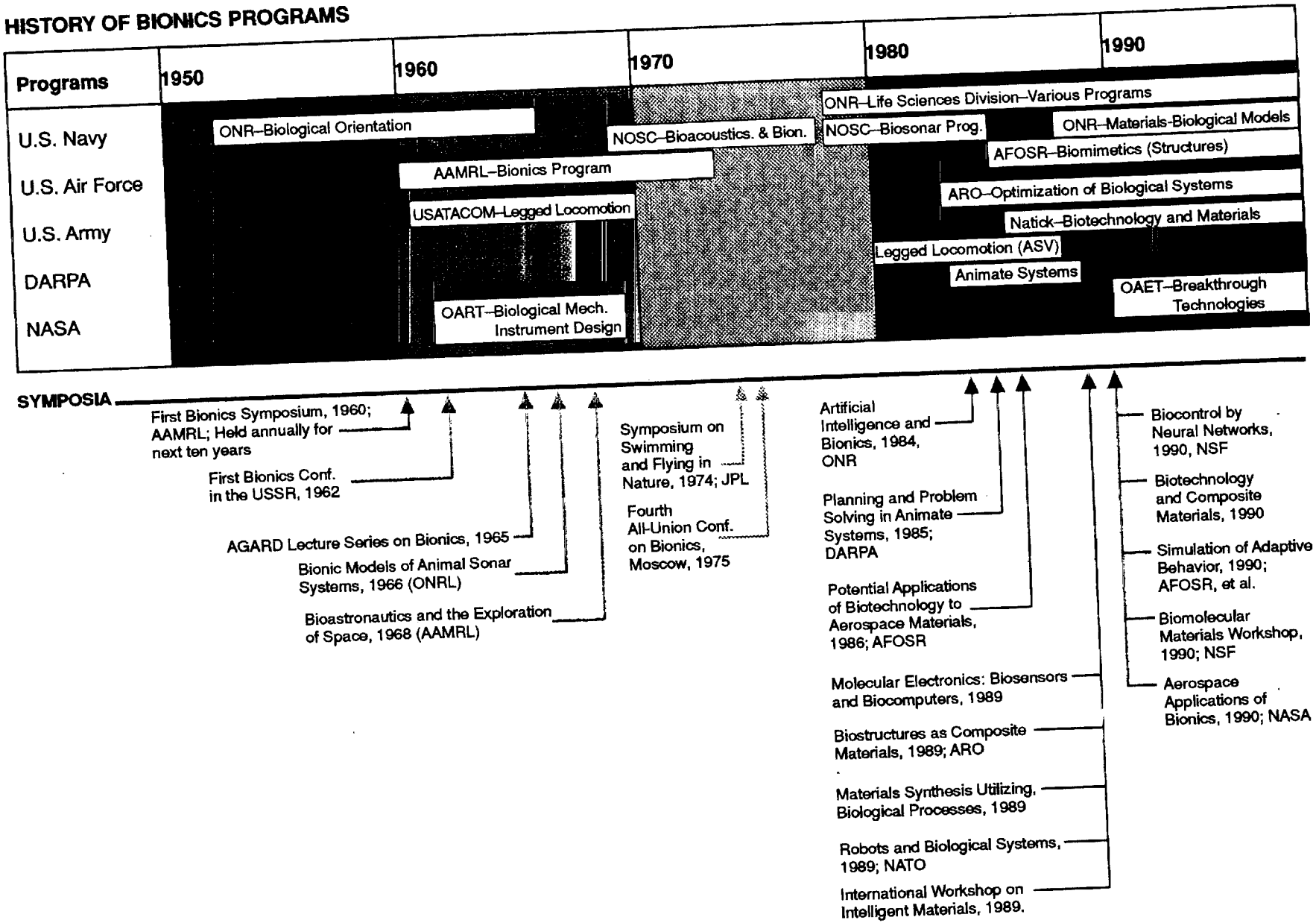
That bionics research has tremendous potential is also evidenced by the active research programs of the U.S. and other countries as shown in the accompanying figure on the history of bionics programs. The Office of Naval Research was the first to initiate a bionics program, called Biological Orientation, but the U.S. Air Force led a major bionics effort in the 1960s and early 1970s. These organizations continue to support bionics research under different program headings as does the National Science Foundation, DARPA and other parts of DOD. The Soviet Union has had a continuous research effort in bionics since the 1960s, much of it focused on naval and aircraft applications. While an unclassified study has difficulty documenting contributions from this Soviet work, the scope of the research can be traced in an annual periodical called "Bionika".

1.2 Study Results

The present study has consisted of a literature survey, a survey of researchers, and a workshop on bionics. These tasks have produced an extensive Annotated Bibliography of bionics research (282 citations), a Directory of bionics researchers, and a workshop report on specific bionics research topics applicable to space technology. These deliverables are included as Appendix A, Appendix B, and Section 5.0, respectively. To provide organization to this highly interdisciplinary field and to serve as a guide for interested researchers, we have also prepared a taxonomy or classification of the various subelements of natural engineering systems.

Finally, we have synthesized the results of the various components of this study into a discussion of the most promising opportunities for accelerated research seeking solutions which apply engineering principles from natural systems to advanced aerospace problems. Section 6.0 of the report includes this discussion of opportunities within the areas of materials, structures, sensors, information processing, robotics, autonomous systems, life support systems, and aeronautics. Following the conclusions are six discipline summaries that highlight the potential benefits of research in these areas for NASA's space technology programs.

HISTORY OF BIONICS PROGRAMS



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TAXONOMY - NATURAL ENGINEERING SYSTEMS

1.0 Sensory Systems
- 1.1 Optical
  - 1.1.1 Imaging/Vision
  - 1.1.2 Optical Surfaces
  - 1.1.3 Photodetection Mechanisms
  - 1.1.4 Glare Reduction
  - 1.1.5 Arrays/Multiaperature Optics
- 1.2 Acoustic
  - 1.2.1 Hearing
  - 1.2.2 Speech Recognition
  - 1.2.3 Acoustic Detection
  - 1.2.4 Acoustic Localization (Imaging)
- 1.3 Tactile
  - 1.3.1 Pressure
  - 1.3.2 Texture
  - 1.3.3 Temperature
  - 1.3.4 Vibration
- 1.4 Biochemical Sensing
  - 1.4.1 Olfactory
  - 1.4.2 Taste
  - 1.4.3 Other
- 1.5 Velocity/Acceleration
  - 1.6.1 Gravity
  - 1.6.2 Wind Speed
  - 1.6.3 Gyroscopes
  - 1.6.4 Accelerometers
- 1.6 Electromagnetic

2.0 Structural Systems
- 2.1 Materials
  - 2.1.1 Compliant
  - 2.1.2 Rigid
  - 2.1.3 Composite
  - 2.1.4 Adaptive
  - 2.1.5 Biomineralization
- 2.2 Structures
  - 2.2.1 Compliant
  - 2.2.2 Rigid
  - 2.2.3 Composite
  - 2.2.4 Pressurized
  - 2.2.5 Adaptive
  - 2.2.6 Collapsible/Erectible
  - 2.2.7 Optical

3.0 Information Processing
- 3.1 Sensory Processing
  - 3.1.1 Visual Perception
  - 3.1.2 Hearing
  - 3.1.3 Taste, Smell, Touch
  - 3.1.4 Pattern Recognition
  - 3.1.5 Sensor Fusion
  - 3.1.6 Object Tracking
  - 3.1.7 Balance
  - 3.1.8 Communication
- 3.2 Neural Processes
  - 3.2.1. Neural Networks
  - 3.2.2 Cognitive Reasoning
  - 3.2.3 Memory/Learning
  - 3.2.4 Biomolecular Electronics

4.0 Navigation Systems
- 4.1 Position/Orientation Sensing
- 4.2 Sonar
- 4.3 Celestial
- 4.4 Magnetic/Gravitational
- 4.5 Navigational Algorithms
- 4.6 Path Planning

5.0 Locomotion
- 5.1 Ambulation
  - 5.1.1 Propulsion
  - 5.1.2 Balance
  - 5.1.3 Bipedal/Multipedal Gaits
  - 5.1.4 Control Systems
- 5.2 Swimming
  - 5.2.1 Propulsion
  - 5.2.2 Hydrodynamics
  - 5.2.3 Control Systems
- 5.3 Flight
  - 5.3.1 Propulsion
  - 5.3.2 Aerodynamics
  - 5.3.3 Control Systems

6.0 Mechanisms
- 6.1 Articulations
- 6.2 Manipulation
- 6.3 Actuators
- 6.4 Fluid Mechanics
- 6.5 Attachment Mechanics

7.0 Biochemical Systems
- 7.1 Membrane Permeability/Selectivity
- 7.2 Thermal Management
- 7.3 Energy Conversion and Storage
- 7.4 Physiology/Metabolism
- 7.5 Bioluminescence
- 7.6 Biosurfaces (Adhesion, Lubrication)
- 7.7 Transpiration

8.0 Components and Subsystems (Organs and Tissues)
- 8.1 Polyfunctional
- 8.2 Confluence to One Function

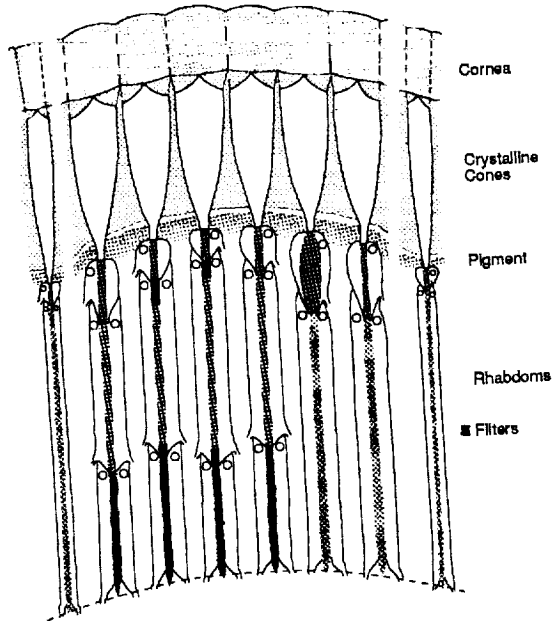
1.3 Conclusions

The primary conclusions of this study are:

- There is overwhelming evidence from past contributions and current research that natural systems engineering principles can advance space technology.
- In many areas, these contributions have breakthrough potential -- the natural systems' capabilities far surpass current technology.
- These bionics research efforts are inherently multidisciplinary, requiring project teams with appropriate mixes of different discipline capabilities and resources.
- Furthermore, this bionics research often is not clearly separated into the traditional disciplines, but instead forms hybrid discipline by combining previously disparate elements or disciplines. How nature has fulfilled a function, and thus how we ultimately apply this knowledge, cannot always be envisioned from previous disciplinary experience. Thus, NASA should consider internal and external mechanisms to foster and support such inter-disciplinary research with widespread impact.
- NASA's efforts should be coordinated with that of other agencies and other countries to achieve maximum benefit.
- More in-depth analysis is required to fully evaluate the research opportunities and to formulate projects which address relevant NASA needs. Additional workshops and other mechanisms are encouraged to more clearly elucidate the basic underlying principles in natural systems and to consider these in light of specific NASA technical challenges.

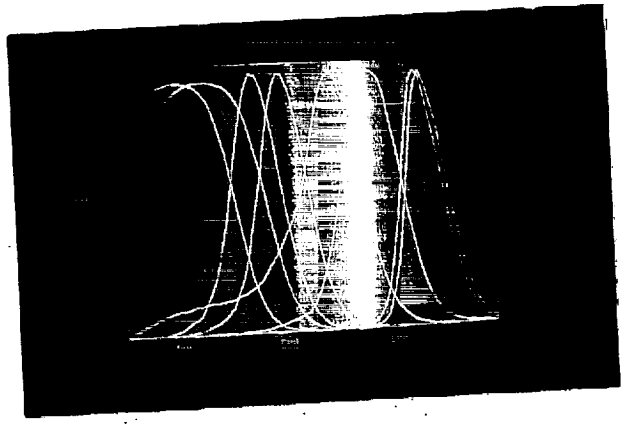
This report provides a survey of the broad field of bionics research, touching on almost every engineering discipline. The reader will develop a keen appreciation for the complex interrelationships and remarkable capabilities of natural systems. The research opportunities mentioned will hopefully stimulate aerospace engineers to consider these natural systems as they seek solutions to difficult technical problems for future space exploration.

Miniaturized Sensors



Imagine a sensor millimeters in size capable of discriminating spectral information in eight wavelength bands with this sensitivity lying in a narrow strip of vision scanning across an image. Couple this with a second independently moving, identical sensor gathering visual data from different directions. Now add a processing unit, cubic millimeters in size, which processes the data for image analysis even as it controls other subsystems. The figures show the structure and spectral response of such a system found in the mantis shrimp, one of inumerable examples of biological sensory systems possessing remarkable capabilities within anatomical packages far smaller than possible with current technologies.

By unraveling the structure and design principles for relevant biological sensory systems such as this shrimp eye, perhaps we can approach their level of miniaturization and robustness. Emerg-



ing capabilities in nanotechnology and micromachines may enable fabrication of such sensors. Such artificial systems could be placed on tiny rovers for exploration or guidance or on robot end effectors for closed loop control. Since size, weight, and power consumption drive designs for all spacecraft systems, the potential applications and payoff for these tiny, powerful systems are enormous.

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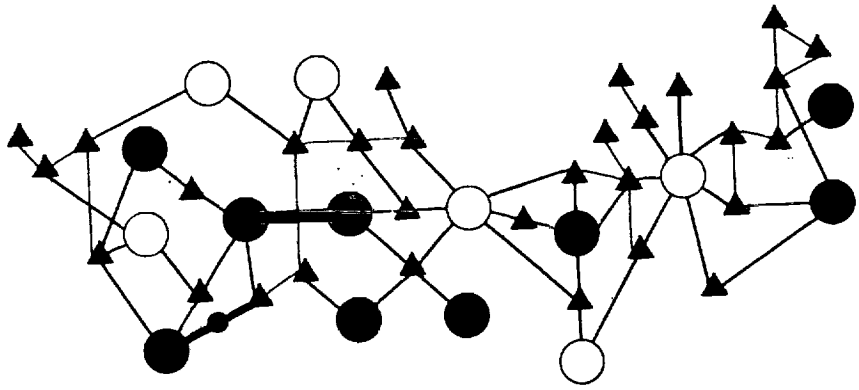
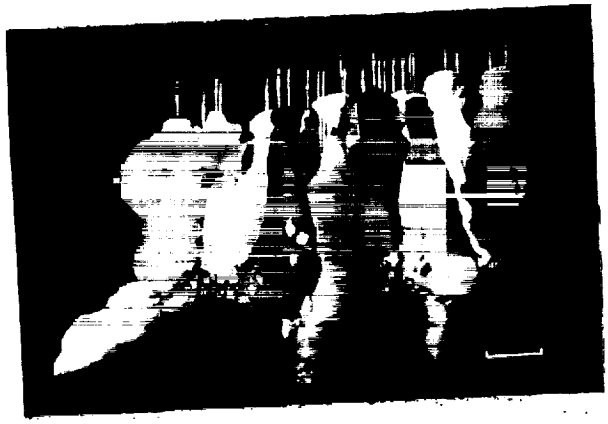
Neural Networks

Neural network processing systems consist of many simple computational units, "neurons," with a high level of interconnectivity, the massive parallelism providing substantial processing advantages. Artificial neural networks have their roots in biology and their implementations in silicon; they are being used extensively in pattern recognition systems, robot controllers, vibration reducers, and many other applications.



THIS IS PART OF THE ACTUAL INFORMATION NETWORK DIAGRAMMED FROM 400 SERIAL SECTIONS OF RAT MACULA. TYPE II HAIR CELLS DISTRIBUTE INFORMATION FOR PARALLEL PROCESSING



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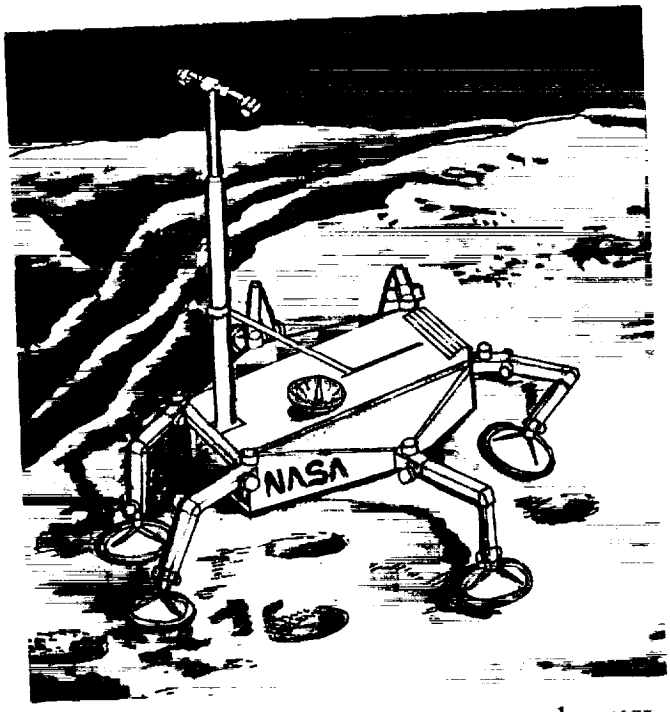
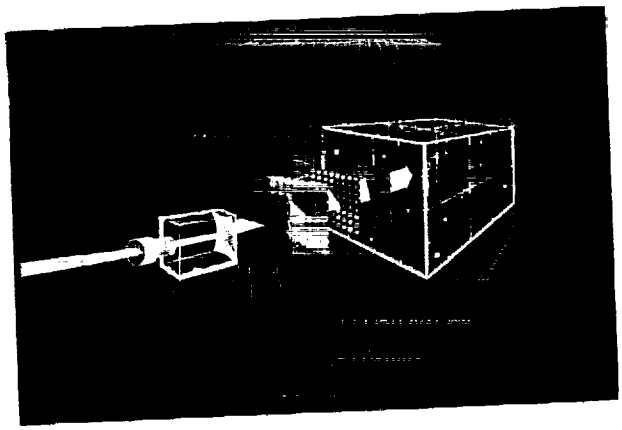
Yet, artificial neural networks fall far short of their potential. A cockroach with a miniscule neural network, whose neurons operate thousands of times slower than their silicon counterpart, can operate a multilegged propulsion system, search for food, navigate unfamiliar territory, and control escape behavior.

Better understanding of biological neural networks is essential to developing working models of neural networks with performance approaching their biological counterparts. The rat gravity-sensing neural network, shown at left, was constructed from detailed anatomical sections of the biological organ and shows how the system is organized in three dimensional space. The spatiotemporal factors that figure into network connections and the organization of the network are two examples of attributes not yet realized in artificial systems. Unlocking the secrets of natural neural networks will provide artificial vision, autonomous navigation, local mission decision capability, and a multitude of other benefits.

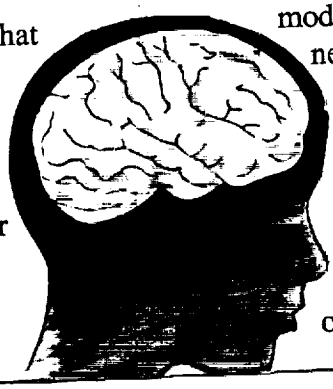
Autonomous Rovers





For future surface exploration, unmanned rovers will play an important role, and autonomous operation will be desired, if not required. In real-time, the rover must acquire data about the environment, process these data into useful form, make decisions based upon this information, and initiate and control motor actions. In developing autonomous, or animate machines, we closely approach true mimicking of the function of living organisms.

Legged locomotion, modeled after that of hexapods (insects), could allow exploration of irregular and, perhaps, more scientifically interesting terrains. Biological sensors can provide insight into new sensors for exploration, and sensor fusion, as employed by all animate systems, will be required.



Control functions are perhaps most critical to achieving agile locomotion, such as that displayed by mountain goats. Current concepts require several processors operating at high speed; animals are obviously more efficient. The cockroach acquires and processes multisensor information, controls all motor functions, and displays rudimentary learning – all with only a one million neuron processor. Neurocomputers, modeled after human and animal neural networks and brain architectures, have superior performance in controlling highly complex systems. Multidisciplinary research to adapt and incorporate these subsystems into working animate systems will allow NASA to construct systems that can only be dreamed of today.

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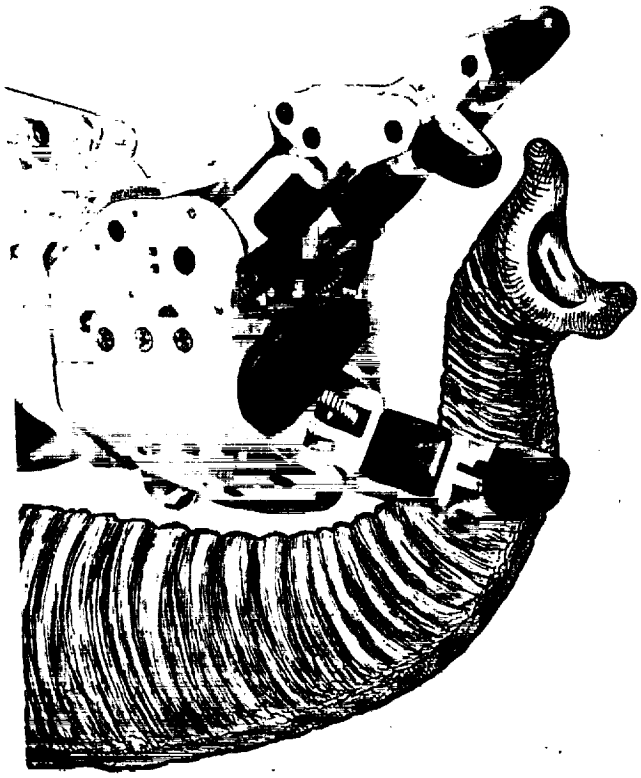
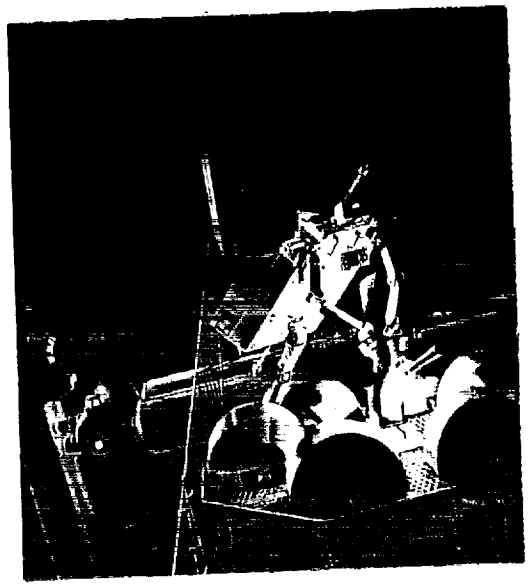
Dexterous Robots





Many future space construction, maintenance, and exploration tasks will be performed by robots due to the operational complexities and cost of manned EVA. These tasks will require robotic devices capable of dexterous manipulation in unstructured environments. Design and control of multifingered hands will continue to benefit from the study of human hand motor control. However, biology may inspire other useful concepts based upon manipulation by insects, crustaceans, squids, elephants, and other species. These biological manipulators may well have advantages for particular handling tasks.

Biological systems employ linear actuators constructed of contractile material (muscle); these may serve as model actuators for robotics. Recently developed contractile hydrogels, contracting in response to a variety of controllable means, have been used to construct "artificial muscles" with strength and reaction times comparable to human muscle. The variety of biological systems employing linear actuators will provide design guidance for entirely new types of mobile machines. Perhaps we can develop a class of artificial muscular hydrostats; mimicking naturally occurring tentacles, trunks, and serpentines. Substantial weight savings and increased power-to-weight ratios will be inherent, and selective activation could produce controlled movement with strength, flexibility, and dexterity.

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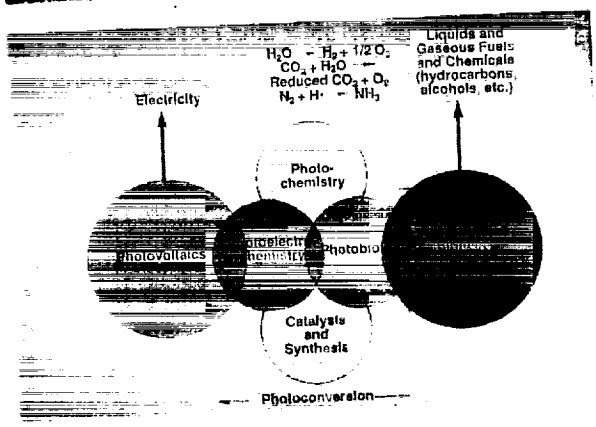
Artificial Photoconversion

Energy requirements are an important design limiter in most space systems. Clearly, more efficient mechanisms of utilizing the primary energy source, the sun, will have major impact on all aerospace missions. The most efficient converter of solar quanta that exists today is the photoelectron transfer system in green plants. Current research is developing the fundamental understanding of natural photosynthesis necessary to develop artificial photosynthesis systems which mimic these processes.

Photoconversion processes can yield stored chemical energy at high theoretical solar conversion efficiencies. To realize such systems, chemists and chemical engineers must develop stable derivatives of photosynthetic pigments, methods to stabilize initial reaction products, and catalytic processes to convert these products to hydrogen, oxygen, or reduced organic compounds. Photoconversion research may lead to the next generation of fuel and chemical producing solar energy technologies. This research warrants NASA's attention as these photoconversion processes have great potential on thermodynamic grounds, and the implications for self-sufficient space missions are significant.



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ENGINEERING DERIVATIVES FROM BIOLOGICAL SYSTEMS FOR ADVANCED AEROSPACE APPLICATIONS

Final Report

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RTI Project #84A-4645

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2.0 INTRODUCTION

Biological systems are marked by their miniaturization, their sensitivity, their high degree of flexibility, their ability to adapt to changing environments, and their high degree of reliability. These design features offer a great range of possibilities for research seeking to derive engineering principles of natural systems and adapt these principles for application to improved man-made systems.

Research Triangle Institute has conducted this study, under contract to NASA Ames Research Center, to identify opportunities for accelerated research using design principles derived from nature to provide innovative solutions to aerospace problems. Within the study, we have emphasized an engineering view of natural forms, processes and systems. Our objective has been to extract from the literature and from current research efforts certain design principles that may provide options for future innovative technologies. Before reviewing the organization for this final report, we should clarify two terms which we use frequently throughout the report: bionics and biological design.

Nature has forever been a source of inspiration for engineers and designers, and there has been a modern emergence of closer ties between engineers and biologists studying the engineering aspects of how organisms function. Major Jack Steele, U.S. Air Force, coined the term "bionics" in 1960 to describe what was then an emerging research approach at the interface between natural and synthetic systems. He defined bionics as "the analysis of the ways in which living systems actually work, and having discovered nature's tricks, embodying them in hardware." Many others definitions can be found in the literature; for the purposes of this study we have chosen the following as our working definition:

> Bionics is the derivation of engineering principles employed in natural systems, and the application of these principles to the design of improved technological systems.

Second, we frequently refer to biological design or to design principles in nature. This terminology is used intentionally as this discussion is directed primarily to engineers and designers. However, design implies some anticipation of future conditions or functions. Nature, on the other hand, has evolved its forms, processes and systems through a multitude of incremental steps which, in scientific parlance, amount to trial and error. But this trial and error is not random; rather it is driven by the complex interaction of forces acting upon the organism and the evolutionary goal to optimize functions within the environment. As engineers we do not know what problems have been solved over the course of evolution; however, we can assume that the resulting "design" is a good design. It is a good design since it has survived; inferior designs being literally eaten up by the good designs.

For centuries the main interaction between biology and technology has been dominated by efforts to explain biological systems in the language of human technology -- a sometimes futile task as the structures and systems of nature are frequently too complex and subtle to be adequately described in the language of human technology. Thus, the key question becomes, can we use biological design as the source - and not merely the demonstration - of technological progress. Closer examination of bionics research over the years, demonstrates that the process is actually a bi-directional flow of knowledge (Figure 2.1). Technology advances to some point where further progress is blocked or marginal; engineers then gain and apply knowledge from biological designs. This allows further technological progress, which, in turn, aids deeper understanding of the biological system. In reading this report, one will readily see that man has indeed used biological designs as the source for technological progress throughout many

engineering fields. The reader will also recognize a multitude of future opportunities, many with direct relevance to the technical challenges involved in developing advanced aerospace systems.

With that introduction, we turn to the contents of this report. The study has consisted of three main components: a literature survey, a survey of researchers, and an interdisciplinary workshop. Section 3.0 describes our methodology for each of these tasks. In Section 4.0, we attempt to provide an overview of the history of bionics research and to list a few of the engineering contributions from this field. The results of the bionics workshop are given in Section 5.0, both in the form of individual working group reports and as workshop conclusions. Details on the workshop organization and attendance are provided in Appendix C. Section 6.0 represents to main component of this report and provides a discussion of bionics research opportunities across a range of technology areas relevant to aerospace systems. The study conclusions and recommendations are summarized in Section 7.0. Appendices A and B contains two deliverables for this contract: an extensive Annotated Bibliography of relevant bionics literature from the past three decades and a Directory of researchers and funding organizations active in bionics research. It is hoped that the organization of this report will facilitate its use by technical management and by researchers to evaluate specific opportunities and identify relevant research activities. The wealth of research examples will stimulate engineers to consider these possibilities as they seek to develop the critical technologies for future aerospace systems.

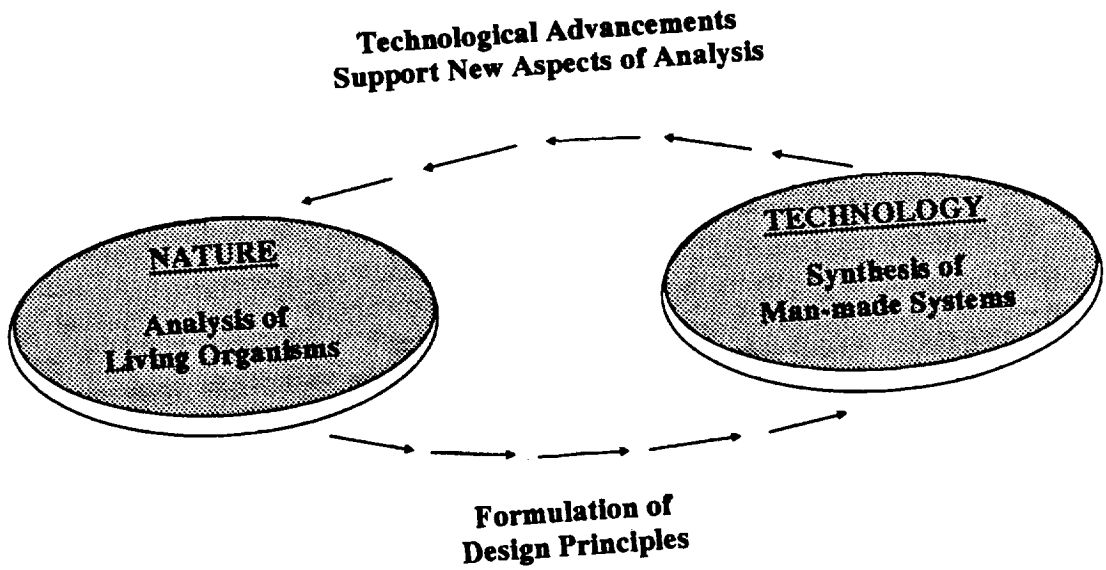

Figure 2.1: Knowledge transfer between natural and technological systems.

3.0 STUDY METHODOLOGY

NASA contracted with RTI to conduct a study of engineering derivatives of natural systems, especially those applicable to advanced aerospace systems. The study focuses predominantly on space technology, with lesser attention to aeronautics as that area has already benefited substantially from bionics. This study consists of a literature survey, a survey of current researchers, and a workshop to help identify priority opportunities for accelerated bionics research which would help solve important aerospace problems. The literature survey produced an Annotated Bibliography, while the survey of researchers was incorporated into a Bionics Directory. These, and the workshop results have been synthesized to produce the section of this report on Bionics Research Opportunities. The present section will summarize the methodology used in each of these components of this study.

3.1 Literature Survey

A comprehensive literature survey of the field of bionics is a difficult task for several reasons. First, the term bionics has different meanings to different people, thus this term as a keyword itself was of marginal utility. Second, as with any interdisciplinary field, terminology differs across different disciplines; no single search strategy is successful in different disciplinary databases. Search strategies found to be useful in searching the biological literature must be adapted for the engineering literature. Also common in interdisciplinary research, the research may be published in more obscure journals. Finally, there is no definitive line where biological research becomes bionics research or where bionics research becomes engineering. For example, the literature of research into biological systems from an engineering perspective is enormous. Likewise, for certain technologies, such as neural networks, although marginally based on biological models, much of the current work has, in fact, little direct connection to biology. For this study, we have included only research which is clearly based in natural systems and in which the author indicates some interest or intent for the knowledge to serve the purpose of improving artificial systems (whether or not he actually is making this translation to hardware).

We used computerized literature database searching techniques for this study. Some searches were performed by the RTI Technical Information Center (TIC) using the DIALOG® system, while more interactive searches were performed by the project technical staff using the BRS Colleague® system. Each of these commercially available systems offer access to dozens of technical literature databases. We also used the RECON system provided by NASA which includes NASA reports and aerospace literature. The National Science Foundation also assisted by conducting a search of Japanese literature using the NACSIS database.

Table 3-1 provides a brief description of the primary databases searched for this study. In the following discussion, we will use the abbreviation for these databases. The databases found to be most helpful for this study were: COMPENDEX, NTIS, INSPEC, and BIOSIS. Other databases were searched, with varying frequency and thoroughness depending upon the topic.

We began our search by using the key words "bionics" and "biomimetics" in the following databases (with the number of citations in parenthesis):

TABLE 3-1: TECHNICAL LITERATURE DATABASES SEARCHED

PTS DEFENSE MARKETS AND TECHNOLOGY. Summaries of major articles and reports from defense sources, includes contracts, industry, and more--defense industry contracting and tracking.

BIOSIS PREVIEWS. Worldwide coverage of research in the life sciences; the major English-language source of information from over 9000 journals and other varied publications--research in all areas of biosciences and medicine.

LIFE SCIENCES COLLECTION. International research literature coverage in major areas of biology, medicine, biochemistry, and all areas of life sciences--biological and medical research.

MEDLINE (MEDLARS onLINE). Comprehensive biomedical literature and research summaries provided by the U.S. National Library of Medicine with information on the entire field of medicine and its related disciplines--medical research and treatments.

ZOOLOGICAL RECORD. Systematic/taxonomic information with worldwide coverage of literature in virtually every area of zoology-research on animal life.

CLAIMS™/U.S. PATENT ABSTRACTS. Comprehensive source of U.S. patent information and international patents, with summaries and claims from the *Official Gazette* and specialized databases for identifying chemical compounds and patents by chemical structures and polymers.

AEROSPACE DATABASE. Summaries of key scientific and technical documents pertaining to all aspects of aerospace research and development in 40 + countries--basic and applied research, technology development in electronics, communications, physics, and related areas.

COMPENDEX®. Synopses of worldwide engineering publications and articles including the entire engineering field and its specialities --reviewing international engineering developments.

FEDERAL RESEARCH IN PROGRESS. Descriptions of current, multidisciplinary research under the sponsorship of U.S. government agencies--locating current research.

INSPEC. One of the largest English-language databases in the fields of physics, electrical engineering, electronics, computers, and control engineering--research and study in engineering and all related fields.

NTIS. Catalog of government-sponsored research, development, and engineering, plus analyses prepared by federal agencies, their contractors or grantees--identifying research, sponsors, and reports.

RECON. NASA-compiled database consisting of International Aerospace Abstracts, NASA Tech Briefs, NASA R&D Contracts, STAR, and NASA RTOPs.

NACSIS. Collection of databases of Japanese scientific literature compiled by the National Center for Science Information Systems.

SCISEARCH®. A multidisciplinary index to scientific and technical literature with unique access to author-cited references--review of worldwide sci-tech literature and authors.

SOVIET SCIENCE AND TECHNOLOGY. Abstracts of journal articles, patents, and reports covering multidisciplinary sic-tech information from Soviet Block countries--monitor technological developments and research.

NTIS (509)
COMPENDEX (132)
BIOSIS (687)
MEDLINE (124)
FED. RES. IN PROG. (40)
INSPEC (140)
ZOOLOGICAL RECORD (13)
CLAIMS (6)
RECON (1977)

NTIS uses bionics to include almost any medical devices, and BIOSIS includes a great deal on biomimetic chemistry, which results in the large number of entries for these databases. Likewise, RECON uses bionics as a major thesaurus term for most life sciences research. Results from this initial search gave us a feel for the volume and types of reports using this terminology. It also served to help us develop detailed search strategies.

To assist us in conducting detailed searches, we developed a preliminary taxonomy listing the major disciplines and sub-disciplines of the field of bionics. Following this taxonomy assured areas were not overlooked and provided a structure to organize detailed search strategies. As we conducted the literature search, this taxonomy was revised to reflect the results of our survey. The final version of our taxonomy of the field of bionics is given in Table 3-2.

Disciplines were assigned to staff members to conduct detailed searches and review relevant literature. These detailed searches covered all areas listed in the taxonomy and utilized the taxonomy listings as keywords. We found that for these searches to be successful, they needed to be conducted at the sub-discipline level. That is, we had to specify "vision" or "visual systems" rather than just "sensors" or "sensory systems." This subcategory keyword was then combined with other keywords to narrow the output and increase the hit rate for articles meeting our criteria for bionics. The additional words varied by topic and by database, and the selection of keywords was largely an iterative process. For example, the term "machine vision" was useful in biological databases to identify research in biological systems with relevance to machine vision, but was useless in the engineering literature as it resulted in a large number of citations.

Engineering terms, such as technology, engineering, computers, and sensors, were useful in searching the biological literature. Biological terms, such as animals, plants, nature, natural systems, biology, and physiology helped to narrow search sets from the engineering literature. Other terms helpful at this stage were model, applications, and design. Generally speaking, however, specific words did the most to aid searching (i.e. particular systems or animals).

Two previous bibliographies were located early in the survey and were helpful in identifying government research efforts. The National Technical Information Service annually updates a continuing bibliography of citations using the term bionics as a keyword in the NTIS database, and we obtained the 1989 version (Anon., 1989). Also, the U.S. Air Force AAMRL Biodynamics and Bioengineering Division has published a bibliography of their reports up to 1980 (Zember, 1986). These bibliographies were particularly helpful in identifying early work in the emerging field of bionics from the 1960s and 1970s.

Relevant articles/reports identified in the searches were requested through the RTI Technical Information Center (TIC). As these were received, they were reviewed to determine if they should be included into our literature survey. Early articles also guided revisions to our search strategy within the topic as new keywords were identified.

TABLE 3-2: TAXONOMY - NATURAL ENGINEERING SYSTEMS

- 1.0 Sensory Systems
  - 1.1 Optical
    - 1.1.1 Imaging/Vision
    - 1.1.2 Optical Surfaces
    - 1.1.3 Photodetection Mechanisms
    - 1.1.4 Glare Reduction
    - 1.1.5 Arrays/Multiaperature Optics
  - 1.2 Acoustic
    - 1.2.1 Hearing
    - 1.2.2 Speech Recognition
    - 1.2.3 Acoustic Detection
    - 1.2.4 Acoustic Localization (Imaging)
  - 1.3 Tactile
    - 1.3.1 Pressure
    - 1.3.2 Texture
    - 1.3.3 Temperature
    - 1.3.4 Vibration
  - 1.4 Biochemical Sensing
    - 1.4.1 Olfactory
    - 1.4.2 Taste
    - 1.4.3 Other
  - 1.5 Velocity/Acceleration
    - 1.6.1 Gravity
    - 1.6.2 Wind Speed
    - 1.6.3 Gyroscopes
    - 1.6.4 Accelerometers
  - 1.6 Electromagnetic
- 2.0 Structural Systems
  - 2.1 Materials
    - 2.1.1 Compliant
    - 2.1.2 Rigid
    - 2.1.3 Composite
    - 2.1.4 Adaptive
    - 2.1.5 Biomineralization
  - 2.2 Structures
    - 2.2.1 Compliant
    - 2.2.2 Rigid
    - 2.2.3 Composite
    - 2.2.4 Pressurized
    - 2.2.5 Adaptive
    - 2.2.6 Collapsible/Erectible
    - 2.2.7 Optical
- 3.0 Information Processing
  - 3.1 Sensory Processing
    - 3.1.1 Visual Perception
    - 3.1.2 Hearing
    - 3.1.3 Taste, Smell, Touch
    - 3.1.4 Pattern Recognition
    - 3.1.5 Sensor Fusion
    - 3.1.6 Object Tracking
    - 3.1.7 Balance
    - 3.1.8 Communication
  - 3.2 Neural Processes
    - 3.2.1. Neural Networks
    - 3.2.2 Cognitive Reasoning
    - 3.2.3 Memory/Learning
    - 3.2.4 Biomolecular Electronics
- 4.0 Navigation Systems
  - 4.1 Position/Orientation Sensing
  - 4.2 Sonar
  - 4.3 Celestial
  - 4.4 Magnetic/Gravitational
  - 4.5 Navigational Algorithms
  - 4.6 Path Planning
- 5.0 Locomotion
  - 5.1 Ambulation
    - 5.1.1 Propulsion
    - 5.1.2 Balance
    - 5.1.3 Bipedal/Multipedal Gaits
    - 5.1.4 Control Systems
  - 5.2 Swimming
    - 5.2.1 Propulsion
    - 5.2.2 Hydrodynamics
    - 5.2.3 Control Systems
  - 5.3 Flight
    - 5.3.1 Propulsion
    - 5.3.2 Aerodynamics
    - 5.3.3 Control Systems
- 6.0 Mechanisms
  - 6.1 Articulations
  - 6.2 Manipulation
  - 6.3 Actuators
  - 6.4 Fluid Mechanics
  - 6.5 Attachment Mechanics
- 7.0 Biochemical Systems
  - 7.1 Membrane Permeability/Selectivity
  - 7.2 Thermal Management
  - 7.3 Energy Conversion and Storage
  - 7.4 Physiology/Metabolism
  - 7.5 Bioluminescence
  - 7.6 Biosurfaces (Adhesion, Lubrication)
  - 7.7 Transpiration
- 8.0 Components and Subsystems (Organs and Tissues)
  - 8.1 Polyfunctional
  - 8.2 Confluence to One Function

Reference lists from relevant articles were reviewed and pertinent references were also requested through the RTI TIC. When particularly relevant articles were identified, we conducted author searches to locate additional references by the same author. However, it should be made clear that we placed greater emphasis on breadth than depth for this study. Thus, we focused on identifying articles by different researchers rather than attempting to assure we had all relevant articles by a given researcher.

To compile the information collected in this study, RTI developed a Bionics Information System which includes records for the Annotated Bibliography and the Bionics Directory. To provide a format for our Annotated Bibliography, we developed a customized relational database using R:BASE V. A typical record in this database is shown in Figure 3.1. This database is searchable for keywords by author, title, classifiers, NASA applications and abstract. The classifiers used parallel the taxonomy listings, although they do not match exactly. This is a menu driven system with menus for inputing new records, editing existing records, and printing reports. Several report formats have been defined including a short report (author, title, journal reference, as for a reference list), a medium report (short report plus abstract), and a long report of the entire record. These reports can be of individual records or of a collection of records sorted by author, title, or classifier. The final R:BASE V Annotated Bibliography database contains 282 entries. The completed Annotated Bibliography is included in this report as Appendix A. It is organized according to major classifier and includes medium reports from all records. A subject index is provided for cross referencing as well as an author index.

ANNOTATED BIBLIOGRAPHY

Angel, J. R. P.; Lobster eyes as x-ray telescopes., Astrophysical Journal, Part 1, 223: 364-373, Oct. 1, 1979.

INSTITUTION: Steward Observatory
FUNDING AGENCY: NSF
CLASSIFIERS: Sensory Systems, Optical
NASA APPLICATIONS: X-ray telescopes, Optical equipment.

A new optical configuration for grazing-incidence, imaging x-ray telescopes is described that is similar to the reflective eyes of macruran crustaceans such as lobsters. The field of view can be made large as desired, and it is practical to achieve good efficiency for photon energies up to 10 keV. Spatial resolution of a few seconds of arc over the full field is possible, in principle, if very small reflecting cells can be fabricated.

Figure 3.1

3.2 Survey of Bionics Researchers

As the literature review began to identify relevant articles, we began contacting key researchers to learn more about their research and other research within their field. We also contacted NASA personnel which we identified as conducting research with relevance to the study objectives. We discussed the nature of this study for NASA and the potential technological applications of their research. We requested additional articles of interest and additional persons we should contact. This proved to be a very valuable mechanism for this difficult-to-search field.

In addition to researchers, we also contacted program managers at various Federal agencies deemed likely to have programs that included research meeting our definition of bionics. Among the federal agencies contacted were:

Air Force Office of Scientific Research (AFOSR)

Wright Research and Development Center

- Materials Division
- Aerospace Medical Research Laboratory

Office of Naval Research (ONR)

- Biological Sciences Division
- Cognitive and Neural Sciences Division

Army Research Office (ARO)

Department of Energy (DOE)

- Division of Energy Biosciences
- Division of Chemical Sciences

Defense Advanced Research Projects Agency (DARPA)

National Science Foundation (NSF)

National Institutes of Health (NIH).

Program summaries and listings of grant awards were obtained where appropriate. Areas of overlap with potential NASA interest were identified.

As with the literature survey, we developed a customized database for a Bionics Directory to include both researchers and funders in this field. A typical Directory record is shown in Figure 3.2. It includes complete contact information for the researcher, title of their project(s), funding source, classifiers, and a brief project/program description. A partially completed copy of this form was distributed to identified researchers with a request to complete and return it for inclusion in the Directory. We made at least two attempts to gather all information. Information listed in the records is believed to be accurate as of November 1990.

The Bionics Directory is included in this report as Appendix B. Contacts are listed in alphabetical order by last name. Like the Annotated Bibliography, this Directory is available to be supplied to NASA as an R:BASE V database file. It is searchable by researcher name, organization, classifier and keyword, and short and long reports have been defined.

The Bionics Information System was developed with R:BASE System V, a state-of-the-art database development and management tool. This system can be configured to run in a multi-user network environment or on a stand-alone, single-user computer. The Bionics Information System is designed to run with PC-DOS on the IBM PC, PC-XT, PC-AT, and 100% compatible microcomputers. The user must either have the R:BASE software installed (in which case RTI can supply a database file for uploading into

BIONICS DIRECTORY

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E-Mail: beer@alpha.ces.cwru.edu

Project Title: Neural Networks for Real Time Sensorimotor Control.
Funding Agency: ONR
Classifiers: Neural Networks, Control Systems

The objective of this research is to elucidate the principles by which invertebrate nervous systems control locomotion behavior, and to apply this understanding to the design of more autonomous, flexible, and robust hexapod robots. A detailed computer model of the neural circuitry and periphery involved in the cockroach escape response will be developed. This simulation will provide an interactive medium for synthesizing results of experimental and theoretical tests of system operation. To demonstrate that biological control principles can be applied to robotic design, they will also construct a hexapod robot and a locomotion controller based upon a neural model under development.

Figure 3.2

R:BASE) or, for a nominal fee, RTI can download the system into an applications software package that will allow the user to access the Bionics Information System.

3.3 Bionics Workshop

The third component of our study was to organize a workshop to identify promising bionics research opportunities for NASA. We worked with the Technical Monitor and the NASA Headquarters Program Manager to define the objectives for the workshop:

1) understand the scope of on-going bionics research,

2) identify promising NASA opportunities, and

3) provide a tutorial and stimulate cross-fertilization between NASA and bionics researchers.

We developed a framework for a working meeting that would include a balance of invited presentations and small informal working groups. We compiled a list of NASA Mission Applications that served to guide our evaluation of the relevance of bionics research efforts. These were predominantly, but not exclusively, space applications as aeronautics has already received emphasis in the field of bionics. As the surveys progressed, we began to identify research areas that would have application to some of the projected NASA technology needs. This information was used to prepare a workshop announcement which was reviewed with NASA prior to finalization. A copy of the final workshop announcement is included in Appendix C.

We sought to identify the best available researchers for each subject area in order to compile a list of candidate invitees. This draft list was reviewed with NASA and additional NASA invitees added. As funds were not available to support workshop participant travel, we anticipated this might pose a problem in securing participation. This was generally not the case, however, as most people who were not able to attend, indicated it was due to schedule conflicts.

As we began to confirm participation, we selected a set of invited presentations and finalized the agenda. The final agenda and final list of workshop participants are included in Appendix C. In order to cover the full breadth of this topic within a two day workshop, we developed four working groups as follows:

- Materials and Structures
- Sensors and Information Processing
- Mechanics and Dynamics
- Biochemical Systems

These working groups were asked to brainstorm new research possibilities and, second, highlight those research opportunities of priority interest to NASA. Detailed instructions provided to the working groups is also provided in Appendix C.

The workshop was held November 12-14, 1990 at the Kiawah Island Inn near Charleston, South Carolina. A very lively, informative and productive meeting resulted, yielding a useful report to NASA. Results of the workshop are presented in Section 5.0 of this report.

4.0 HISTORY AND CONTRIBUTIONS OF BIONICS

While the term "bionics" dates back to around 1960, the concept of mimicking nature very likely dates to prehistoric times. One can envision prehistoric man fashioning a weapon something like the claws of the wild animals he fought. Another adaptation from nature was that of camouflage. Just as lesser living creatures survive by concealing themselves, man learned to conceal himself with artificial covering.

Leonardo da Vinci, however, may have been the first true bionics researcher. Many, if not most, of his designs were based on designs observed in nature; including an ornithopter, a flapping wing aircraft patterned on his careful anatomical studies of birds. Despite many failures the concept of copying nature's flying creatures hung on for many years, even centuries. Sir George Cayley was the first to recognize that the force needed to hold a craft aloft might be separated from the horizontal propulsive force. He was well aware of the problems of resistance and studied the shape of living things to find the most streamlined forms. From this study of nature, Cayley designed two wing curves almost identical with two modern airfoil sections: the NACA 63A016 and LBN-0016 (Halacy, 1965).

Man's early attempts at flight were accomplished by copying nature to the extent that the curve of birds' wings were followed and wing loadings approximated that of birds. Clement Ader's Eole, one of the first machines to fly, was patterned after the flying fox with propellers added for propulsion (Gerardin, 1968). The Etrich Dove of 1913, another classic example, is shown in Figure 4.1 (Hertel, 1963).

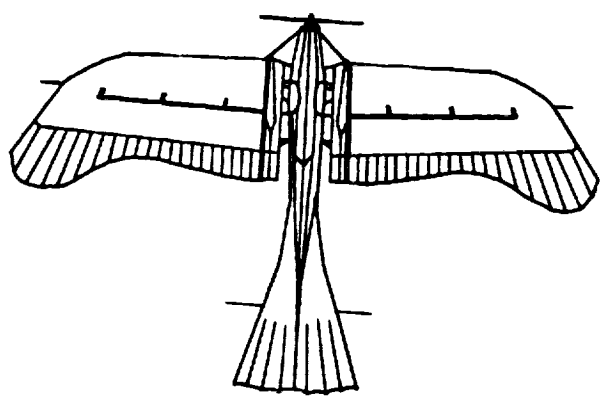


Figure 4.1: This outline of the Etrich Dove displays the common use of natural systems (avians and nektons) in the design of early flying machines.

Once the theoretical field of aerodynamics began to influence design, man turned away from nature as a design source for flying craft. More recently, there has been a resurgence in this interest, however. A major symposium was held at the Jet Propulsion Laboratory in 1974 on Swimming and Flying in Nature (Anon., 1974). Aeronautics engineers at NASA Langley Research Center have investigated drag reduction mechanisms in nature that have shed light on new methods to yield small reductions in aircraft drag. Riblets, small microscopic grooves similar to that found on shark denticles, have been found to contribute to drag reduction and

have been employed on sailing and rowing vessels; and experimentally on aircraft (Bechert, 1986; Raschi, 1986). Crescent wings and fins (van Dam, 1987), leading edge bumps, and filleted fin-body intersections are additional biological morphologies that have contributed to aerodynamics/hydrodynamics (Bushnell, 1991). These topics are covered in more depth in Section 6.5 of this report.

Early contributions from the mimicking of nature extend beyond the field of transportation. The South American water lily, Victoria Regia, inspired 19th century architect Sir Joseph Paxton to design the Crystal Palace in Hyde Park, London (Figure 4.2) (Hertel, 1963). This plant has delicate floating leaves up to two meters in diameter, yet able to support a weight of 90 kg. The underside of the leaf carries a system of hollow ribs which give both strength and buoyancy. Of this building, Paxton wrote, "Nature was the engineer - nature has provided the leaf with horizontal and transverse girders and supports that I, borrowing from it, have adopted in this building."

The mechanistic world view of the 17th and 18th centuries spread to the study of nature and led to a number of plans for machines based on the adoption of biological design. Yet, the development of science and technology, and the scientific knowledge of living organisms were not sufficiently advanced for the realization of many of these ideas. The emergence of modern science in the 19th and 20th centuries, while initially causing people to turn away from nature for design ideas, has now provided the basis to adequately understand many of the principles underlying biological systems and apply this knowledge to artificial machines.

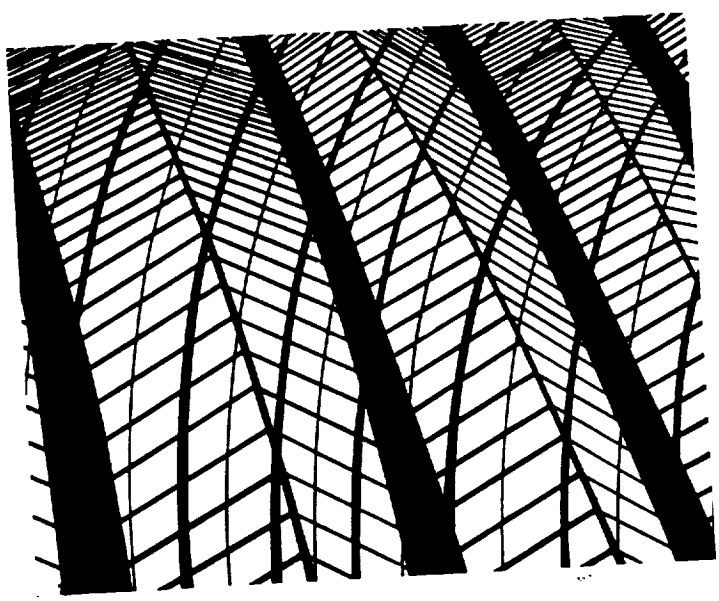


Figure 4.2: Line drawing of the ribbed structure of the Crystal Palace.

The modern emergence of bionics can be traced to the 1940s, as the first researchers began considering the possibility of a "thinking machine". McCulloch and Pitts derived an electronic model of the neuron, or nerve cell (McCulloch, 1943). This electronic neuron offered the promise of constructing a device which could learn and think in manners mimicking that of a human. Around the same time, Weiner launched the field of cybernetics, the study of control in machines and animals. The birth of the concept of neural networks, based upon biological networks of neurons, occurred with the design of the Perceptron; although the promise of neural networks were not realized until the most recent decade as new learning algorithms have been developed.

Sir H. S. Maxim was the first to suggest that bats avoid obstacles in their path by using some echolocation mechanism and that this principle could have application in detecting submerged icebergs (Maxim, 1912). The Office of Naval Research initiated the first formal Federal funding program in the area of bionics in the 1950s. This program, called Biological Orientation, was led by Sidney Galler and sought to take a biological approach or orientation in the search for solutions to technological problems. Donald Griffin was funded to study the echolocation mechanisms used by bats with the hope of improving artificial sonar systems (Griffin, 1958). As an aside, the noctuid moth has been found to detect and track bats up to 100 feet away using hearing; yet, its auditory systems is comprised of only two cells (Roeder, 1961). An example of miniaturization to its ultimate. Dolphin echolocation has also been extensively studied as part of the Naval Ocean Systems Center Bioacoustics and Bionics Program in the 1970s, and these studies continue today at NOSC in Hawaii.

Hartline's discovery of lateral inhibition in the horseshoe crab eye in the 1950s, led General Electric engineers to apply this technique to develop much sharper images for television screens and for radarscopes in military applications (Miller, 1961). GE also developed the VISILOG, a sensor and computer for pattern recognition based upon studies of human visual space perception (Marteka, 1965). At the Max Planck Institute in Germany, researchers studying the vision of the beetle compound eye developed the first reliable ground speed indicator for aircraft (Reichardt, 1961; Savely, 1960). A gyroscope of a radically new design, with very thin vibrating lamina, was created following careful study of the clavate organ of double-winged hexapoda. Similarly, the vision of hexapoda, specifically their ability to locate the sun, even on cloudy days, by using ommatidia as polarization filters, led to the design of a celestial compass using polarized light.

In 1960, the U. S. Air Force held the first Bionics Symposium with the subtitle, "Living Prototypes - The Key to New Technology." This was the first in a series of symposia sponsored by the Air Force (Bernard, 1962). Their program at the Wright-Patterson Air Force Base took a lead in the emergence of bionics as a scientific field and was easily the most concentrated research effort through the early 1970s. This program was motivated by the technical needs for increased reliability and compactness and reduced weight and power consumption; common requirements for today's space program.

Interestingly, many of the topics at these early bionics symposia are still at the forefront of today's research needs; e. g., muscle-like contractile devices, pattern recognition devices, information processing of olfactory information, etc. Other symposia held during the 1960s included an AGARD Lecture Series on Bionics (Peiss, 1966) and a Symposium on Bionic Models of Animal Sonar (Trott, 1966). Other programs funded during this period include investigations into legged locomotion by the U. S. Army Tank Automotive Command (Hanamoto, 1966; Parker, 1968). NASA also explored the potential of bionics through a program

funded by OART in the 1960s to review biological mechanisms for application to instrument design (Anon., 1983).

The Soviet Union initiated an active bionics program in the 1960s and has maintained a high level of research activity to this day. The Ukranian Academy of Science has taken a lead role in much of this work. Bionics research funded by the Soviet Navy has been concentrated on physiological, chemical, and mechanical approaches to improved underwater performance for submarine applications. Research into dolphin echolocation is only a minor subset of this effort. Research funded by the Soviet Air Force has, likewise, focused on aerodynamic applications. There apparently has not been any organized activity to consider bionics in relation to space technology applications. The best source for continuing information on the Soviet Bionics effort is a series of annual periodicals published since 1967 by the title "Bionika".

The Air Force program in bionics was discontinued in the 1970s, but not due to any lack of interest in the field. Rather, the potential applications were in too many fields, making it impractical to manage under one program. In addition, the term bionics was distorted in meaning by its use in popular television shows of that time. Great interest in research into biological mechanisms continues today, although this work is embedded within funding programs by other designations. For instance, DARPA has funded biologically based research into legged locomotion for walking machines, including research at Ohio State University to develop the Adaptive Suspension Vehicle, and research into autonomous vehicle control and navigation, including research at Martin Marietta for the Autonomous Land Vehicle. More recently, DARPA activity in this area has been under the heading of "animate systems" (i.e. synthetic systems that demonstrate life-like qualities). They sponsored a workshop in 1987 on Planning and Problem Solving in Animate Systems.

The National Science Foundation's basic research programs include bionics-type research. In fact, it was the early funder of the above mentioned work on legged locomotion at Ohio State. Current programs of the most relevance include research into biosensors, neural networks for control, and smart materials. NSF recently sponsored a workshop on Control by Neural Networks (Bekey, 1990), chaired by Dr. George Bekey, under the management of Paul Werbos. Even more recently, Hollis Wickman of the NSF Materials Research Division organized a workshop on Biomolecular Materials, Oct. 10-12, 1990.

The Army Research Office has a small program entitled "Optimization of Physical Principles in Biological Systems" that seeks to broaden fundamental knowledge of biologically evolved adaptations and solutions. Recent interest has been in olfactory sensors, actin-myosin force generators, neural networks, and vision systems. The Army Materiel Command has investigated the opportunities for biotechnology to enhance Army capabilities (Kaplan, 1989), and some of this overlaps into the bionics field. Research supported includes advanced materials, biosensors, bioelectronics, navigation, and power generation. The Natick Research and Development Center is active in the use of biotechnology to produce spider silk which is stronger than that of silk worms (Lombardi, 1990). They have developed genetic means to produce the silk and now hope to mimic the biological process to produce fibers for potential use in synthetic materials.

The Office of Naval Research has two divisions that support research that can be categorized as bionics. The Biological Sciences Division's interests include the study of electrochemical properties of integral membrane proteins to mimic their mode of action in biosensors. The Cognitive and Neural Sciences Division supports research into neurophysiology to provide future robotic devices with intelligent manipulators; the study of the operational

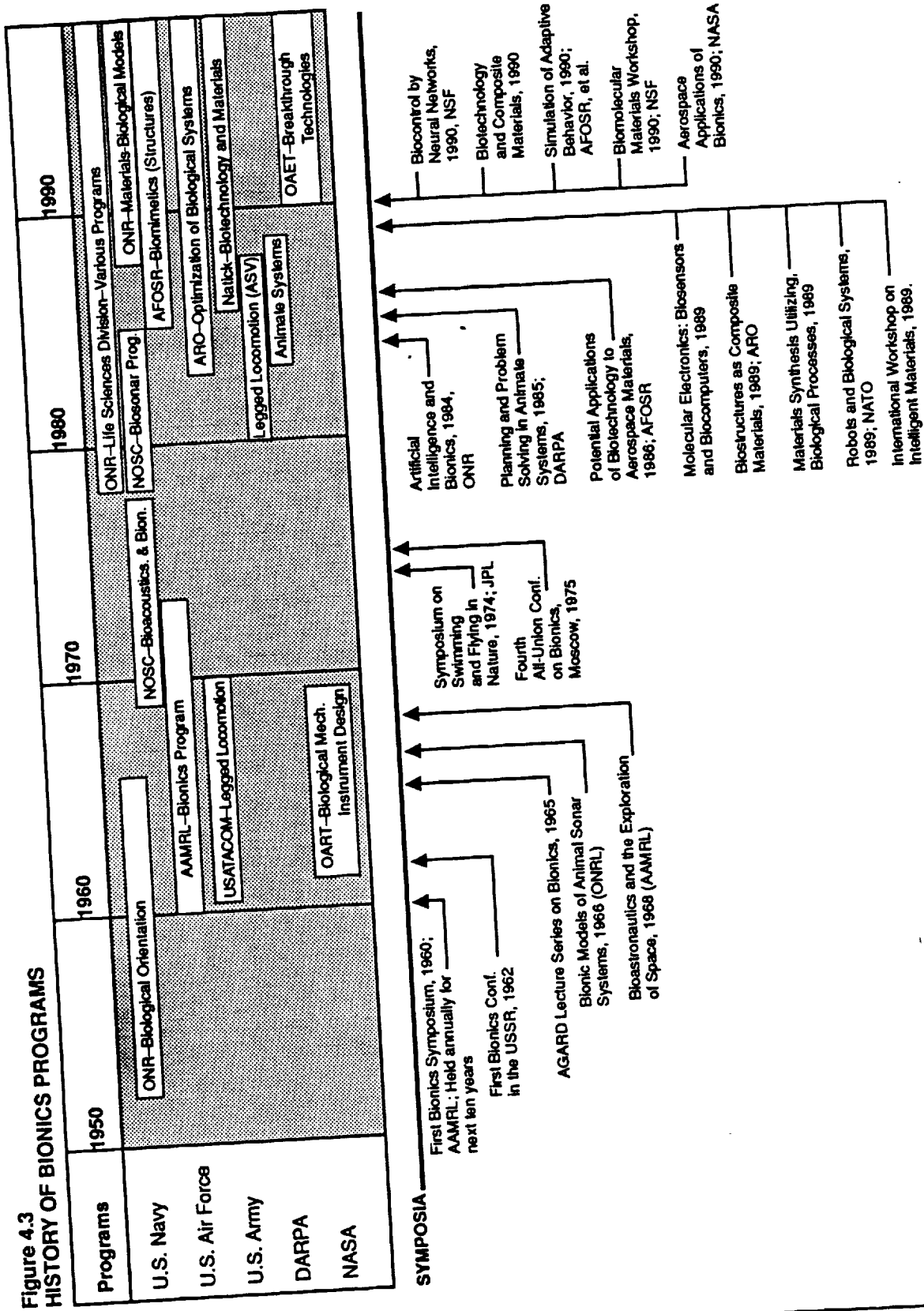
principles of neural networks to emulate these network characteristics within electronic information processing systems; and research into echolocation capabilities of dolphins for potential exploitation in artificial systems. In 1984, ONR sponsored a workshop, organized by the Naval Ocean Systems Center, to investigate possible applications of current knowledge of animal sensory, cognitive and motor abilities to discover new directions or issues in the continuing effort to build intelligent systems (Haun, 1984). In the 1991 DOD University Research Initiative - Research Initiation Program, ONR has solicited proposals to explore novel routes to tailor chemistries and microstructures for advanced materials. One approach suggested in their solicitation is to use natural biostructures as models for such advanced materials and to develop synthetic routes to simulate their hierarchical structures.

The Air Force has been a leading player in recent years in this concept of mimicking natural material structures (Anon., 1987; Schiavone, 1986). They have supported projects to use the beetle exoskeleton as a model fiber-reinforced composite with high stiffness-to-weight ratio (Gunderson, 1989) and to use the mollusc shell as a model of a laminated composite for high impact resistant metal-matrix composites (Sarikaya, 1990). The AFOSR hopes to expand this program in FY92 and is holding a workshop in April 1991 to identify research priorities in this area.

The recent history of this field of bionics is summarized in the Timeline shown in Figure 4.3. The top portion of this figure shows the duration of major programs with bionics focus within various Federal agencies. The lower portion shows the dates of significant symposia held on bionics related topics.

In this section, we have attempted to provide the reader a brief overview of some of the significant developments in the field of bionics research. The section also summarizes the emergence of bionics as an active, federally-funded research effort over the last three to four decades. The scope of the current project does not provide for a comprehensive treatise on the contributions of bionics. Complete books have been written on this subject (Geradin, 1968; Halacy, 1965; Marteka, 1965). Rather, this section sets the stage for discussion of the key findings of this study. The following two sections provide more in-depth discussion of current research focus in biologically-derived technology, and the potential opportunities for accelerated research leading to aerospace applications.

Figure 4.3
HISTORY OF BIONICS PROGRAMS



5.0 BIONICS WORKSHOP

One component of this study was to organize and conduct a workshop of leading bionics researchers and NASA scientists and engineers. The workshop sought to explore research opportunities of possible interest to NASA with emphasis on space applications, and to serve as a tutorial to communicate current bionics research activities to the NASA participants. The NASA Workshop on Aerospace Applications of Bionics was held at the Kiawah Island Inn, Charleston, SC on November 12-14, 1990.

The objectives of the workshop were:

- Establish a dialogue between NASA participants and bionics researchers through which NASA technology needs and relevant designs from nature can be investigated.
- Identify and develop recommendations from promising areas for bionics-derived technology research of interest to NASA.
- Brainstorm ideas for relevant bionics research in light of projected NASA space capability requirements.

A copy of the workshop announcement is provided in Appendix C and includes background discussion of the topics areas. Appendix C also includes the final agenda for the workshop and a final list of workshop participants with addresses and phone numbers.

In planning the workshop, we felt that accomplishing these objectives would require a mix of selected formal presentations and informal discussions. Thus we arranged for several invited presentations from NASA participants on their perception of the potential of bionics research for NASA and from bionics researchers on selected research topics. To facilitate the informal discussions, we organized four working groups that met twice during the workshop. The working group topics were:

- Materials and Structures
- Sensory Systems and Information Processing
- Mechanics and Dynamics
- Biochemical Systems

This mix of presentations and working sessions led to fruitful discussions of the relevant research areas; the working groups generated very useful reports for consideration of selected research areas by NASA.

The following is a synopsis of the workshop proceedings and includes discussion of the opening presentations, the working group reports, and the workshop conclusions.

5.1 Opening Presentations

Mr. Dan Winfield of Research Triangle Institute opened the workshop with a brief introduction of bionics, how the workshop fit within the overall RTI study, and the objectives for the workshop. He then introduced Mr. John Anderson of the Directorate for Space within the Office of Aeronautics, Exploration and Technology of NASA Headquarters. Mr. Anderson discussed the Breakthrough Technologies Program and his motivations for supporting this study of potential aerospace applications of bionics. Mr. Anderson indicated several areas of focus for this program including power and propul-

sion, sensing, information acquisition and utilization, materials and structures, vehicles, human support, and autonomous and adaptive performance. The program is intended to support truly innovative space technology ideas from concept definition through proof of concept. The bionics initiative is within this breakthrough program and is seen as one of several mechanisms to encourage interdisciplinary approaches that will lead to innovative concepts.

Next, two NASA engineers gave brief presentations summarizing their perspective on the past, current and future applications of natural systems design to their areas of interest. Dennis Bushnell of the NASA Langley Research Center discussed drag reduction mechanisms in nature and how some of these mechanisms have been and/or could be applied in the design to advanced aircraft and submarines. He mentioned the applications of winglets, riblets, and leading edge combs (vortex generators) as natural drag reduction systems that have been adapted for use in aerodynamics. He also discussed the use of fillets at intersections of surfaces (used widely by fish and swimming mammals) for quieting submarines. The macromolecular viscoelastic slime on the surface of fish serves both in drag reduction and as an anti-fouling mechanism; perhaps this can be adapted for artificial systems. Numerous opportunities exist for adaptation of natural systems design; however, he cautioned that the impact will be incremental not breakthrough, although the potential financial impact can be quite significant.

Harry Frisch of the NASA Goddard Space Flight Center gave a biomimetic viewpoint of the needs for the Flight Telerobotic Servicer and other robotics programs in NASA. Deriving basic engineering principles from biological systems can provide orders of magnitude improvements in design and performance of robotic systems. Areas of immediate interest include actuator systems, biostructures, sensors and sensory processing, path finding, and adaptive robust control. Mr. Frisch used the cockroach as an analogy; this fairly "primitive" organism demonstrates amazingly sophisticated distributed adaptive control with numerous sensors despite a relatively modest central processor - all in a very compact package.

On the following morning, four overview presentations on selected bionics research topics were given. Dr. Stephen Wainwright of Duke University used whale blubber as a model system to illustrate how investigation at a single level can enlighten us at other levels as well. Whale blubber is actually a multifunctional material serving as an energy source, an insulator, and a means of defending against predators (few predators are large enough to bite through the fat layer). Yet whale blubber also serves as an energy storage mechanism during swimming; the three dimensional nature of the fiber reinforcement in the blubber gives it its highly elastic nature, allowing it to store a portion of the energy during the swim stroke. Dr. Wainwright indicated that many researchers have been studying mechanical designs in nature, but only recently, to his delight, are people beginning to attempt to apply this knowledge in engineering systems.

Dr. Evangelia Tzanakou of Rutgers University discussed some of the on-going research into biological, particularly human, visual systems. She stated that a long desired goal is to build artificial visual systems that act and behave as much as possible like the real ones. Much of this work is on pattern recognition systems that resemble the human visual system in some aspects. She discussed the use of neural networks in modeling how the visual system and the brain process large amounts of information quickly and efficiently. Finally, she described an optimization procedure called

ALOPLEX that is used to provide for a response feedback that mimics synaptic changes and may help close the loop for memory and learning.

Dr. James Wilson of Duke University gave a biomimetic viewpoint of the mechanics of fluids and solids. Based upon his experience in collaborations with Dr. Wainwright, he described the methods for biologists and engineers to (1) investigate structural forms and materials of animals/plants for performing particular tasks, (2) determining how these tasks are performed, and (3) designing efficient synthetic analogs. Areas addressed by Dr. Wilson included aerodynamics, locomotion, manipulators, and structures. He also presented some specifics regarding his research in applying mechanisms used by elephants, squids, and spiders to the design of compliant robotic structures.

Finally, Dr. Michael Seibert gave an overview of biochemical systems with particular emphasis on artificial photoconversion systems. He provided insight on the mechanisms of producing energy from light and other light reactions in plants. The process of using photobiology, photoelectrochemistry, photochemistry synthesis and catalysis to study and mimic plant energy processing may lead to promising energy conversion and storage applications.

5.2 Working Group Results

As mentioned above, the workshop separated into four working groups for detailed, informal discussions. The working groups were supplied with a preliminary list of candidate topics, as well as a copy of our draft annotated bibliography. The four working groups met in two separate sessions with intermediate and final reports to the workshop. The first session was intended to be largely a brainstorming session identifying promising work in the field of bionics. The groups were asked to use the second session to focus on specific priority opportunities for accelerated research with an emphasis on those that might most apply to aerospace problems. In between, their interim reports to the workshop allowed for cross-disciplinary input and discussion on the research topics.

Each working group prepared a final report either in the form of handwritten viewgraphs or flipcharts. The groups were given some guidance on the form of these reports, but each group was left to its own accord in determining the final organization of the report as well as determining who presented it to the workshop. These rough, handwritten reports were transcribed by RTI following the workshop and mailed to all workshop participants. Comments were received, edits made, and the final working group reports are included in section 5.4. Included with the reports is a list of members for each group. The following briefly summarizes the key points addressed by these working groups.

The Materials and Structures Group reported that biological materials are characterized by precision levels of scale, functional architecture, and complex laws of interaction between levels of scale. Biological structures are inherently lightweight and frequently multifunctional as they are "designed" with conservation of materials in mind. Some examples discussed were the precision structures used to generate color in butterfly wings, the hierarchical structure of tendon, fiber reinforced biological composites, cross-helix reinforced tubular structures in nature, and precisely segmented structures such as the hummingbird chest as a focusable reflector. Rather than present many examples of functionally interesting biological structures, this group chose to compile a list of scientifically and technologically important principles used in these natural systems.

These principles are (1) use of large, nonlinear deformations as accommodation to force, (2) use of novel architectures for functionality, (3) processing of precision microstructures, (4) multifunctionality, and (5) adaptive response to changes in external environment or internal condition. The group advocated an approach driven by the design objectives for a synthetic structure. Investigation of these principles in analogous biological systems should lead to potentially fruitful concepts that may be implemented within current or projected fabrication capabilities.

The **Sensors and Information Processing Group** reported that the area of sensors and information processing has functional impact on almost all NASA mission areas. This productive group generated a large number of bionics concepts for consideration during their first working session. They concluded that significant additional research is needed into biological information processing in order to understand the principles of neural organization. They felt that current artificial neural network research barely touches the potential that neural networks have to offer. A better understanding of how biological neural networks process information will be the key to future applications.

Animals demonstrate remarkable ability to integrate information from multiple sensor systems for making complex real-time decisions. Such sensor fusion capabilities could impact many areas for NASA including non-destructive testing of materials, satellite remote sensing, and control of autonomous robotic systems. Such autonomous systems must mimic biological sensory-motor systems by organizing information into an internal model of the world, executing behavior based upon this model, and refining the model (i.e., learning) based upon experience. Also, it was proposed that a better understanding of the underlying methods of biological information processing may lead to fundamentally different computing strategies incorporating distributed processing and spatial-temporal processing.

In the area of sensors, this group espoused the high degree of miniaturization in biological transducing mechanisms for all sensory pathways. Such miniaturization will have obvious weight saving and efficiency benefits for space applications. Opportunities exist through multidisciplinary approaches to design opto-electro-mechanical analogues based on specific biological receptor systems for well defined tasks. Specifically, biochemical sensors are an emerging technology area that has much to gain from natural systems. Molecular sensors have high discrimination and high sensitivity to detect subtle changes in the environment, and incorporation of such systems into sensor devices will have widespread applications for NASA.

The **Mechanics and Dynamics Group** focused their attention on the problems to be addressed in developing improved robots. Artificial (contractile gel) muscles offer the potential to produce high response actuators with high power to weight ratio. These contractile gels are able to generate up to 5 times the force of human muscles with a speed of 0.5 seconds using 10 micron fibers. Smaller fibers should achieve response times in the 5 millisecond range. The problem in implementing these fibers is one of architecture, and analysis of biological muscles may offer insight into design of effective actuator mechanisms employing this new technology. Similarly, hydrostatic actuators modeled after hydrostats, squid tentacles or elephant trunks, may yield lightweight, compliant actuators. Another interesting area is that of protein motors which are responsible for the movement of very small bacteria. These actin-myosin motors might serve as the basis for a completely new means of actuation.

Other applications include the use of biological systems as models for smart materials and structures which respond to stimuli to modify their structure or geometry and the use of smooth muscle as a model for peristaltic pumping of fluids around a space vehicle.

Control systems for autonomous or semi-autonomous robots is another area of critical concern since they provide a mechanism for robots to perform adequately in unstructured environments. Perhaps biological systems can provide insight into the optimum level of redundancy for such systems or into processing strategies to accomplish "anytime" control.

Finally, the **Biochemical Systems Group** proposed that NASA consider artificial photoconversion systems based upon the primary electron transfer reactions in natural photosynthesis as a potentially more efficient means to utilize solar energy. While such systems will require long term research, continuing support may be warranted as these systems may allow direct synthesis of most expendables needed for a space vehicle or space colony. On a related topic, this group argued for innovative concepts for the use of bacteria, algae, and plant tissues for waste processing/water purification and for production of biomass for prolonged space missions.

This group also provided a good deal of information on biomolecular electronics including concepts for implementing neural networks with molecular components, cell assembly techniques, and photo-transducer trigger mechanisms. Molecular electronic devices, based upon natural membrane phenomena, will yield much faster and more robust sensors and processors. For example, a group in Munich has developed a hologram using bacteriorhodopsin with less than a picosecond rise time. Neural networks implemented in molecular electronics will be far more robust, and NEC Corp. of Japan has a five year plan to do just this.

Research into denning bears may have applications for a sleep control model and for altering metabolism to counter the calcium loss experienced in microgravity. Denning black bears are in a tranquil but alert state; understanding how this is accomplished may lead to constructive use of sleep time during flight. Research has indicated there is a substance that allows these bears to maintain calcium despite being recumbent for periods of four to five months. Such a substance may help solve the important problem of loss of bone calcium resulting from decreased mechanical loading of bone in microgravity.

This group also proposed a system for carbon dioxide recycling using electrochemical carrier molecules such as those employed by some plants in C_4 photosynthesis. Also, the stomata on leaves of plants, which control transpiration of CO_2 and water, might serve as models for miniature valves.

5.3 Workshop Conclusions

The workshop participants were emphatic in their conclusion that there is **tremendous potential for technical advancements realized through the study and understanding of the engineering principles employed in natural systems.** While it may be a foregone conclusion that a group assembled for this workshop would reach such a conclusion, the workshop itself gave much greater breadth to this belief. Clearly, researchers came in with a belief that their research, based in biology, might be of use to NASA. Yet, comments heard throughout the workshop pointed out that researchers were frequently enlightened to see bionics applications in other scientific areas that also

offered exciting opportunities. In addition, the participants obtained a broader understanding of the technical needs of NASA; needs going far beyond space vehicles and space flight. The participants departed the workshop with a much broader appreciation of the many bionics opportunities that can support technical advances to solve a wide variety of important technical problems.

A common recommendation from all working groups is the **need for multidisciplinary investigator teams** performing bionics research. The very nature of bionics precludes any one researcher from having all the tools, resources or background necessary to address the multitude of issues associated with bionics research. The process of autonomous motor control based on visual data, for example, requires knowledge of biological sensors and information processing, control systems, simulation, mechanics, and materials. A systems approach is essential to understand the complex interactions of these system components. The amount of time to investigate and understand how a natural mechanism or process works requires parallel research from different viewpoints. As man tries to push artificial systems to performance levels comparable to natural system robustness and adaptability, communication between specialists in different areas is paramount, and such information exchange must be on a semi-continuous, working basis, not solely through scientific literature or conferences. The workshop participants are finding such interdisciplinary teams a necessity at present and see them as critical in the future.

As evidenced by the extensive Annotated Bibliography and Bionics Directory as part of this report, there is a great deal of research currently underway. It was recommended that **NASA coordinate its efforts with other agencies** supporting research in this field. These include ONR, AFOSR, DOE, NSF, and others. Many of NASA's technical objectives are complementary with those of other agencies, and cross communication, or even collaboration and co-funding, between agencies should be encouraged. Where unique NASA requirements do exist, these likely will also build on other research completed or in progress. Collaboration with foreign researchers should also be encouraged where appropriate. Leading bionics research efforts can be found in many countries, including England, Germany, Italy, Japan and the Soviet Union. We should attempt to work with these foreign researchers to maximize progress toward realization of the potential of bionics.

The inherent performance of any biological system, whether sensory, neural or musculoskeletal, can be traced to events occurring at the molecular level. Modern technology has recently developed new instrumentation, such as scanning tunneling microscopes, for visualizing molecular level structures, and emerging nanotechnology may soon offer new methods to fabricate such nanoscale structures. These technologies provide the **tools for scientists to unravel the basic building blocks in biological systems**. This knowledge, married with reliable models of system performance, will provide the basis for many of the advancements we will see in technology and in bionics in the years to come.

The workshop generated a list of a number of opportunities for accelerated research in bionics with applicability to aerospace problems. The workshop participants felt it inappropriate for this group to winnow this list further as they had neither the time nor all the knowledge necessary. Critical evaluation of the opportunities of most interest to NASA will require greater consideration of NASA's requirements, more focused evalua-

tion of the biological analogues, and clearer definition of the research steps required. **The workshop recommended that NASA support future workshops** that will be more focused in scope. Such workshops should include NASA personnel with in-depth knowledge of the technology area and NASA's requirements. These individuals would then explore, with leading biologists and bionics researchers, the current knowledge of biological system performance, potential capabilities offered by a bionics system over current technology, and the key research steps needed to understand the biological system and apply these principles in synthetic systems.

In addition, many participants observed that the basic underlying principles of biological systems are of key interest, rather than particular implementations (i.e., organisms). These principles, governed by the interplay of internal and external forces, are adapted and employed by individual species as evolution seeks to optimize specific functions within the environment encountered by that species. Accordingly, it is these basic principles that we, as engineers, seek to adapt and employ in a myriad of implementations to achieve specific functional systems. Thus, the workshop recommended that NASA **conduct a workshop to elucidate these underlying biological principles** so that engineers may consider these in the design of future technological systems.

5.4 Working Group Reports

WORKING GROUP I - MATERIALS AND STRUCTURES

Working Group Members

Eric Baer
Case Western Reserve University

Dave Bowles
NASA Langley Research Center

Harris Burte
Wright Patterson AFB

Helen Ghiradella
SUNY-Albany

Stephen Gunderson
University of Dayton Research Institute

Fred Hedberg
AFOSR

Mahmet Sarikaya
University of Washington

Stephen Wainwright
Duke University

Daniel Winfield
Research Triangle Institute

Past/Current Examples:

- Camouflage
- Corrugated Containers
- Fiber Reinforced Composites
- Ceramic - Metal Matrix Composites

Insect Cuticle as a Model for Fiber Reinforced Composites:

- Novel Architecture Suggests Design Advantages (vs. current synthetic composites).
  - Variable fiber cross-section (primarily elliptical)
  - Variable fiber/ply thickness
  - Variable matrix properties
  - Microfiber bridging
  - Preformed holes - reduces stress concentrations

Biological Materials Characterized By:

- Scale - precision structure at macro, micro, and nano-level. (Frequently up to 6 or 7 levels.)
- Architecture - Levels of scale are organized into a functional architecture that determines final properties.
- Interaction - Principles of interaction between levels of scale not well understood.

Between phases or levels of scale, it is difficult to define where one ends and another begins, i.e. a smooth transition.

FUTURE RESEARCH

- Accommodation to force rather than resistance to force.
  - Synthetic structures are commonly designed for stiffness while biological structures are compliant and accommodate force via controlled deformation. Can we learn principles which will allow us to make lighter structures?
- Processing of high precision bio-like structures.
  - Biological structures display precise architecture. Current manufacturing methods cannot achieve this 3-D precision. To take full advantage of these hierarchical structures, we must develop processing methods which may be modeled after biological processes.
- Novel architectures in nature - design lessons for synthetic materials.
  - Use of the Bessbeetle exoskeleton as a model for fiber reinforced composites is an example.
- "Tailored" crystal growth.
  - Controlled biomineralization can achieve useful bulk properties in crystalline structures.
- Multifunctional units and their materials.
  - Many biological materials serve multiple functions, e.g. whale blubber.
  - Certain cellular units can actually switch their "materials production" in response to environment.
- Adaptive materials which sense environment and respond.
  - Biological materials adapt to environmental stress. Can these serve as models for "smart materials?"
- Gradient structures/information.
  - Regional change in material characteristics or architecture to obtain different structural properties. Typically, structures with smooth transition of microstructure and properties from outside to inside.
- Large deformation recovery.
  - Man-made systems rarely can achieve reliable performance at high strain levels as can biological materials.
- Coping with and/or repair of discrepancies or damage.
  - Biological materials respond to inherent discrepancies or inflicted damage by adapting and/or repairing to remain functional. This can be a model for "self repairing" materials.

These nine "principles" which were identified as areas for research were consolidated in five research areas and used in the following matrix. The areas represent design principles and processes used by natural organisms to achieve reliable materials performance in their environment. Investigation of examples of the principles and processes can lead to new design concepts.

However, this exploration should be driven by design objectives in aerospace materials and structures; hence, the purpose of this matrix. For any given design objective, examples can be found in (usually) more than one of the research areas which contribute to this design objective in nature.

For example, take the design objective of "long service life." Bionic investigation would follow the following path.

Inquiry: Methods by which biological systems cope with preexisting defects or in-service/accident degradation/damage (particularly the latter). Biologic systems often repair/regenerate themselves.

Initial Exploratory Phase

1. Analyze/identify life limiting damage/wear out difficulties with current/future satellites. Object is to find approaches to increase life and/or avoid need for a human EVA.

   e.g. - bearing wear, atomic oxygen surface degradation.

2. Identify examples in biological world which must cope with similar types of degradation and review the approaches used by these biological systems.

Mid Range

3. Select (if they emerge) particular biological approaches to study and evaluate in depth and analyze the potential systems worthy of such an approach.

4. Develop new "self repair" approaches if such appear to be promising.

DESIGN OBJECTIVES / RESEARCH AREAS	Long-Life e.g./SurfaceRegeneration	Lightweight e.g./Fiber Composites	Adaptability e.g./Segmented Structures	Other ....
Accomodation of Force Large Deformation (Non-linear Response)				
Novel Architectures in Nature - Design Lessons				
Processing of Bio-like Precision Structures - Tailored Crystal Growth				
Multifunctionality				
Adaptive Material - Sense and Respond to Ext. Environ. and Int. Condition				

WORKING GROUP II - SENSORY/INFORMATION PROCESSING

Working Group Members

Richard Altes
Chirp Corp.

John Anderson
NASA Headquarters

Eric Bobinsky
NASA Lewis Research Center

Thomas Cronin
Univ. of Maryland - Baltimore County

Dean Hering
Research Triangle Institute

John Hines
NASA Ames Research Center

Pentti Kanerva
NASA Ames Research Center

Larry Myers
Auburn University

Coe Miles
McDonnell Douglas Space Systems Co.

Paul Nachtigall
Naval Ocean Systems Center

Muriel Ross
NASA Ames Research Center

Evangelia Tzanakou
Rutgers University

Igor Vodyanoy
Office of Naval Research

Sensors and Information Processing encompass all aspects of NASA's missions and technologies.

Functional Areas

- Sensing/Processing
- Monitoring/Control
- Analysis/Interpretation
- Enabling Technologies/Tools

Breakthrough Technologies

- Biological Information Processing - M. Ross
- Sensor Fusion - R. Altes
- Autonomous Sensory Motor Systems - P. Kanerva
- Miniaturization - T. Cronin
- Advanced Computation/Information Processing - C. Miles
- Molecular Mechanisms of Sensing - L. Myers

BIOLOGICAL INFORMATION PROCESSING

Deduction of neural organization principles leading to more accurate models of biological information processing. (Heterogeneity) (Energy [Power] Efficient).

Further investigation into biological mechanism of fault tolerance.

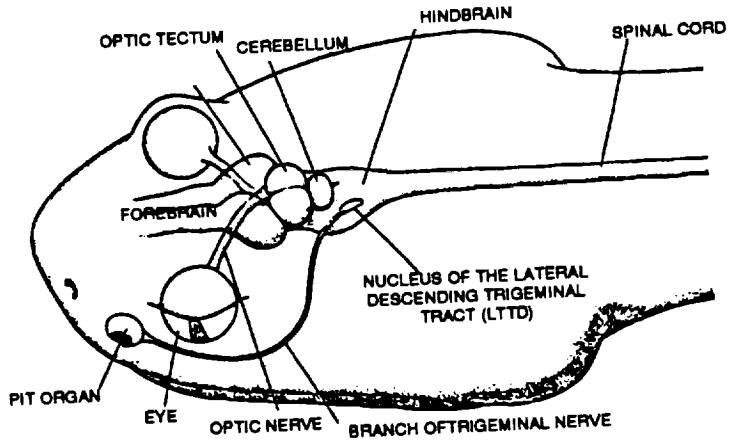
- Redundancy
- Constr. Randomness
- Self-Repair
- Adaptability/Plasticity

Further investigation/development of nonlinear dynamical systems theory with respect to modeling and analysis of biological information processing systems.

- Potential Benefit to NASA:
  - Enabling technology for highly advanced autonomous exploration systems.
  - Context-sensitive information processing.
  - Provide high visibility for NASA in a leading edge technology.
- Resources/Time:
  - Leverage existing programs with reasonable augmentation.
  - With above 5-10 years development time using team approach.
- Likelihood of Success:
  - Excellent if we start with more simple architectures and build from there.
  - Treat the neuron as a collection of simpler computational elements.
- Breadth of Technical Impact:
  - Would revolutionize computer technology, both inside and outside NASA.
  - Would regain U.S. preeminence in computer technology.

A. An Example of Sensor Fusion

LOCATION OF THE OPTIC TECTUM IN THE RATTLESNAKE BRAIN
(Newman and Hartline)

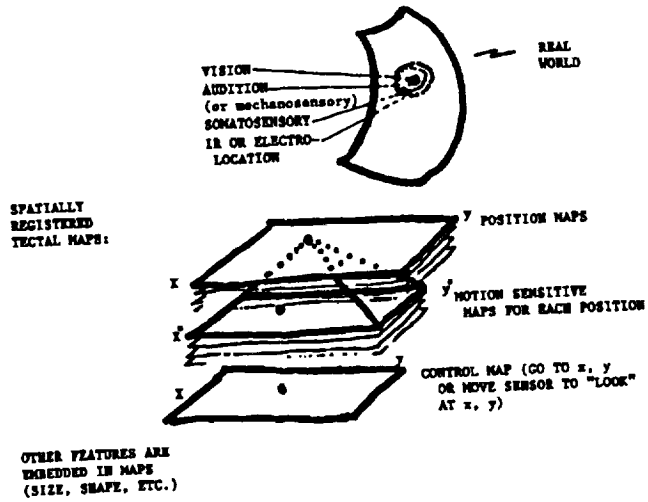


MULTISENSOR INTEGRATION IN THE OPTIC TECTUM
(MAMMALIAN SUPERIOR COLLICULUS)

The optic tectum or superior colliculus contains position sensitive neurons that respond only to stimuli from a given point x in the environment, measured relative to the animal.

The position sensitive neurons are arranged to form an internal map of the external environment.

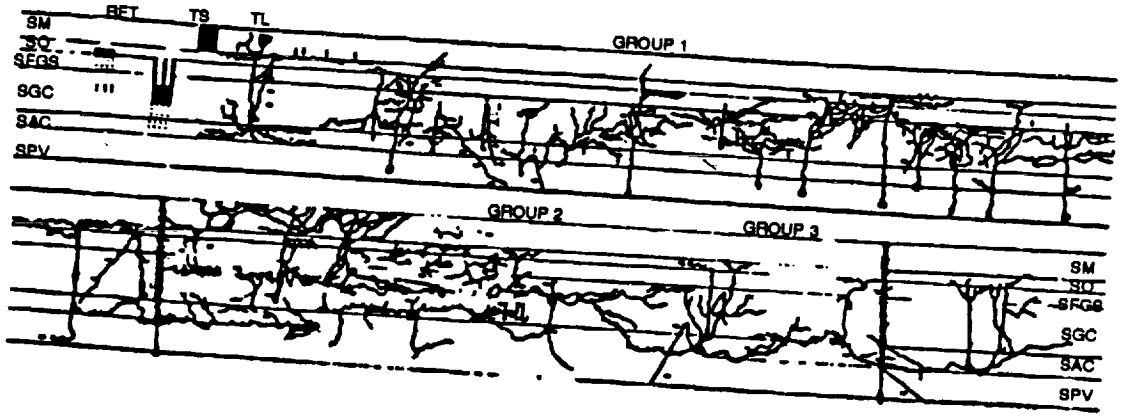
The maps from different sensors are arranged in spatially registered layers. Several layers are obtained from each sensor. Some of these layers contain movement insensitive neurons, while others contain neurons sensitive to motion and direction of motion.



EXAMPLES OF REGISTERED SPATIOTOPIC REPRESENTATIONS IN OPTIC TECTUM OR INFERIOR COLLICULUS

1. Rattlesnake: Vision and Infrared
2. Electric Fish: Electrosensory, Vision, Auditory, and Mechanosensory
3. Barn Owl: Vision and Hearing
4. Toad: Vision and Tactile
5. Mouse: Vision, Auditory, and Tactile

LAMINAR ORGANIZATION OF OPTIC TECTUM IN ELECTRIC FISH

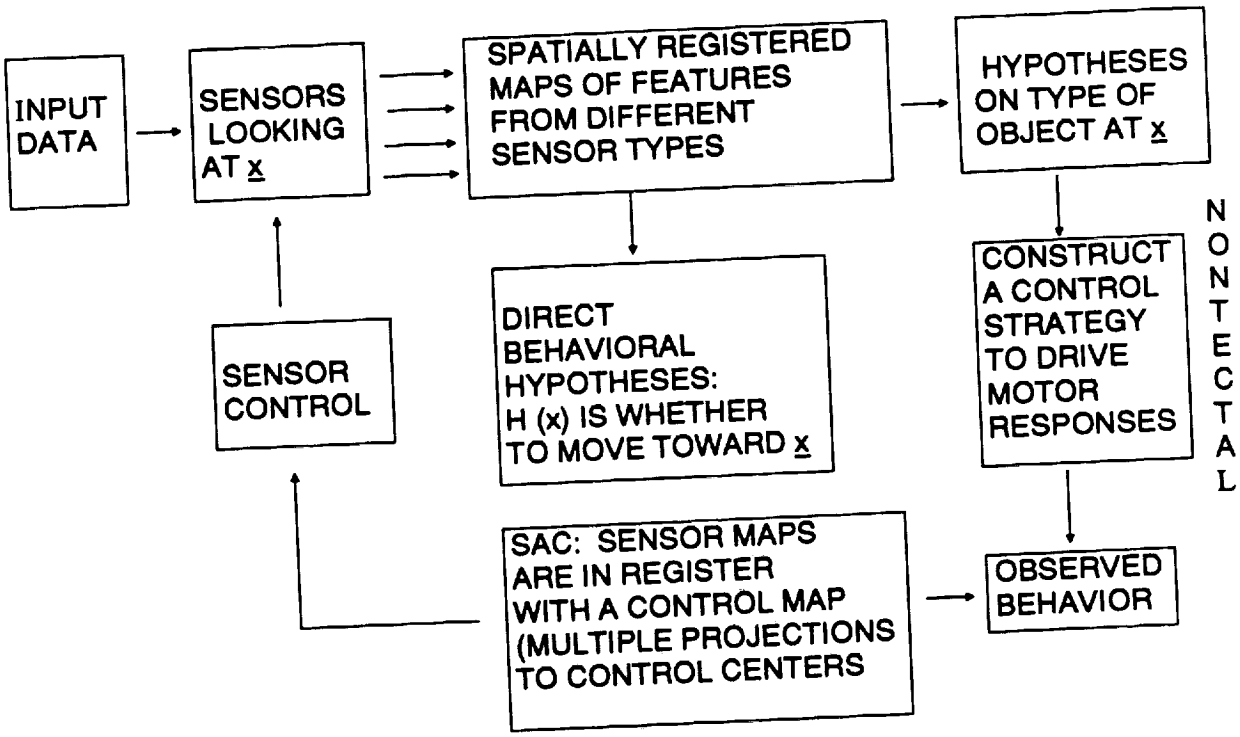


SM (Stratum Marginale): Eye Movement Control
SO (Stratum Opticum): Visual, No Motion Sensitivity
SFGS (Stratum Fibrosum Et Grissum Superficial): Visual, Motion Sensitive
SGC (Stratum Grissum Centrale): Electrosensory, Motion Sensitive
SAC (Stratum Album Centrale): Auditory, Mechanosensory, Motor Map
SPV (Stratum Periventriculare): Diverse Sensors, Possible Motor Map
(Illustration from Carr and Maler; Functions of layers from Heiligenberg and Rose.)
"Motor Map"→ Control of Sensors or Motion of Whole Animal.
Electric Stimulation of Neuron at Point x.
In Motor Map → Fish Moves Toward x.

Optic tectum has control maps in register with sensor maps for direct hypothesis tests that control sensor movement and movement of the whole animal.

Neurons in control map (SAC) form linear (and perhaps nonlinear) combinations of features in sensor maps. Excitation of control neuron at x causes movement toward x. (Heiligenberg and Rose)

Corresponding Hypothesis: Move toward x.

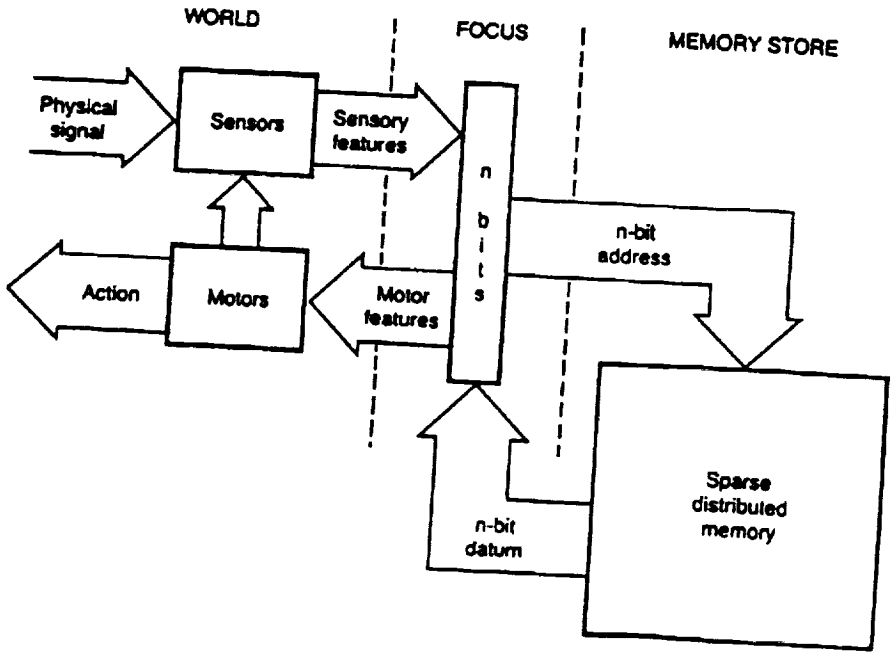


B. NASA Concerns

1. Likelihood of Success: High (good bio. models)
2. Technical Impact
   a. Characterization of environment
   b. Nondestructive testing
   c. Sensor/system control for autonomous systems (ex: tactile and vision for robotic hand)
3. Potential Benefit
   - Earth resources
   - Robost sensing (e.g., SAR through cloud cover)
   - Diagnose and repair faults in autonomous systems (self-diagnosis and repair)

AUTONOMOUS SENSORY - MOTOR SYNTHESIS

- Total systems approach: View animals as complete autonomous systems.
- Control of the system: The nervious system (the brain) integrates the functioning of the animal.
- Engineering principles of the nervous system
  - Distributed representations
  - Expressed in the activity of very large numbers of neurons
  - Organized in many specialized networks for
    - sensing
    - motor action
    - memory
- Model of an autonomous learning system as a framework for the study of the total system.



- SENSORS and MOTORS for interaction with the world.
- MEMORY for storing an internal model of the world.
- FOCUS for connecting the world to the world model.
  - contents are a long, inexact vector
  - represents moment of sensory-motor experience
  - serves as an address to an associative memory

- Basis in nature: The examples come from nature--we are trying to understand the generation and control of learned animal behavior.
- Applications R&D: Many applications will need high-density, low-power computing circuits beyond the capacity of present silicon-based semiconductors.
- Projected NASA benefits: Adaptive ("intelligent") monitors, detectors, and controllers for remote, long-lasting, tedious, and dangerous tasks and missions. The research is also of major national importance.

Brief outline of research plan:

- What needs to be done?
  - By NASA: Long-term commitment to a basic, multidisciplinary research program consonant with the magnitude of the task and with the potential benefits.
  - By the researchers:
    - Specify a mathematical model of autonomous learning system in detail
    - Conduct proof-of-concept experiments
    - Refine the model based on the experiments and on data from neurobiology
    - Conduct neurobiological experiments suggested by the mathematical model
    - Build and test prototype systems with autonomous learning controllers
    - Iterate this entire process.
- How long?
  - Ongoing, well into the next century. The full task of understanding the brain is huge and will require the work of hundreds of scientists over decades, but great incremental benefits can come from incremental understanding. The discovery of a few basic principles can result in major breakthroughts in 10-15 years.
- Resources?
  - Computers for simulation. Neurobiology laboratory facilities. Infrastructure to facilitate multidisciplinary research and interaction. Later, facilities for assembly of hardware prototypes.
- Likelihood fo success: Good. Significiant progress has been made in conceptualizing the problem since the resurgence of the mathematical study of neural nets, but we need to be aware of two pitfalls: oversimplification and getting lost in detail. When in doubt, nature provides many examples to look at.
- Breath of technical impact (i.e., many applications): Broad. Successful uncovering of the principles of information processing used by the brain would have as wide an impact as computers have had to date. A new level of automation would be seen in consumer products and services, transportation, manufacturing, exploration, emergency operations, defense, and environmental monitoring and control.

MINIATURIZATION

- Likelihood of Success - excellent (examples exist)
- Breadth of Technical Impact - wide (e.g. sensors of all modalities, integrators, analyzers)
- Potential Benefit to NASA - obvious
- Resource - Time Requirements - variable (depending on project)

.....

Examples:

1. Sensors
   a. Immunosensors, metal ion sensors, enzyme-based sensors, engineered microorganisms
   b. Bacteriorhodopsin - based photoreceptors
   c. Bioaccelerometers
   d. Modularized, parallel array detectors
   e. Phased - array detectors
   f. Peripheral sensory fusion or specialization
2. Integrators
   a. Advanced semiconductor technology - using principles derived from biological information processing
   b. Distributed processors
   c. Artificial neurons
   d. Sensory feedback

- What needs to be done?
  - Work on specific receptor systems for well-defined tasks
  - Design of optoelectromechanical analogues
  - Emphasize multidisciplinary approaches
- How long will it take?
  - Months to years
- Resources required?
  - Fund basic research on receptors
  - Fund development of sensors

BKTHR TECH:	Advanced computation and information processing; breaking the von Neumann bottleneck.
BASIS:	Observed Biological Systems
APPL:	Sensor Fusion; Pattern Recognition; Dist. Control; Modular and Fault Tolerant Systems
NASA BENEFITS:	[Land] potentially revolutionary, [Space] depends upon success/integration with other technologies such as materials and miniaturization.

RESEARCH:

1. Number of different studies on different species to build-up "Functional Database".
2. Multidisciplinary: (Man-Power)
3. $ $ $ (live exp. are time consuming and very expensive).
   - spread among a number of efforts.

1. IDEA is to generate a fundamentally different way of thinking about how to perform computations.

   2 Major Aspects:

   [a shift in the way engineers think --]

   1) Distributed Processing: job break-down and task processing.

      This arena could make an immediate and significant impact on the way we process data.

   2) Spatial-Temporal Processing: extend dimensionality of current techniques.

      Enable real-time, predictive, control.

2. BASIS: it was noted that animals specialized in their ability [Fly - tracking visual system; dolphins and bats for echo location, Dogs - olfactory acuity]. MAY NEED TO SPECIAL-IZE PEs.

3. APPL: taken from our list of 35 -- presented yesterday!

4. BENEFITS: [Land] can affect the entire technology arena, if successful in the most general case, Data Analysis; Predictive Control; Autonomous Operation, Continuous Operation; Signal Processing.

   [Space]: depends upon success of other Technologies.

5. RESEARCH

   a. One idea espoused in last 2-days was that it may be true that living organisms process info in similar ways -- that is to say, the underlying methods of visual processing etc. may be fixed across a number of species; e.g. mammals.

      One approach is to then perform enough experiments so that an analysis will reveal underlying processes.

   b. By definition this is, or requires, a multidisciplinary activity -- base data is biological, end use is engineering applications/designs.

   c. Live exp. are $$.

   d. From an analytical point of view, we need to construct functionally accurate simulations. I believe this will require large amounts of processing power.

      SUCCESS: Short-term: certainly make incremental improvements in our ability to understand dist. processing - at least in specialized areas.

      Long-Term: GOKASAT! certainly think it possible; the potential benefit is tremendous so risk is worth taking.

MOLECULAR MECHANISMS OF SENSING

L. J. Myers, IBDS, Auburn University
Robert Campbell, ARO

Description:	Encompasses many modalities and includes the study of the interaction between the stimulus event and receptor molecular system and the signal transduction apparatus following that interaction. Particular emphasis upon effective incorporation of such systems into sensor devices is desirable.
Basis in Nature:	Nature holds a substantial lead in its ability to rapidly and selectively detect minute changes in an organism's internal or external environment.
Applications R&D:	Incorporation of biological or biomimetic systems into sensor devices.
Likelihood of Success:	Very high. Bulk of projects are low to moderate risk. Some high risk.

Research Plan:

- Membrane biophysics
- Sensory organ studies
- Recognition and transduction functions
  - ion channel studies
  - second messenger systems
- Incorporation into prototype sensors
  - olfactory based chemo sensors
  - metal-ion sensors
  - rhodopsin-based sensors
  - immunosensors
  - bioaccelerometers
  - many others

Projected NASA benefits:

- Generally: Sensors which have

1) High discrimination/selectivity
2) High sensitivity
3) Real-time performance
4) Adaptability - Optimal for conditions

5) Maximized signal/noise

Novel, improved concepts, materials, and architectures.

- Specifically:
  - Chemical sensors - will change life support and biomedical functions.
  - Visual and mechanical sensors - vital for effective robotics.
  - All - system monitoring and with potential to many other applications.

BIONIC CONTRIBUTIONS TO ENGINEERING

E. Tzanakou and P. Nachtigall

Short Term

1. Interdisciplinary approaches
2. New algorithms
3. Sensory fusion
4. Attention - Data compression
5. Modular electronic analogues
6. Representation of signals
7. Spatio-temporal effects
8. Adaptation mechanisms
9. Man-machine interface
10. von Neumann "bottleneck"
11. Sensory and motor enhancement (lateral inhibition)
12. Computer vision systems based on animal models

New Algorithms

- Distributed control and comp.
- New ways of processing info.
- Hopfield demodulator
- Alopex
- Other . . .

Long Term

1. "Designer" receptor molecules
2. Physics of biological interfaces
3. Bioaccelerometer
4. New algorithms
5. Phased arrays

6. Measurements and control systems
7. Biological amplification and integration
8. Representation of signals
9. Separate tasks for separate machines and animals
10. Fault tolerant systems
11. Computer Vision (cont)
12. Information transmission and telemetry
13. Telescience - Telepresence
14. Faster reaction times
15. Parallel processing with sophisticated artificial neurons

WORKING GROUP III - MECHANICS AND DYNAMICS

Working Group Members

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Duke University

Objectives for Improved Robots:

- Lighter
- Smaller
- More Action
- Cheaper

Current Problems:

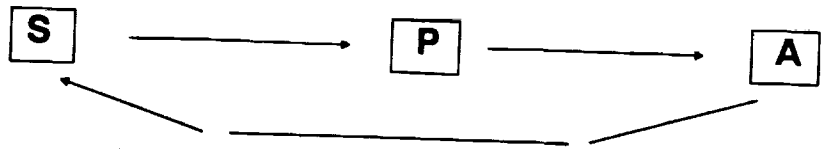
- Size restraints on mechanical/electrical actuators
- Energy conversion devices-now too large

Bionic Derived Solutions:

- Gel actuator (muscle) helps reduce size
- Haptic perception sys.
- Hydrostatic actuators
- Energy conversion (direct)
- Highly redundant systems
- Smart Materials
- Heterogeneous neural networks

Smart Materials:

- Basis in nature - with a processing system, sensor leads to desired actuation.



Needs to Be Accomplished:

Unit Types	Characteristics	Examples
• Sensors	Embedded Redundant Multipurpose	Fiber Optics
• Actuators	High Response High Ratio of Power to Weight High Ratio Power to Volume	Gels Piezoelectric Megnetostrictive
• Processors	Low Level Information High Level Information Integration of Sensor Information	Neural Networks

WORKING GROUP IV - BIOCHEMICAL SYSTEMS

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I. Current Technology

Energy Storage & Conversion:

- High value algal products (activated by stress conditions)
  Ex: Protein, β-carotene
- H_2 production (from waste using photosynthetic bacteria)

Biomolecular Electronics:

- Enzyme sensors
- Immobilization techniques
- Nano-lithography
- Bacterorhodopsin-based switches, memory devices, and imaging

Physiological Systems:

- Drug administration using sensors and physiological models.
  Ex: glucose, blood pressure
- Drug targeting.
- Animal and human models of physiological deconditioning.

Waste Processing/Reclamation:

- Digestion (CH_4)
- Oil-eating bacteria
- Fermentation (ethanol)

- Examples are not all enclusive.
- Technology exists but in many cases needs more development to be practical.

II. Existing Bionics R&D/ III. New Concepts (*)

Energy Storage and Conversion/Photoconversion

(*) • Artificial Photosynthesis.

- H_2 and NH_3 production
- charge separation (light reactions)
- CO_2 fixation (catalyzed dark reactions for product synthesis--i.e. fuels such as methanol and ethanol; chemical intermediates such as ethylene).

• Biological fuel cells and electrolyzers.

Membrane Electrochemistry/Biomolecular Electronics

(*) • Implement neural networks with molecular components (using technology from I.).

• Phototransducer trigger mechanisms (control of ion currents by surface electrochemistry).

(*) • Cell assembly (self assembly techniques).

• ISFET, CHEMFET devices.

• Protein engineering.

Metabolism

(*) • "Bear" model for deep space flight (adapt human physiology to decrease life support requirements such as water, food, and waste).

Physiological Systems

(*) • "Aging" model for physiological deconditioning (weightlessness). Identify counter measures.

(*) • Understand complex control systems (central vs. local control).

• Sleep research - sleep phase changes - 90 min. cycles.

(*) • Radiation protectants (DMSO, radical scavengers - Vitamins C&E, β-carotene, glutathione).

• Plant and animal gravity sensing - isolate molecular species.

Life Support Systems/Air Revitalization

(*) • Re-visit algae for O_2/CO_2/food as well as plants.

(*) • CO_2 pumping/concentration (electrochemical carrier molecules to remove CO_2 from air).

• Bioreactors - light pipes.

(*) • Smart sensors/materials, e.g. turgor pressure as a monitor of watering requirements, bioluminescence devices.

(*) • Stomata as miniature valves.

Water Purification/Waste Processing and Reclam.

- Sterilization/destruction via UV, O_3, $OH^{\bullet}$, and semiconductor processing.

(*) • Biological processing (algae and photosynthetic bacteria).

Bioluminescence

- ?

Biosurfaces

- Natural membrane studies: high surface/volume ratio separations
- Channels
- Wetting properties
- Gills
- Bioadhesive/antifouling
- Micells as bioreactors (star-burst polymers)

BIOCHEMICAL SYSTEMS

Final Priority Concepts

Artificial Photosynthesis:

- Basis - Natural photosynthesis.
- Applic. R&D - Total synthesis of all expendables (i.e. industrial products through ethylene; O_2, glucose, fuels (H_2), amino acids, lipid, energy storage).
- Benefits - Life support, recycling, multifaceted approach to solving problems.
- Research - Long term research problem (10 - 30 years depending on product) to make electrocatalysts to do the above. Continuing long term support is necessary.

Molecular Electronics:

- Basis - Biological information processing; natural membrane phenomena.
- Applic. R&D - Implementation of neural networks with molecular components. ISFET and CHEMFET Devices.
- Benefits - Produce smart devices for life support (monitor trace contaminants and reprocess).
- Research - What needs to be done?
  - R&D of molecular assemblies, nanolithography characterization techniques (for quality control).
  - Prototype ISFET, CHEMFET devices. Multifunctional sensors, flexible actuators, on-chip processors.
  - Theoretical Analysis/Simulation of models based on prototype devices.
  - Methods of making novel and smart molecules.
  - How long? Sensors/actuators - 3 or 5 years. Molecular neural network - 5 to 10 years.

Sleep Control Model:

- Basis - Constructive Use of Sleep Times.
- Applic. R&D - Animal and human models of space flight adaption (sleep cycles and extended passive-alert state).
- Benefits - Improve psycho-social behavior. Reduced life-support requirements (see below).
- Research - Bears.
  - To Be Done:

    EEG patterns during denning.

Isolation of substance(s) responsible for prolonged tranquil but alert state.

How Long - 2 years.

Resources - University Illinois and associated resources.

- Research - Humans
  - To Be Done:

    Exploit coinciding 90 minute space station orbit with established 90 minute human sleep cycle frequency.

    How Long - 2 years.

    Resources - Harvard University Lab.

Secondary Opportunities: (of Sleep Control Model)

- Model for Altering Metabolism
  - Basis - "Denning Bears".
  - Applic. R&D - Dietary control for deep space flight.
  - Benefit - Reduced dietary requirements; prevention of loss of lean body mass; prevention of calcium loss from bones.
  - Research Plan:

    To Be Done: Continuation of isolation of substances which maintain lean body mass and continue normal bone remodeling in the fasting, non weight bearing state.

    How Long - 2 years.

    Resources - University of Illinois and associated resources.

Concentration/Reprocessing:

- Basis - C_4 photosythesis/CO_2 removal from air.
- Applic. R&D - CO_2 recycling using electrochemical carrier molecules.
- Benefits - Life support, gas recycling, trace waste removal for molecules other than CO_2. Can be sized to a space suit. Energy efficient.
- Research - Synthesizing carrier molecules, 3-5 years depending on molecule to be concentrated. Engineering a working system, 1-2 years after suitable carrier molecule synthesized.

Stomata as Miniature Valves:

- Basis - Stomata on leaves.
- Applic. R&D - Miniature Valves.

- Benefit - Miniaturization, weight reduction, power reduction.
- Research - Apply stomatal operating principles to create a miniaturized valve. (Microscopic motors already exist.)
  - Explore bionic model to create a self-regulating gas exchange control membrane (clothing, e.g.).
  - How Long - 3-5 years with immediate start.
  - Resources - National Nanofabrication Facility.

Other Secondary Opportunities:

- Biological Processing Using Bacteria
  - Basis - Normal biological microorganism metabolism.
  - Applic. R&D - Water purification; waste processing.
  - Benefit - Life support system.
  - Research - down-sizing processes to space craft requirements.
- Algae and Plant Tissue Production/Food Processing
  - Basis - New techniques in photobioreactor design and tissue culture production.
  - Applic. R&D - Efficient and diverse biomass production; production of specialized substances (hormones, vitamins).
  - NASA Benefits - Food supply for prolonged space missions.
  - Approach - Innovative bioreactor designs to increase surface/volume ratio and improved light sources (fiber optics and light pipes). Technology to convert biomass to palatable, nutritious food.

6.0 BIONICS RESEARCH OPPORTUNITIES

In this section, we present the key findings of this study; opportunities for accelerated research in bionics that may lead to technological advances of interest to NASA. As a framework, we discuss general features of natural systems with relevance to advanced technology. Incorporated within this framework are specific examples of current research to illustrating how such features are understood and exploited and pointing toward the potential benefits of this type of research. Any study of this type represents a survey of an enormous amount of research activity, and, accordingly, the examples used are for illustration purposes. The discussions are not complete reviews (volumes would be required), nor are we advocating the examples as the best technical approaches. Rather, readers should develop a keen appreciation for the design sophistication in nature, stimulating them to consider such approaches while seeking innovative solutions to technical problems in advanced aerospace systems.

Understanding natural systems design and performance and applying this knowledge to artificial systems is inherently a multidisciplinary task. Natural systems are highly integrated, and systems performance is commonly a function of complex interrelationships between components or subsystems. Bionics research opportunities frequently cross such boundaries; however, in order to provide organization to our discussion, we have segmented it into six topics areas: Biodesign, Materials and Structures, Information Processing, Robotics and Mechanics, Life Support Systems, and Aeronautics. The latter five topics focus upon the technical and scientific principles and the efforts to adapt these principles to artificial system design and construction. As an introduction, the discussion in the first section (authored by Dr. Francesco Iannetti) is from a designer's viewpoint. It describes an approach, perhaps more philosophical in nature, which assumes that nature has achieved a "good" design, if not optimum, through the complex interplay of evolutionary forces. Such design superiority can provide valuable insights even without complete scientific understanding of the basic principles.

6.1 Bio-Design

6.1.1. The Natural State

A simple description of any physical object in nature is that it is made of a material and a design and that its function is the result of the relationship between these entities. This object would be made, of course, from metals, ceramics or polymers, but more than likely from a combination of these, present as a solid, liquid, gas or in a combined and balanced physical state. The design of this object would correspond to the internal and external forms, arrangements or structures of these materials necessary to perform its function in the desired environment.

Biological systems, that is, natural systems that exhibit life or the ability to grow, reproduce and self-repair, have as a strategy the development of highly sophisticated designs to minimize the use of materials (mainly lightweight polymers) and space in the making of their form and to reduce their energy consumption while performing their function(s). These highly advanced designs have as a common objective the harmonization of form and function, achieved through the balance of internal and external forces acting on the natural system and the integration of several functions into the form (Thompson, 1952; Otto, 1967; Williams, 1981; Lenihan, 1986; Halacy, 1965).

The design of biological systems, as well as human or artificially developed ones, improves through constant modification of the existing forms or structures due to a better understanding of the environment. The well known advantage of natural over artificially developed designs is, of course, that nature has had unlimited time to develop them. It is quite obvious that if we took the basic materials that make any example of the living world and gave them to man, he would not be able to achieve the level of design integration and efficiency obtained by nature. An example of this design integration is clearly observed in the analysis of the shape of a powerful swimmer such as the shark. This creature has devices like the mouth, gills, eyes, and other sensors integrated into its form in a way that the interference with flow is minimal, yet the function of these organs are unimpeded (Hertel, 1963). Its skin has many functions: it is a heat exchanger, an environmental sensing device, a self-sealing tank, just to mention a few.

To regard the form of a creature as the result of a force balance is clearly evident when an analysis is made of the mechanical efficiency of the skeletal system of vertebrates. The overall design of this system and the way it is subdivided corresponds to a mechanical design that reduces stress while concurrently increasing its load-carrying capability. Stress reduction is achieved by aligning individual members along tensile and compressive force fields while reducing the alignment along the weakening shear stress component. This mechanical design criteria is repeated from the large scale down to the smallest elements of the system. If one performs a finite element analysis of the structure of bone, the resulting stress field pattern accurately matches the pattern of bony components present in its cross section (Hastings, 1984; Hulbert, 1971).

6.1.2 Bio-Design

The design sophistication of biological systems has encouraged many to develop solutions inspired by the forms and structure of living creatures. This design philosophy is known as Bio-design. Bio-design considers the internal and external architecture of living machines to be extremely efficient design solutions developed to perform multiple role functions in their corresponding environments.

Bio-design is probably the earliest type of design methodology used by man and examples of its application are abundant throughout our history. Probably the greatest beneficiary of this design methodology is the area of transportation design. Early conquest of the air and oceans by man was made possible by using bio-design as the base-line of the objects travelling through these mediums. The use of a fish form for a boat hull or a submarine and the form of a flying bird for the basic configuration of an airplane are not coincidental design solutions. Interestingly enough, these design adaptations were made with very little, if any, scientific knowledge of fluid dynamics but with only the convictions of the pioneer designers that the shapes of these living machines were the best suited forms to perform in the respective environments.

One of the strongest supporters of this design philosophy of our time is Luigi Colani, a Swiss designer based in Germany, who for over 30 years has used bio-design as an inspiration in the design of a wide spectrum of objects, large and small, including several innovative transportation vehicles for all environments. His bio-design approach to aerospace vehicles has resulted in futuristic concepts which

provide a source of inspiration to designers involved in this field, even though some of them are not presently possible.

In 1977, he proposed a super-large size passenger plane concept name "Megalodon", capable of transporting up to 1000 passengers (Figure 6.1). Its aerodynamic shape was obviously inspired by the very efficient fluid-dynamic form of a shark, and thus nicknamed "the Shark Plane". Equipped with ten jet engines, this STOL plane has been designated to reach a cruising speed of Mach 0.98. Once a certain altitude is reached, the main wings have been designed to fold backward (Colani, 1978). Another feature of the extraordinary shape of this creature is being used by fighter aircraft designers who are adapting the "shark nose" configuration as a result of studies that indicate this nose shape produces vortices which are more effective in flow separation control than "conventional" axisymmetric noses (Bushnell, 1991).

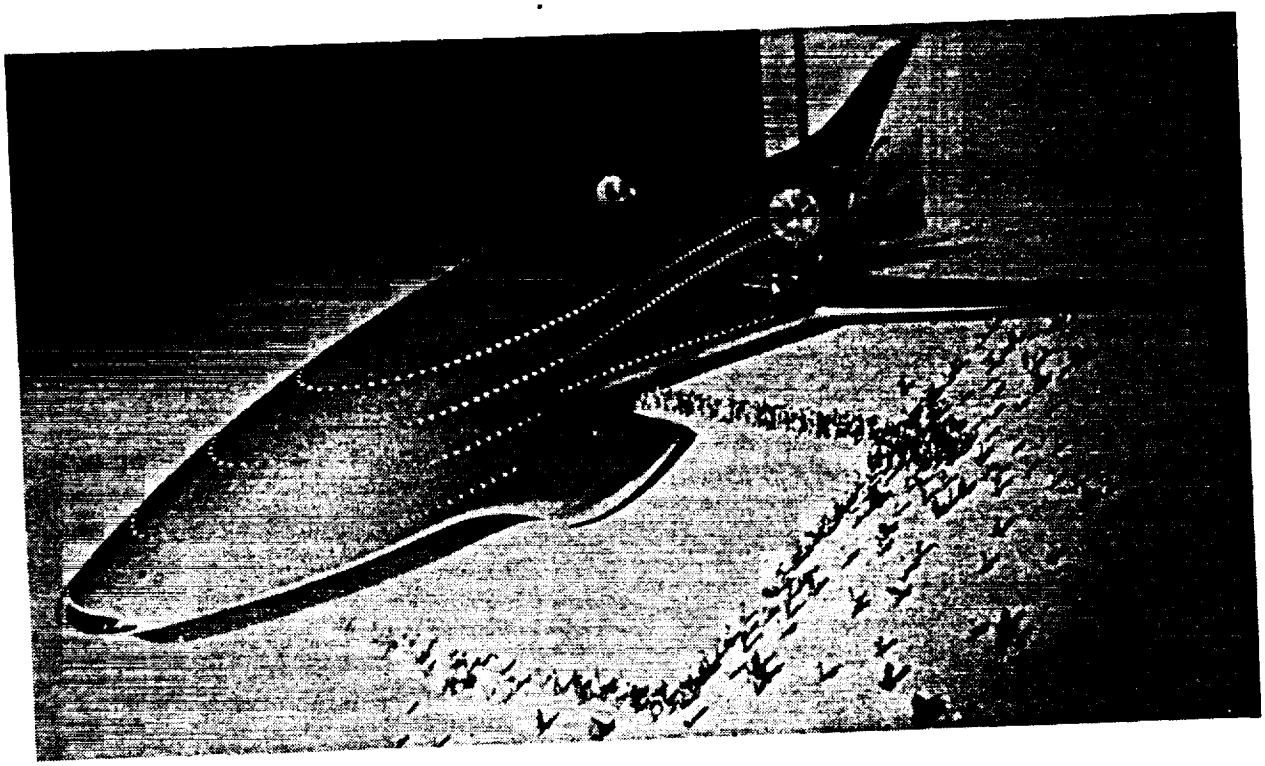

Figure 6.1: Super-large size passenger plane named "Megalodon" whose shape was inspired by that of a shark (Colani, 1977).

In 1978, a Jumbo cargo airfoil was proposed by Colani making use of the high- lift wing developed by Professor Lippisk, an aircraft designer responsible for the first German rocket engine plane during the Second World War (Figure 6.2). Lippisk's inspiration for this flying wing concept was the flight of ducks as they skim over the water surface. Colani's airfoil was additionally influenced by the manta ray, the only large fish to "fly" through water. Similar in shape to the new B-2 bomber developed by Northrop, this airfoil has cargo space within the hollow wings (Coloni, 1978).

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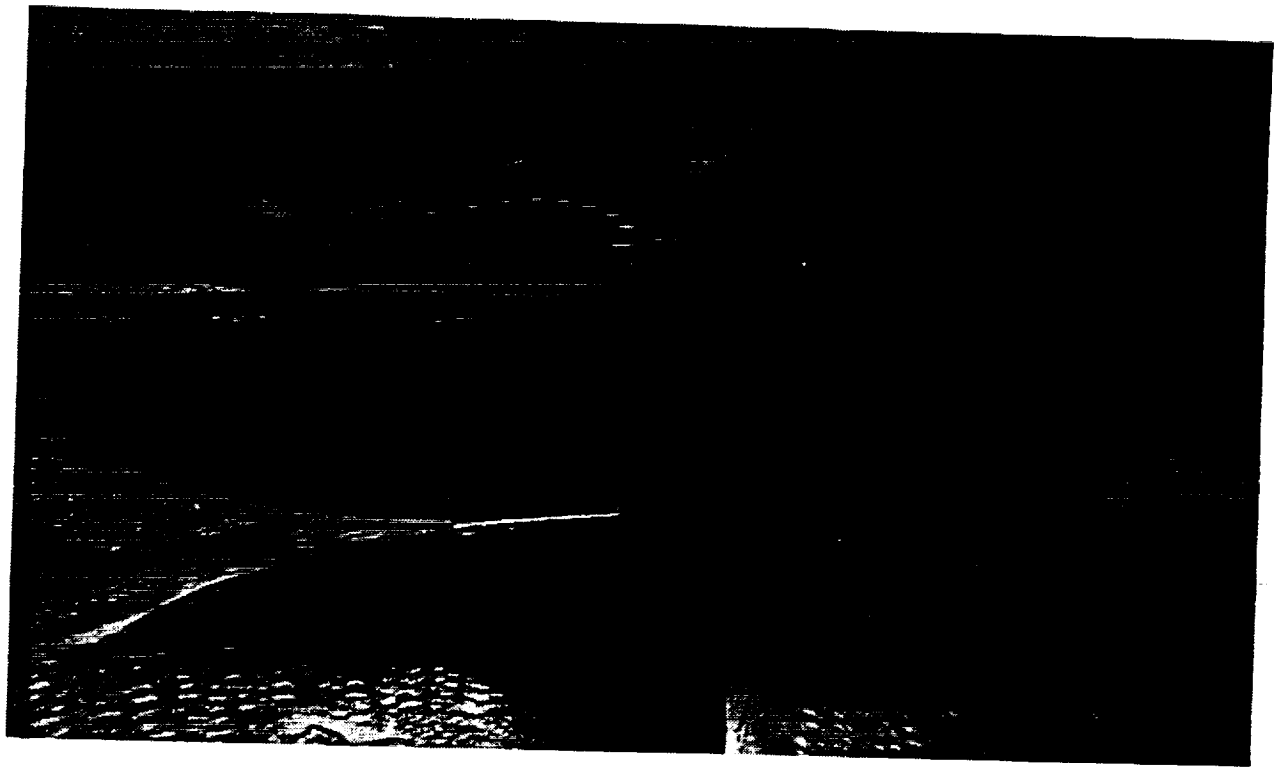

Figure 6.2: Jumbo cargo airfoil similar in concept to the B-2 bomber. Its shape was probably influenced by that of the manta ray (Colani, 1978).

At the request of Rockwell International, Colani developed a Space Shuttle concept named "Polymorph" which seems to have been inspired by the forms of flying insects (Figure 6.3). According to Colani, this concept maximizes the efficiency of both reentry and gliding through the air by composing the overall body in a half circular cone with the nose being the apex (Colani, 1981). The booster rocket would be mounted within the inner bottom of the cone. At the time of return from outer space, the central tail stand would be turned 180° so that it could be used as a vertical stabilizer/rudder. The name "Polymorph" symbolizes the insect-like form change.

Colani has proposed many marine applications of bio-design. One of the most interesting concepts is that for a large sail yacht based on the form taken by the whale as it feeds on plankton (Figure 6.4). According to Colani, the whale is the only aquatic animal to swim in the boundary layer separating the media of air and water when it feeds on plankton (Colani, 1984). The hydrodynamic bio-design displayed by the whale during this activity should serve as a source of inspiration to designers involved in this area of transport.

Many other designers have used bio-design to develop practical solutions to difficult engineering challenges. For instance, Frank Harrod and Francesco Iannetti, Design Ideas of Raleigh, North Carolina, have developed two concepts for an Extravehicular Activity (EVA) glove of a space suit inspired by the external architecture of reptiles and crustaceans. These EVA gloves have been appropriately

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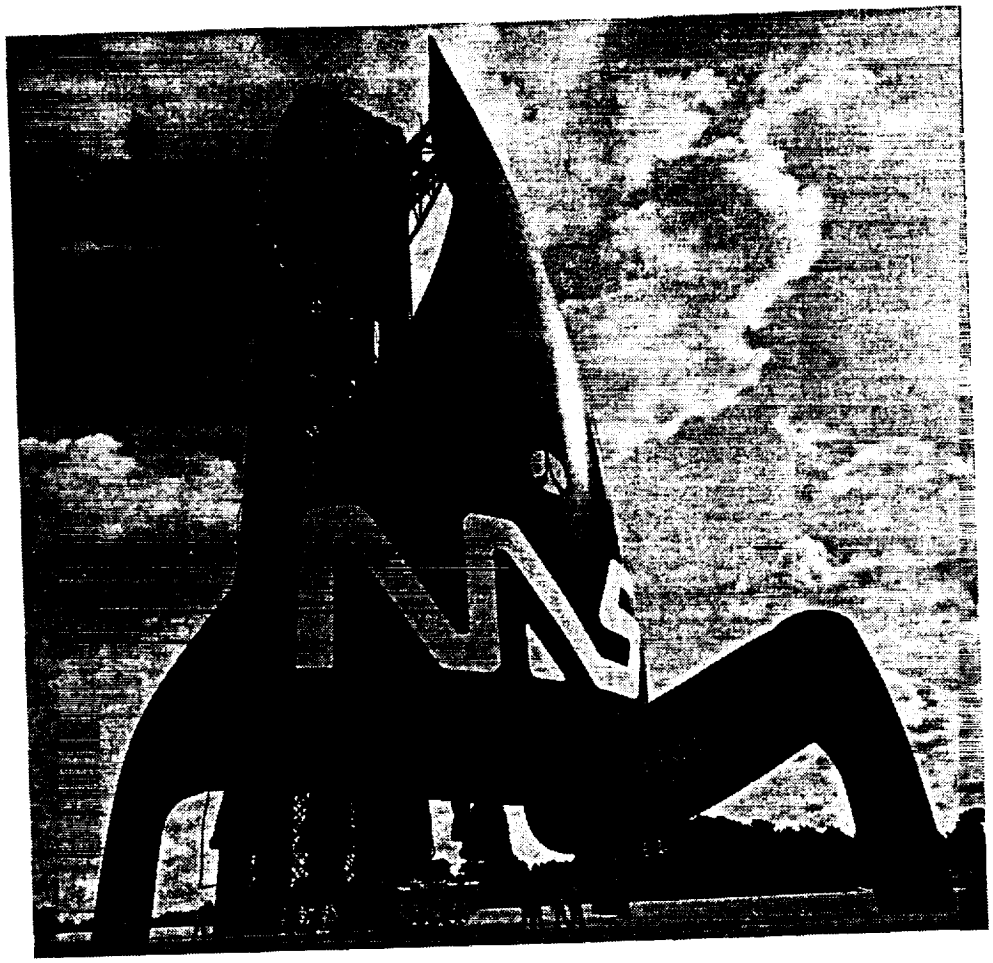

Figure 6.3: Space Shuttle named "Polymorph" designed for Rockwell International (Colani, 1981).

chitecture of reptiles and crustaceans. These EVA gloves have been appropriately named the "Reptus Glove" and "Crusta Glove" concepts, Figures 6.5 through 6.7.

The inspiration to use these living bodies as a design base-line originated because these creatures can easily adapt to different pressure environments with almost negligible effect to their functionability or dexterity. The greatest challenge in the design of an EVA glove is that it must provide efficient hand dexterity while a restraint pressure of 8 psi (14.7 psi would be ideal) is applied inside the glove to protect the hand against the vacuum of space (Cleland, 1985; Parker, 1990). Using current NASA EVA glove designs, it is almost impossible to hold very small objects or to perform more than 6 hours of continuous activity. These problems are due to the amount of extra effort the hand must exert against the restraint pressure, simply to reach and maintain a fixed position.

One of the main innovations of these bio-gloves is the design of the internal pressure layer which is made up of small compartments rather than larger bladders (Figure 6.5). Hand dexterity improves because the small bubble-like structures allows easier bending of the pressurized layer of the glove while concurrently maintaining the required internal pressure. The small subdivisions of this bladder

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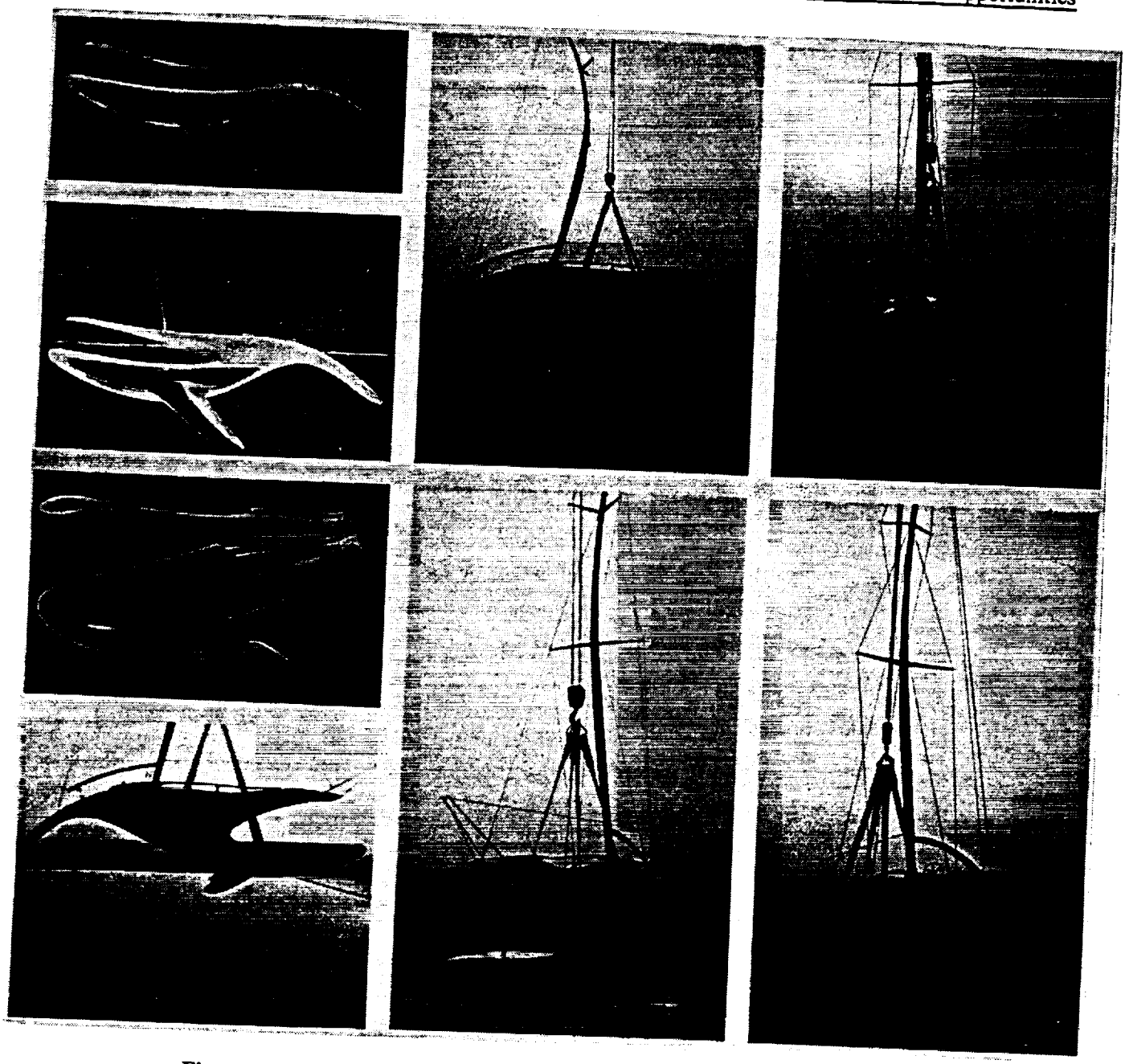

Figure 6.4: Large sail yacht based on the form of a whale as it feeds on plankton (Colani, 1984).

layer was not incidental, but rather it is another aspect of how nature seems to arrange the skin and skin-like layers in living bodies.

The main difference between the two glove concepts is the approach used for the outer protection layer. The Reptus Glove concept has the outer layer based on the skin of a crocodile, that is, a tough surface layer that is made flexible by a high degree of segmentation.

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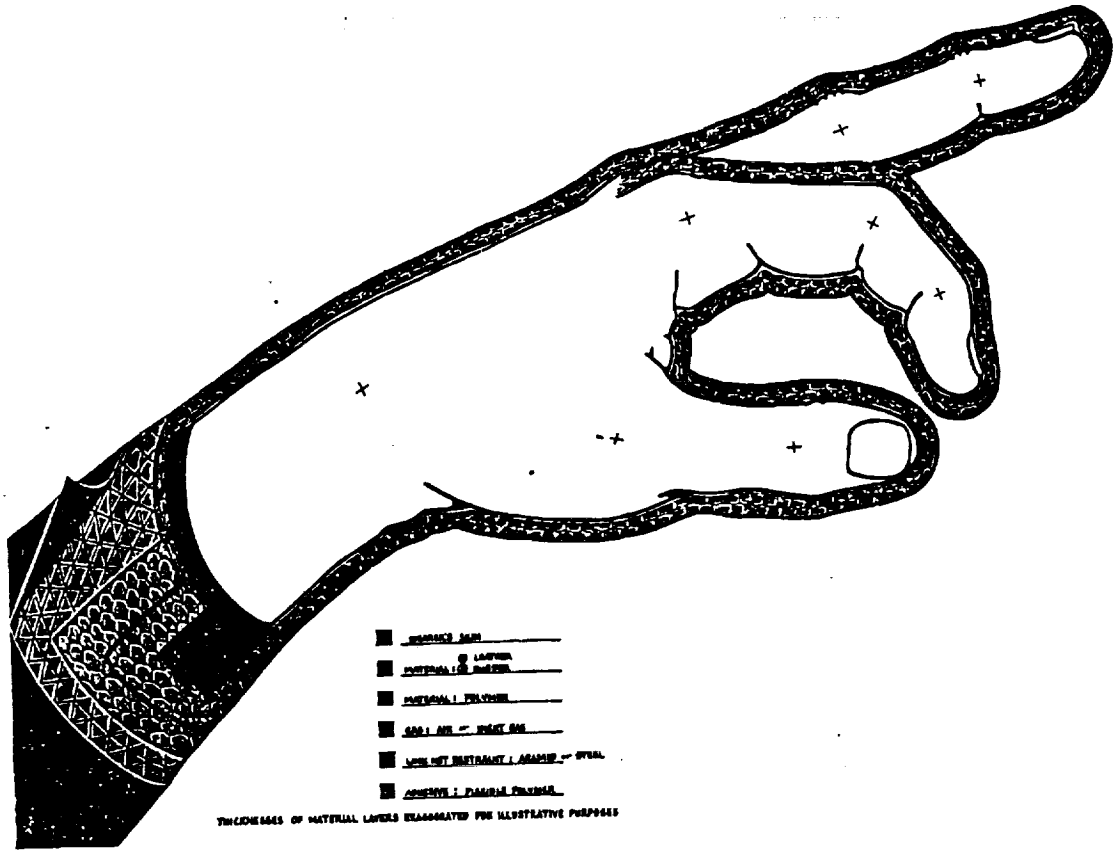

Figure 6.5: Cross-section of the internal pressure layer of the bio-designed extravehicular activity gloves (Reptus and Crusta) showing the highly subdivided pressure layer. (©Design Ideas, 1985).

The Crusta Glove concept instead used the exoskeleton design of crustaceous creatures such as that of a lobster. An important feature of this bio-design is that it not only imparts hand dexterity by incorporating the crustaceous joint configuration throughout the hand, especially around the fingers, but also provides more pressure restraint and hand protection than current NASA EVA glove designs. The exoskeleton idea could be used on current NASA EVA glove technology or on the Reptus Glove outer surface. The outer structure of the Crusta Glove was previously presented to NASA, although details of its internal structure or how it functions were never submitted (Cleland, 1985).

6.1.3 Summary

It is hoped that the above discussion has provided the reader with supportive evidence of the importance of Bio-design as a design philosophy. The fact that Bio-designers refer to the forms or structures of the living as design models is based on the abundant evidence that shows these forms or structures to be accurate mathematical representations of the balance between environmental and functional forces exerted on the creature, and not the result of random or spontaneous events. As was mentioned earlier, a key objective of a biological system is the harmonization

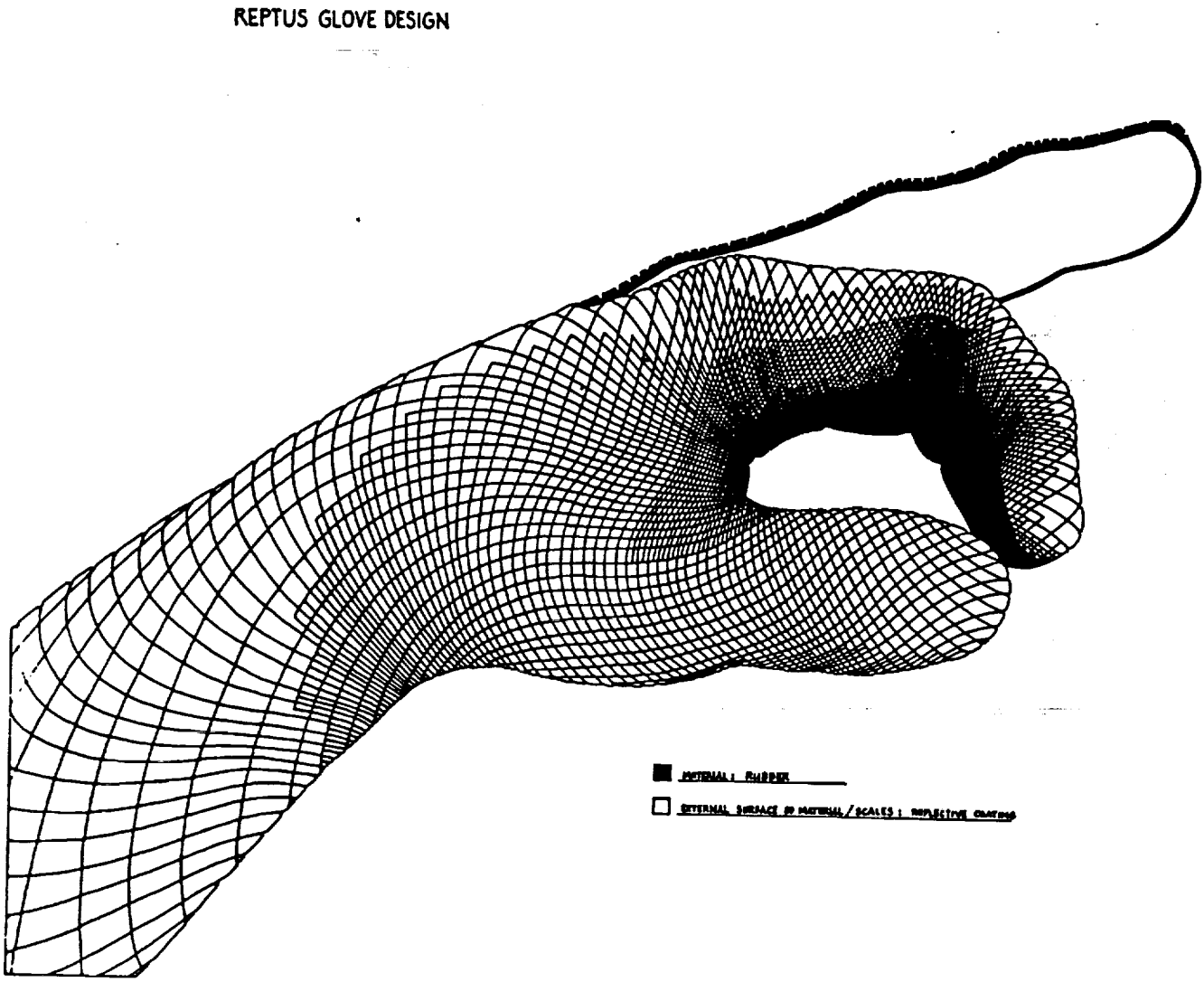

Figure 6.6: Extravehicular Activity Glove concept named the "Reptus Glove" based on reptiles skin (© Design Ideas, 1985).

of form and function achieved through the adoption of a design strategy that allows a high degree of integration or packaging of as many functions as possible into a minimum space with least amount of energy expenditure and material consumption. This excellent design strategy does not imply, however, that biological designs are perfect or optimum, since even nature is in search of this ideal state, continuously adapting to an ever changing environment. Biological systems do present us, however, with a design sophistication that is frequently yet unattainable by man, and thus can provide not only an amazing wealth of easily available design models but also a source of inspiration to designers in search of solutions to difficult and challenging applications.

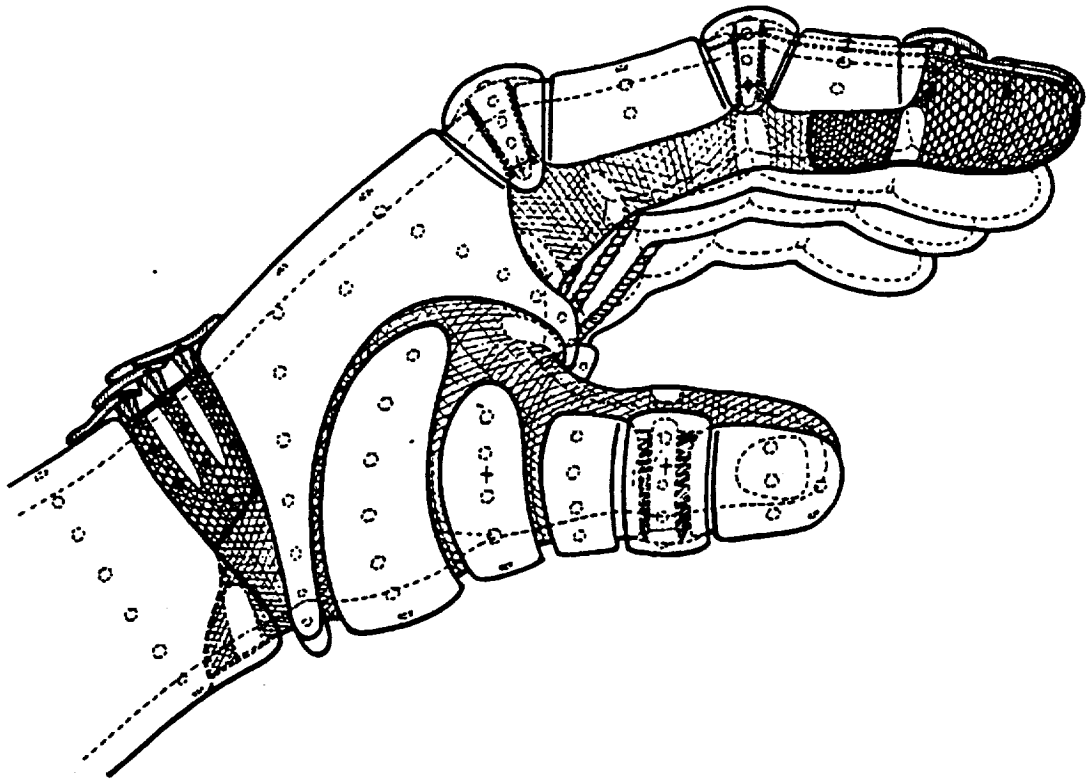

Figure 6.7: Extravehicular Activity Glove concept named the "Crusta Glove" based on the crustacean exoskeleton (© Design Ideas, 1985).

6.2 Materials and Structures

6.2.1 Hierarchical Structures

Significant progress has been made in recent years in determining the structure of biosystems and elucidating the mechanisms involved in some of the biological processes of growth, repair, and mechanical/physical functions. Nature works with a relatively small set of "wet" materials. To accomplish structures with varying mechanical properties, nature organizes the hierarchical structure at the nano-, micro-, and macro-scale. The interaction of materials at various levels of scale is highly advanced in nature. Whereas, the state-of-the-art of synthetic materials is almost primitive by comparison.

The musculoskeletal systems of man and animals, with the combination of bones, muscles, tendons and ligaments, are truly remarkable and efficient load bearing structures. Bones, mostly tubular with dense outer layers and less dense but oriented inner layers, are suitable for resistance to pressure but to only a limited extent to bending. Tendons and ligaments permit tension only. These structural principles lead to elasticity, stiffness, and considerable materials savings. This near perfect combination of compressed and tensioned elements using corresponding materials is rarely used in the field of construction. Interpreting the "knowledge" used by nature in designing such systems may lead to new structural designs for spatial structures, trusses, fabric-covered structures, etc. Yet such an approach must be tempered by the "realities" of materials fabrication technology and construction methods.

Nature designs its materials with all levels of structure, from molecular to macroscopic, intimately related to meet the desired mechanical performance, and, accordingly, the dividing line between structure and materials cannot be defined precisely (Figure 6.8). Baer has proposed three "laws of complex assemblies" that guide the design of all biological connective tissues (Baer, 1990b). First, the macromolecules associate into discrete levels of organizations. Fibrils, composed of smaller subfibrils and microfibrils, are arranged into layered structures. The minimum number of levels he has observed is four, and frequently up to six or seven levels are seen. Second, these levels are held together by highly specific interactions between surfaces. Strong interfacial interactions are required, having chemical and physical specificity. Third, these interacting fibers and matrices are organized into an oriented hierarchical system designed to meet a spectrum of property or function requirements. Materials science has not approached this level of complexity in organization of levels of scale, and interfacial forces are an inherent weakness in most synthetic composite materials. An analysis of these hierarchical structures must interrelate our understanding of structures at various scales, and such analysis may prove valuable in the development of new advanced composite materials and structures.

Baer organized an interdisciplinary workshop, sponsored by the Army Research Office, in 1989 to focus on the fundamental design-property relationships in hierarchical structures and to recommend areas for research to develop new materials and systems in which the design principles used in nature can be employed (Baer, 1990a). Primary recommendations from this workshop were to (1) encourage research into characterization of the structure property relationships in biosystems,

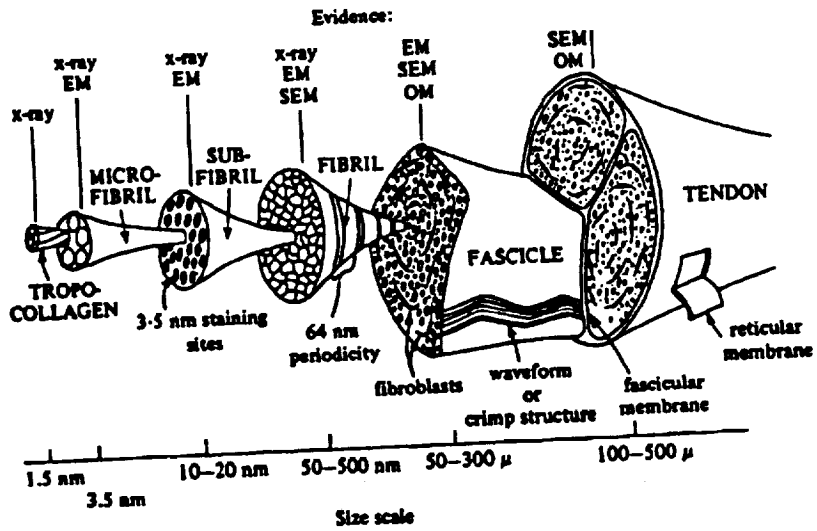

Figure 6.8: Hierarchical tendon structure showing precision levels of scale. (From Baer, 1990b.)

(2) understand the processes of biomineralization so that we may identify techniques for remodeling, self-repair, and developing adaptive structures, (3) investigate biological systems in unusual environments, and (4) study self-assembly and adaptation in biostructures for concepts leading to "smart" materials. More recently, the National Science Foundation sponsored a workshop on Biomolecular Materials, and the National Academy of Sciences has commissioned a panel to produce a report on hierarchical materials. The reader is referred to reports from these three sources for a more in depth discussion of the opportunities in this field.

6.2.2 Novel Architectures

An increasing number of scientists and engineers now see the potential of biosystems and are studying the concepts and principles employed in natural biomaterials and biostructures in order to apply these principles to the next generation of advanced composite materials. This truly is an emerging field in that our literature review reveals few examples until the 1980s. Dr. Stephen Wainwright has led a program at Duke University since the early 1970s in mechanical design in organisms (Wainwright, 1976). He and numerous collaborators and students have studied and elucidated many examples of the use of materials properties and mechanical design to achieve certain mechanical functions. However, for many years, the only substantial interest in this area by engineers was in the study of biomaterials in the human body for the purpose of developing synthetic materials to replace them directly in their function, e.g., optimization of materials for prosthetic devices. The concept of learning design strategies and the complex interactions between biomaterials and applying these to new materials and structures has only recently emerged.

Yet, there is clearly a great deal to learn. First, and perhaps most importantly, bio-structures are organized into very precise structures down to the nanometer

scale. Precise repetitions of molecular structures serve as building blocks for higher levels of organization. For modern technology to achieve this level of hierarchical organization, we must develop processing methods modeled after biological processes. Now that nanotech fabrication techniques are being realized, the potential exists to begin to mimic some of these extraordinarily fine structures.

Nature employs novel architectures in the organization of materials to achieve physical properties for specific mechanical functions. Current researchers are finding that by studying these design architectures, important insights can be gained in the design of similar synthetic structures. For example, researchers at the University of Dayton Research Institute, funded by the Wright R&D Center and AFOSR, are studying the exoskeleton, or cuticle, of the bessbeetle as a model for fiber reinforced composite designs for lightweight, high stiffness aerospace structures (Gunderson, 1989, 1990). The cuticle consists of unidirectional plies of fibers (2-7 microns) arranged in various lay-up orientations ranging from unidirectional to random to a dual helicoid pattern and embedded in a protein matrix (Figure 6.9). There is little or no fiber pull-out upon fracture indicating a potentially superior fiber-matrix interface. Among the interesting design features displayed by insect cuticle and not by current synthetic composites are:

(1) variable fiber cross-section - fibers are primarily elliptical in cross-section (not circular) and vary through the thickness of the structure,

(2) variable fiber/ply thickness - fibers and plies are generally smaller toward the surface, probably contributing to surface stiffness,

(3) variable material properties - the protein matrix is sclerotized, or hardened by cross-linking, near the surface,

(4) microbridging between fibers - microscopic cross fibers connect fiberswithin plies and between plies, thus aiding in maintenance of 3-D fiber orientation and in load transfer, and

(5) preformed holes - in the growth process, fibers are laid down in a continuous manner around holes thus reducing any stress concentrations.

The fiber structure, size and geometry found in insect cuticle may contribute to enhanced mechanical properties by incorporating a fiber size geometry parameter into composite design.

Plant materials can also be a source of inspiration. Wood cells are formed by cellulose microfibrils arranged into concentrically layered cylinders in a hemicellulose-lignin matrix. The cellular structure, the use of internal hydrostatic pressure and prestressing in tension are all methods employed to resist compressive forces. Chaplin, et al have patented a composite structural panel where a series of composite cylinders, panels and sandwich structures were constructed based on the helical winding angle of cellulose fibrils in the wood cell (Chaplin, 1983).

6.2.3 Biomineralization

When biological systems do require compressive strength, this is accomplished by reinforcement with minerals in the form of platelets and crystallites. The processes of biomineralization control the deposition of minerals such as

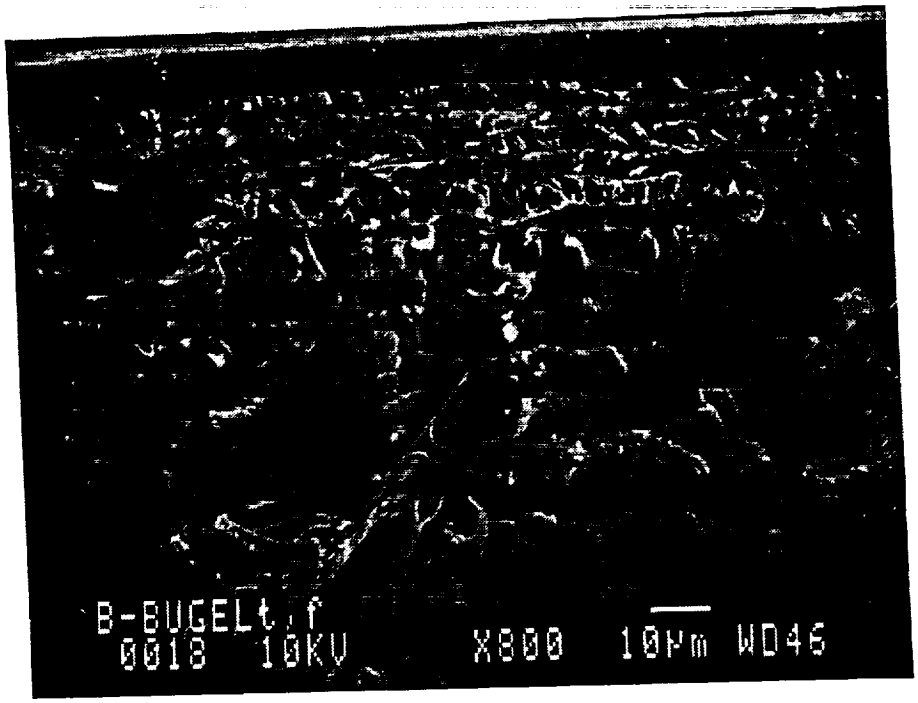

Figure 6.9: Scanning electron micrograph of the bessbeetle cuticle showing the fiber reinforcement. (From Gunderson.)

calcium carbonate and calcium phosphate into tissues to produce materials of great subtlety and complexity when compared to analogous synthetic composites. Most biological composite materials are produced by in situ precipitation while few synthetic materials are produced in this manner. There are three key features which biology adopts in the controlled deposition of mineral particles within polymeric matrices: (1) ion flux regulation at the matrix interface, (2) growth and habit modification by soluble molecules present within the matrix, and (3) crystallographic mediation of nucleation and growth by molecular-specific interactions at the polymer surface (Mann, 1987, 1990; Calvert, 1988).

Scientists at ICI Chemicals have been inspired by the low temperature reproducibility of design and precise functional application of biogenic materials, and have developed materials with high flexural strength and fracture toughness, such as "macro-defect-free" cement (Birchall, 1989). The fundamental role played by organic macromolecular frameworks in the regulation of the mineral deposition might be applied to the formation of complex three dimensional structures for sensors and other devices.

At the Weizmann Institute, researchers are seeking to understand the mystery behind the extremely tough spines of sea urchins (Berman, 1988, 1990). Each spine is composed of a single crystal of calcite, which is normally a brittle material. They have found that as a crystal is being grown from a protein-bearing solution, the proteins are incorporated into the crystal on planes that lie at an angle to the cleavage plane. The proteins apparently act to prevent crack propagation, but synthetic crystals grown in this manner still were not as fracture resistant as sea urchin spines. More recently, the researchers have found that the domains within the

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crystal of urchin spines are smaller (150 nm vs. 500 nm) than those in synthetic calcite, and these domains are misaligned by a larger amount (0.15 deg. vs. 0.03 deg.) Thus, in addition to the crack blunting effect of the protein, since the domains are smaller and less perfectly aligned, any nascent crack will run into a boundary of a domain more quickly and will be less likely to jump to the next domain. How the sea urchin constructs a single crystal remains a mystery, but processes based upon controlled intercalation of macromolecules inside single crystal lattices will be of substantial importance in the material science community.

Processing of ceramic composites for electronic and structural applications requires precise control of compositional and density variations in scale ranges from molecular to microscopic to macroscopic levels. At the University of Washington, Aksay and Sarikaya are trying to improve the toughness of ceramic metal matrix composites (cermets) with a laminate fabrication approach, using the layered structure of seashells as a model (Sarikaya, 1990). The nacre section of abalone shells consists of laminated crystalline calcium carbonate (aragonite) as thin as 0.25 micrometers and 20 nanometer thick layers of organic materials, mostly proteins. This microstructure yields the shell's high fracture toughness and fracture strength. Upon impact, the hard aragonite slides along slip planes formed by layers by riding on the ductile proteins. The aragonite sheets are arranged so as to deter the propagation of cracks through the thickness of the shell. Using this as a model, the researchers have produced lay-ups of ceramic tapes and aluminum foil to produce boron carbide-aluminum cermets with a 45% increase in fracture toughness. Current research to develop means to produce submicrometer layer thicknesses can be expected to yield further dramatic increases in mechanical properties.

6.2.4 Other Design Properties

Mechanical properties are not the only design properties found in natural systems. Iridescent butterfly scales are structurally colored, relying upon the interaction of light with detailed architecture to produce their color. Research by Ghiradella and others (Ghiradella, 1989) has shown that color is produced by two basic forms: lattices that produce diffraction colors and stacks of laminae that produce thin-film interference colors (Figure 6.10). Both structures are remarkably precise. Cowan has used this natural system as inspiration for a new surface relief volume diffractive structure for holographic optical elements (Cowan, 1990). His Aztec grating is designed after the wing scales of the South American morpho family of butterflies in which the structural color is produced by a series of terraced steps placed onto regularly spaced rib vanes. The vertical spacing between two steps is typically 0.2-0.3 nm, which is equal to one-half the wavelength of the color that is seen in reflection from the wing surface. Figure 6.11 shows the similarity between the natural system and the volume diffractive grating. Further precision mimicking of this structural color mechanism has the potential to produce color displays with extraordinary pixel density. Perhaps in the long term, one may even be able to manipulate these structures for an active display.

Another optical structure that has served as the basis for a new optics technology is that of the anti-reflective corneal surface of the moth eye (Schefter, 1989; Wilson, 1982). The absence of reflections from its corneal surface helps the moth avoid detection by predators. Inspection of the corneal surface reveals a three

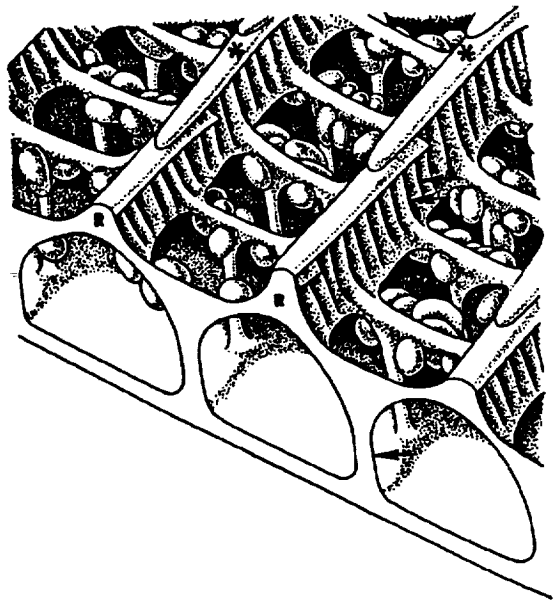

Figure 6.10: Illustration of the structure of the butterfly scale. The structural colors areproduced by diffraction and interference effects. (From Ghiradella.)

dimensional hexagonal grid consisting of peaks and valleys whose contours are smaller than the wavelengths of incident light. This allows the surface to trap or absorb most of the incoming light. This characteristic led scientists at PA Technology, Inc. to develop a method to produce a similar texture into commercially useful films or surfaces (Kalstrom, 1988). This new technology has been applied to high density optical storage discs and will have applications in holographic displays, anti-glare instrument panels, and to a system for instant blood typing.

In miniaturized sensors and electronic devices of the future, the ultimate goal will be fabrication of structures in which the principle active elements are single molecules (see the sub-section on Biomolecular Electronics for more detail). Such a molecular technology will be based on building up structures by using atomic and molecular level forces rather than sculpturing techniques such as lithography. Sleytr and others (Sleytr, 1989) are studying the structure, chemistry, self-assembly and technical application of crystalline bacterial cell surface layers (S-layers). These supramolecular structures represent ideal model systems for learning how nature accomplishes producing and maintaining nanometer structures. The periodic nanometer structures of two dimensional protein crystals have been used as patterning elements for inexpensive parallel nanostructuring of surfaces (Rothschild, 1989). Douglas and Clark (Douglas, 1990) at the University of Colorado have demonstrated a fabrication process for making composite biological/solid state heterostructures of nanometer dimensions. In this process, S-layers of archaebacteria are used as self-assembled templates to produce thin metal films with a two dimensional periodic array of holes. The individual protein molecules selectively self-assemble onto a 1.2 nm thick tantalum-tungsten oxide film which has been patterned into a screen-like lattice with holes of 22 nm periodicity by parallel nanometer molecular lithography. Self assembly is accomplished by preferential electrostatic bonding of the protein molecules to selected sites on the solid state

Figure 6.11: The Aztec grating design (left) was based upon the diffraction mechanism employed by the Morpho family of butterflies (right). (From Cowan.)

lattice. Selective bonding of biomolecules into such a lattice provides a means of fabricating new materials on the nanometer level.

Certain bacteria have the ability to navigate in the geomagnetic field. These magnetotatic bacteria are able to deposit Fe_3O_4 particles in a controlled fashion to optimize the magnetic moment per cell in relation to its receptivity to the geomagnetic field (Mann, 1990). The ability of magnetotactic bacteria to produce magnetite in this highly ordered crystallographic form is of immediate relevance to electronic and magnetic devices.

Using nature as an engineering model, the Center for Biomolecular Science and Engineering within the Naval Research Laboratory is studying how microscopic biological structures assemble themselves. By tinkering with certain biological self-assembly processes, researchers such as these hope to cause self-assembly of microstructures, opening up a whole new area of biomolecular materials. In the Center's most successful project to date, Joel Schnur's group has achieved self-assembly of tiny tubules of phospholipids (Schnur, 1988). The walls of these tubules are made up of several bilayers allowing the tubules to store and release chemicals at a controlled rate. This unusual lipid-based microstructure can be the starting point for many novel applications including drug delivery, producing mildew-resistant, anti-fouling or anti-corrosive paints, or producing lightweight crack-resistant ceramics. The Center is also studying biological receptor membranes for application to new electronic biosensors.

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6.2.5 Biomolecular Electronics

Performance of synthetic systems (and natural systems) is inherently dependent on the fundamental properties of materials and structures employed within the system. Biological systems universally utilize intimate interactions between biological structures to maximize system performance. This section provides a brief discussion of molecular structures that control electrical processes; an area that bridges between "materials and structures" and "information processing", the following section of this report.

The emerging interest in molecule-based electronics is a natural consequence of the trends in the electronics industry toward smaller and smaller dimensions in semiconductor devices. As the scale of electronics structures goes below 100 nanometers, the breakdown in transport laws precludes the use of conventional design and device geometries. Thus, achieving true nanoscale technology relies on the emergence of the ability to produce devices based upon the laws of quantum mechanics. Recent years have seen chemists and biologists develop the ability to fabricate and modify molecular-scale architectures thus opening the opportunity to approach nanoscale technology by building devices from molecular structures (La Brecque, 1989).

Feynman was, perhaps, the first to address the problems of a quantum mechanical computer. He concluded that the laws of physics did not forbid the existence of such a machine, but that its realization would be difficult as not only are the essential interaction coefficients unknown, but also the importance of certain interactions may not be recognized. Since nature has, in fact, been producing and maintaining molecular electronic machines for million of years, it seems natural that biology may hold the key to applying these principles to tomorrow's computer technology.

In biology, there are numerous examples of the organization of molecules into structures that control the transport of mass, charge and energy with time scales ranging from picoseconds to milliseconds. Biological microstructures perform a variety of chemical and electrical functions: switches, proton pumps, power supplies, receptors, effectors, and transducers. The underlying principles are parallel processes and feedback control, and the mechanisms involve electron tunneling, diffusion within or adjacent to the matrix, charge separation across a highly resistive low capacity membrane, energy stored in chemical bonds, and near-thermodynamic equilibrium pools for electron transport. An entire field is emerging for the study of molecular biology with the objectives of (1) uncovering the principles for constructing molecular-scale devices, (2) mimicking nature through application of these principles, and (3) using nature to produce such devices through biosynthetic processes.

New bioelectronic technologies offer potential, yet to be fully assessed, for key advantages relative to semiconductor electronics: (1) self assembly of circuits, (2) extremely small structures measuring possibly 50 nanometers or less, (3) high computing speeds resulting from the fact that bioelectronic processes can handle much information in a single step that even millisecond bioelectronic processes can outperform nanosecond electronic processes, (4) high energy efficiency, (5) flexible biological interfaces that can connect with biological systems, including human

beings, (6) new sensors that are capable of recognizing complex materials or patterns, such as sensors that can smell, (7) high reliability, and (8) intelligent functions through imitation of neural and intelligence patterns of biological systems to perform very complex functions.

Biomolecular systems that store energy of incident photons as chemical energy have a number of features in common with proposed optically coupled molecular electronic devices. Photosynthesis affords numerous examples of energy transduction and charge transport at the nanometer level. Photosynthetic reaction centers contain a chain of dye molecules that mediate the initial stages of phototransduction and charge transport. Studies of the fundamental interactions of the components of these reaction centers may reveal the criteria for design and implementation of molecular charge transporters (Hong, 1989).

Rhodopsin, a membrane glycoprotein integral to the phototransduction mechanism in vision, has attracted considerable interest; as has Halobaterium halobium, a photosynthetic bacterial system which contains a membrane protein similar to rhodopsin. Bacteriorhodopsin absorbs light, which initiates a picosecond isomerization of a chromophore. At cryogenic temperatures, the photocycle is stopped at the primary event, and bacteriorhodopsin is stable in two forms with maximum wavelength absorptions at 568 nm and 610 nm respectively. The corresponding forms can be interconverted with high speed and efficiency by using different excitation wavelengths, thus this is an example of a high efficiency, optically-coupled molecular switch.

Dr. Robert Birge and others at Syracuse University has developed the ability to stabilize these photochromic proteins at higher temperatures (Schick, 1988). They use bacteria to grow protein, harvest it, produce thin films and make thin film devices. They have used a bacteriorhodopsin trimer as a building block for a memory array with high density and capable of optical read/write functions at the picosecond switching rate. Dr. Birge and Dr. Steven Boxer have joined with private investors to form a company to exploit this technology. They are applying this technology to detectors, memory devices, and spatial light modulators.

Dr. Felix Hong and Dr. Michael Conrad are two additional investigators at Wayne State University who are exploring this new field of biomolecular electronics. They have investigated the properties of reconstituted bacteriorhodopsin membranes and demonstrated their suitability for prototype molecular optoelectronic devices (Hong, 1988, 1989). They have proposed a membrane consisting of patches of different structure and composition placed in a two or three dimensional array. Such lateral heterogeneity in a membrane array would make possible a physical realization of a cellular automaton where stimulation of a photocurrent in any given subcell will have an effect on the photocurrent in neighboring subcells (Conrad, 1987, 1988). Computer models indicate that such a device would be a highly efficient pattern recognition device.

6.3 Information Processing

Natural information processing systems allow animals to obtain data concerning internal and external environments and to process the data into an understandable form for making decisions and for control purposes. Man-made systems, especially those designed for aerospace and/or autonomous operation, share at least some of these information processing requirements. Nature's ability to accomplish complex processing within extremely small packages provides motivation in itself for investigating natural processing systems. Coupled with the sensitivity and sheer breadth of the natural processing system's abilities, understanding how nature accomplishes these feats can provide the enabling technologies necessary to overcome current limitations in the exploration of space.

Natural systems operate in a host of environments. One of the fascinating aspects of animals is the wide variety of adaptation strategies that have evolved to survive in these vastly different environments. Animals take advantage of the types of information available to them, filtering and processing the pertinent data to extract the necessary information. Nature provides a number of transducers for extracting this environmental information. Table 6.1 shows some examples of these specialized and incredibly sensitive animal transducers.

TABLE 6.1: Selected Biological Sensitivities of Animal Sensors

Biological Sensor	Sensitivity
Sight (dark-adapted eye)	10 photons/sec-cm^2
Infrared (snake)	10^{-4} W/cm^2 @ 300K
Acoustic (ear)	0.5-angstrom vibrations
Electric Field (fish)	$10^{-2}\mu$ V/m
Displacement (scorpion)	1 angstrom
Smell (moth)	1 molecule
Ultraviolet radiation (bird)	10^{10} photons/sec-cm^2
Seismic (frog)	1 micro-g
Magnetic (pigeon)	10^{-2} gauss
Smart sensor (frog's eye)	"On-chip" processing with algorithms for array processing, edge enhancement, and changing contrast

Traveling to the woods, ocean or zoo is not necessary to observe remarkable natural processing systems; one need look no farther than the mirror. Humans possess an amazing array of sensors and a marvelous real time sensory processing system unmatched by present technology. The human nervous system has been described as an enormously complex real-time parallel computing and control system (Westbrook, 1984). The human senses provide a wealth of information about the environment as shown in Table 6.2. Our own transducers have been optimized for size, energy consumption, adaptability, and to convey a level of detail unmatched by engineering equivalents.

Table 6.2: Physical Effects Detectable by Human Body Senses. (From Westbrook, 1984)

Sensor	Human Transducer	Physical Effect
Vision	eye	electromagnetic radiation between 0.4 and 0.8 μm wavelength--amplitude and directional variations.
Hearing	ear drum cochlea	air pressure waves between 30 Hz and 18 kHz frequency--amplitude and directional variations.
Air Pressure	eardrum/ vestibular system	Static and very slowly varying air pressure
Balance	ear drum vestibular system	variations in gravitational force and direction
Heat	skin nerve cells and hair cells	electromagnetic radiation between 0.8 and 10 μm--amplitude, directional variations and convected air movements
Physical pressure and force	skin nerve cells and muscle strain nerve cells	mechanical pressure and force
Smell	nerve cells in nose lining	selected chemicals diffused in air
Taste	nerve cells in tongue and nose lining	selected chemicals distributed in food and drink

By understanding the design of nature's sensors, we can potentially build devices with similar sensitivities. Similarly, unraveling the remarkable processing techniques that dwarf technological equivalents (if they even exist) promises to enhance future capabilities of man-made systems.

The purpose of this section is to explore some of these areas in the vast array of research being performed in the information processing area of bionics. We shall include both the sensors and processing in the broad definition of information processing, since they are necessarily intertwined.

Sensor mechanisms and design ideas about information processing obtained by studying a particular sensory system may be applied to an entirely different application than in the original system. For example, the brain structure that the cockroach uses to coordinate its movements need not be restricted to six-legged walking machines; the control mechanism might be applied to stabilizing a space vehicle or controlling another dynamic system. It might also reveal principles of parallel computing useful for solving other sorts of processing problems.

While natural sensor and processing techniques may be combined and applied in multiple areas, it is generally instructive to examine natural information processing via the types of sensing that exist in nature. In that light, our examination will be sectioned

into eight areas, some with either sensors or processing and some with both. The areas are: vision, tactile, acoustic, biochemical and olfactory, electromagnetic, navigation, sensory processing, and neural networks and brain structures. Throughout the discussion, we will reference research and related topics to provide a common framework for understanding the interrelated areas of information processing.

6.3.1 Vision

The first area of information processing deals with one of the primary senses that humans and animals use every waking moment: vision. The human eye has much less efficient lens operation in comparison to optical instruments; the eye's lens projects a rather faded image on the retina, with color errors and geometric distortions (Maguerre, 1988). Nonetheless, the human eye is unsurpassed in detecting the differences in brilliance or the finest nuances of color. Given that the system autoadjusts, autorepairs, and has a service life of a senior citizen, the human eye is indeed an amazing structure.

The structure of the eye provides clues to portions of the vision process. Many researchers using different techniques are attempting to decipher these and other mechanisms underlying the visual process. Most researchers concentrate on specific areas, due to the complexity of the processing that exists in a natural visual system. Current researchers, for example, investigate the responses to various stimuli, such as contrast, spatial and temporal frequency, and orientation. Since a vision system needs to process large amounts of information quickly and efficiently, how would we build a system that has a performance similar to humans? Tzanakou's approach was to design a neuromime on a chip that has a number of features that allow it to be used for the study of neurons and neural networks (Tzanakou, 1988). Figure 6.12 shows the block diagram of the chip. The chip can interpret and emit biological level action potentials and standard TTL (transistor-transistor logic--the technology used in digital circuitry) level pulses. Hence, standard logic such as microprocessors, analog to digital (A/D) and digital to analog (D/A) converters,

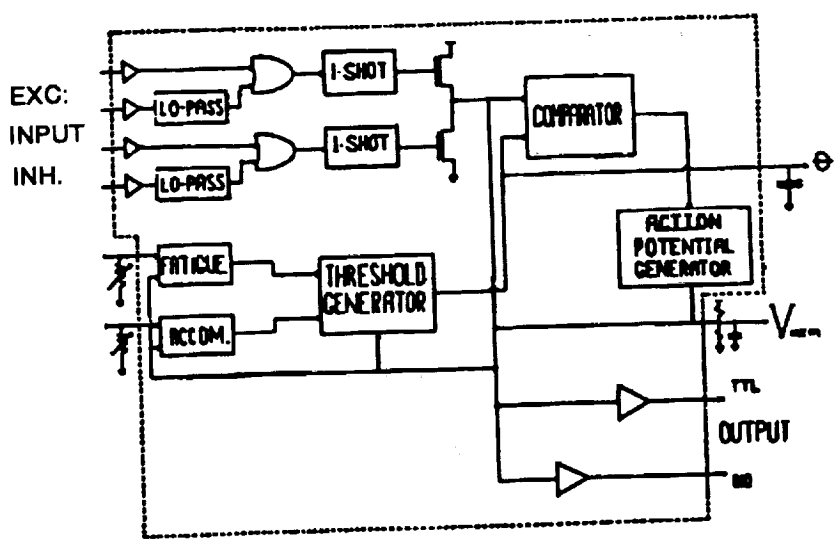

Figure 6.12: "Block" diagram of the IC base neuromine. (From Tzanakou, 1988.)

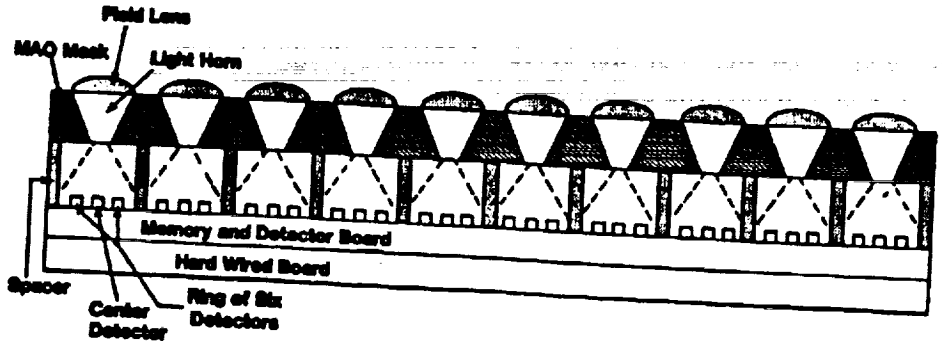

Figure 6.13: Multiaperture Optics (MAO) Device. (From Schneider, 1987.)

memory, etc., may interact with the chip without special interfaces. Since the chip can utilize action potentials from either an electronic or biological source, it can be used to control electromagnetic devices such as motors, relays, and solenoids from biological outputs. Possible applications include robotics, prostheses, artificial retina and vision systems, and future complexneural circuits. This approach reflects the increasingly popular view that the only way to build artificial vision systems is by learning the mechanisms underlying natural vision systems.

The idea of an artificial retina also attracts researchers. By closely following the structure of the human eye, they hope to achieve the same advantages that it has over conventional artificial vision systems (Chiang, 1989; Sandini, 1989). For example, a fully functional VLSI (Very Large Scale Integration) chip was constructed to perform a low level of image feature extraction: orientation selectivity. The chip further demonstrates the suitability of VLSI arrays of photoreceptors and analog CMOS processing circuitry (so called silicon retinas) for early vision processing (Allen, 1988, Mead, 1989). Another VLSI circuit implements a non-linear resistive network for the problem of 2D surface interpolation in the presence of discontinuities (Harris, 1990). The investigators are building a variety of networks which can find edges and compute depth and optical flow in the presence of discontinuities. These networks allow for simple navigation tasks such as following edges or tracking moving light sources.

Human eyes are not the only visual sensors examined in bionics research. The compound eye of insects enables them to perceive a panorama without turning their head. Additionally, a flying insect can steer a steady course by ensuring that the sun only shines on one particular facet of the eye (Maguerre, 1988). The same technique could simplify the design of electronic guidance sytems for better reliability.

The principles of multiaperture eyes are also being used for object recognition and presence detection, and for improving periscopes (Schneider, 1987). They may also provide clues to making smaller vision systems, allowing cameras the size of postage stamps to be fitted on a robot end effector for identifying and picking up objects. Other applications include tracking and measuring, and gazing sensors for detecting pilot eye direction. Figure 6.13 shows an example multiaperture optics device.

Land provides an excellent summary of these multiaperture imaging processes and the other known mechanisms of imaging in animals (Land, 1988). Such applications as an x-ray imaging telescope for deep space research based on lobster eyes are mentioned in his summary (see also Angel, 1979).

Other sea creatures possess phenomenal vision systems. The mantis shrimp eye possesses a diversity of spectral classes that is unsurpassed by any visual system (Land, 1990, Cronin, 1989). The shrimp's eye can discriminate among spectra that have broadly similar shapes but differ slightly in detail. There is an amazing sensitivity to different wavelengths thanks to built in banks of filters. Additionally, the researchers are studying the extreme mobility of the independently moving eyes to understand how information is processed by the shrimp. Since the advanced color vision lies in a narrow strip of the eye, the eyes may actually be scanning to put together the information for the brain. The movement may also be used for tracking. Possible applications for utilizing this research include new methods for scene construction and analysis for narrow but highly sensitive instruments, advanced tracking mechanisms, and schemes for combining information from independently moving sensors. Positioning telescopes and sensitive measuring equipment, autonomous vehicle path planning, and multispectral astronomy research are other applications.

Combining multiple sensor information, as in the mantis shrimp, is also known as sensor fusion. It was an area identified by the Sensors and Information Processing Working Group at the Bionics Workshop as one of the important areas for future research. This applies to many areas of information processing--including the vision area, where the integration of the different types of sensors and processing explored by bionics researchers promises to yield applications which, in addition to those discussed above, include image analysis, guidance, control, inspection, autonomous operations, display techniques, perception, gazing methods, compression, tracking, and a host of others.

6.3.2 Tactile

One of the sensors that is frequently identified as being a candidate for sensor fusion with vision is the tactile sensor. A number of tactile sensors using different techniques based on natural systems are under investigation by bionics researchers.

One bionic tactile robot probe imitates the whiskers found on cats and mice, and antennae/feelers found on insects (Wilson, 1989). The inspiration for the probe designs were the structure and functions of the Johnson organ--the antenna found in most adult insects. The probe's functions/applications include:

1) detecting objects, voids and surface irregularities
2) indicating flight speed
3) detecting the direction of gravity
4) Directional hearing for communications (sensitive to vibrations in the range of 200 to 400 Hz)

First generation probes fulfill the first function reasonably well; suggestions for other applications include robotic collision avoidance, and object outline tracing.

Other tactile sensors resemble the human finger. A four degree of freedom finger, actuated by tendons torqued by DC servomotors, has been developed to work like a finger (Dario, 1985). A multilayer tactile sensor provides sensory information on the physical interaction between the fingertip and the object, much like the human epidermis after which it was modeled. This system is very useful, because it provides end-effector sensitivity for scooping or picking up fragile objects (or those with unknown characteristics) and examining surfaces for variations in texture or composition. It is also important that the sensor is compliant like our skin, providing more friction for grabbing objects without as much force (e.g., it's tough to pick up an egg with a vice).

Several researchers are exploring artificial skin and skin sensor mechanisms based on natural systems. One issue identified is the widely occurring measurement problem of determining the time-space distribution of contact forces between body tissues and the surfaces of bodies either supporting or bounding them. De Rossi's group implemented a synthetic analog of human dermis that mimics the rheological behavior of the human skin (see Figure 6.14). The skin is being used to address the distribution of contact forces problem (De Rossi, 1986). Tactile feedback for EVA gloves, remote sensing such as "feeling" objects on a planet being explored by an autonomous vehicle or by a teleoperated manipulator are possible applications for this research.

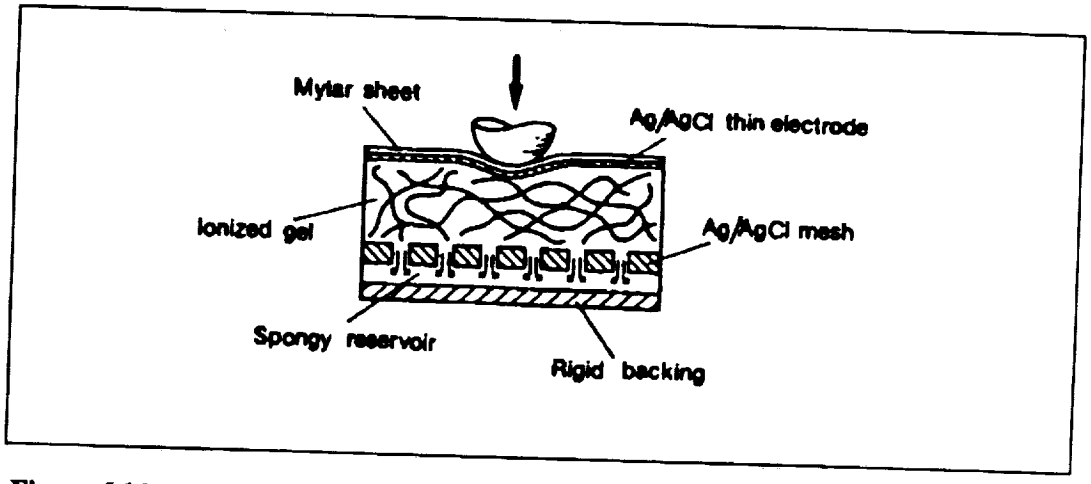

Figure 6.14: Synthetic analog to human skin (DeRossi, 1986).

Another skinlike sensor is the Induced Vibration Touch Sensor (IVTS) (Patterson, 1986). The IVTS exploits motion between the sensor and surfaces for tactile perception in a manner that is based on psychological studies of human sensing strategies. The prototype they fabricated is made of silicone rubber with ridges on the contact area of the sensor (similar to a fingerprint) that slide over surfaces; features and objects of interest and induce vibrations in the sensor. The sensor performed well in experiments in which the sensor had sliding contact with objects such as spheres, Braille alphabet patterns, slotted screws, and sandpaper. Since the sensor is simple, low cost, and sensitive, it may be applied in planetary exploration or space robotic systems for tactile data collection and processing.

6.3.3 Acoustic

A fair body of work has been done in the acoustic area as researchers strive to assist people with hearing difficulties and to understand the echolocation mechanisms of bats and dolphins. Cochlear implants, hearing aids, and the like are significant benefits from research into human audition. In terms of bionics and aerospace applications, the majority of researchers are working on the natural processing of acoustic signals for various applications.

Altes has studied acoustic processing and published a large number of papers--most of the ones discussed in this report are contained in the sensory processing section below. In terms of physical attributes of natural acoustic systems, investigations support the hypothesis that the use of large signal bandwidths by dolphins and some bats may serve to compensate for limited array size (produced in the animals by evolution) (Altes, 1978). A simpler array than current arrays could have considerable impact on the design of future man-made sonar and other applications that use sonar-like techniques. Tradeoffs between bandwidth and array size apply to both target localization and to the measurement of tangential (cross range) velocity--two processes that have aerospace applications in the tracking, landing, and localization of vehicles and objects.

In the same investigations, by studying the dependence of expected error in a cross-range velocity estimate upon parameters such as range, interaural distance, and signal to noise ratio, it is shown that cross range velocity estimation is a feasible process for bats and dolphins to use to compensate for evasive maneuvers by moths and fish--feasible for targets less than one meter from the animal.

These results and the echolocation processing discussed below have applications in the design of man-made systems for communication, radar, sonar, ultrasonics (including medical diagnosis), and telerobotics.

6.3.4 Biochemical/Olfactory

Instruments that perform like noses, sensing and discriminating airborne (or perhaps waterborne) chemicals would be valuable within a closed loop life support system, especially since the human senses do not detect certain chemicals present in air, food, and drinks. Natural olfactory systems display high sensitivity and high discrimination between complex odors. Commonly cited is the fact that the silkworm moth can detect the presence of a single molecule of a chemical (the female's pheromone) in the air. The dog is also a primary biological model capable of detecting concentrations of 10^{-18} molar.

Several researchers have been studying the simulation of the olfactory sense from neural and sensor standpoints (Eisenberg, 1989, Shurmer, 1987). Shurmer discusses the types of sensors that are of current interest and the progress that is being made towards the design and construction of an electronic nose.

The possibility of using an electronic nose has entranced industries with highly varied interests. One example is Krishna Persaud's development of artificial noses and tongues to replace human detectors in such industries as food and brewing. He has designed a truffle hunter to replace pigs and dogs in truffle hunting--the

hunter did quite well in the first round of tests and Persaud expects the device to outperform the pigs and dogs next year (Science, June 22, 1990).

One practical gas sensing device consists of an array of 20 sensor elements on a standard 40 pin integrated circuit. The sensors respond in various degrees to different classes of chemicals, allowing it to "smell" in a manner that resembles receptors found in biological systems (Persaud, 1989). Applications for such systems include detection of gases, evaluation of mixtures for quality control, environmental monitoring, and safety in enclosed environments such as space vehicles, space stations, and planetary colonies.

These examples point to the two research fronts currently being pursued in natural olfactory system investigations: receptor mechanisms and neural network strategies for processing the information. Understanding whether protein receptor sites within a cell membrane interact with odorants to alter the protein structure to perceive odors or if it is the cell membrane itself which acts as the receptor may lead to understanding olfactory perception mechanisms (Ito, 1989). There are other possibilities under investigation as well. The molecular mechanism of ion transport associated with the initial steps in olfaction have been modeled to build novel transducers responsive to different chemicals (Vodyanoy, 1988). Figure 6.15 shows a schematic of the natural sensing membrane and a typical example of an artificial bilayer lipid membrane developed by olfactory researchers.

Researchers are also investigation the neural network processing of olfactory information. One group designed and constructed an electronic neural network which replicates many features exhibited by the olfactory bulb (Eisenberg, 1989). The design uses analog computations analogous to neural networks coupled with digital memory for storing synaptic strengths. Results from the system concur with experimental results. Environmental control, chemical sensing, and detection of dangerous air born molecules are among the many applications of artificial olfactory systems with neural network processing systems.

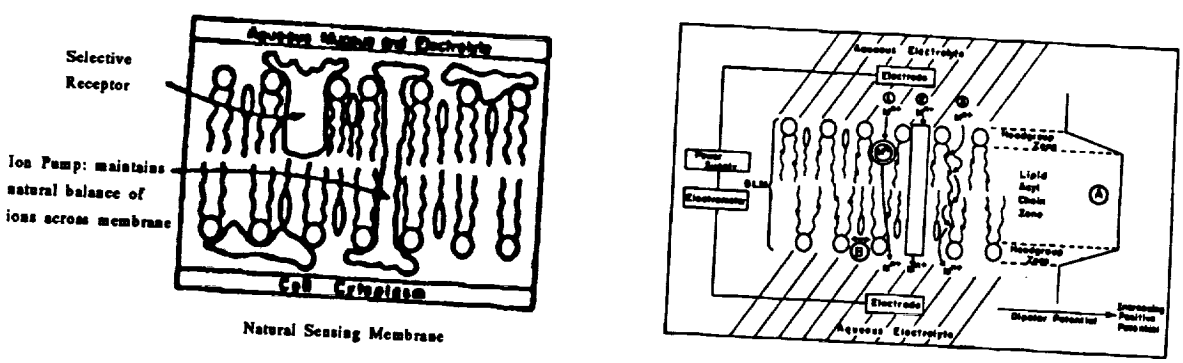

Figure 6.15: Natural olfactory sensing membrane, left, and typical artificial olfactory sensing membrane, right. (From Krull, 1985.)

Even without the electrochemical transducers, the neural networks supporting olfactory recognition provide powerful processing capabilities. Neural networks, parallel and extremely effective structure for general sensory and information processing, are discussed in section 6.3.8.

6.3.5 Electromagnetic

Birds and fish use the earth's magnetic field for guidance; sharks, rays, and eels locate prey and communicate using electric fields. Since man apparently does not possess the capability to naturally sense field effects and since many man-made electromagnetic sensors pale in comparison to nature's, researchers are studying natural systems to understand their electromagnetic sensing capabilities.

Several theories have been proposed to account for the acute sensitivity of marine elasmobranches (cartilaginous fishes) to electric fields (e.g., Pickard, 1988). Some species can detect fields as weak as 0.5 μV/m. The methods achieved by understanding the mechanisms these fish use could be applied to detection and monitoring of electric fields caused by various sources for use in monitoring and control.

Electric fish are capable of detecting modulations in timing of an electrical signal at least as small as 400 ns--a detection mechanism which exceeds the temporal resolution of individual receptors. This phenomena is called "temporal hyperacuity" (Rose, 1985). Some, like the sternopygus, use first order processing mechanisms to distinguish between localized changes in amplitudes of discharges caused by other fish and large field amplitude modulations caused by jamming. This mechanism acts as a local contrast detector, allowing the fish to echolocate even in the presence of jamming (Matsubara, 1981). Potential applications of this sensing ability include detecting signals in noise, communication techniques, and natural and man-made interference/jamming compensation. From ground control to mission or station communication, the animal world may provide the mechanisms for enhanced communication processes.

The sensitivity of electric fish to electromagnetic fields provides them with a wealth of sensor information including direction and orientation cues (Kalmijn, 1987). Furthermore, fields induced by animals passing through the earth's magnetic field provide compass data for navigation and guidance. The detection of fields by the fish is a passive process while deriving the compass heading is active; thus, the fish utilizes both active and passive techniques for electromagnetic field detection and processing. Kalmijn developed a new object detection algorithm based on his work. In a related paper, he discusses, from a relativistic standpoint, how fish orient themselves based on the electric field interacting with the magnetic field of the earth (Kalmijn, 1988).

Applications for electromagnetic sensing include those listed above as well as electromagnetic interference detection and control, autonomous control and guidance, field strength measurement and control, and novel communication techniques. Developments in this area may also provide skin sensors for collision avoidance in robotic manipulators and proximity measurement for space structures.

6.3.6 Navigation

The electromagnetic sensing research discussed above includes navigation processes and applications. Researchers are also studying other navigation techniques employed by natural systems.

The auditory localization behavior of the barn owl is an example of how biological systems may be modeled for application to underwater vehicles (Guastella, 1987). The owl has an audible range of 0.1 kHz to 12 kHz and a sensitivity of -18 dB SPL. It can get bearing, azimuth, and elevation without leaving its perch and can localize pure tones almost as well as noise. The owl uses these processes to arrive at a go/no go decision once prey is identified. If a go decision is elected, the sensory information is continuously updated by the owl while it is in motion until the final phase of attack. The applications listed in the paper are for autonomous underwater vehicles, but other applications including control decision making, navigation and guidance processing, and autonomous control are possible.

Not all researchers are confident in man's application of nature based navigation techniques. Kayton discusses observations on how animals navigate, especially homing pigeons and other birds. Although he foresees a number of potential benefits to utilizing natural navigation techniques, his conclusion in this work is that sensor processing algorithms are inaccessible to man at present (Kayton, 1989).

Pye, on the other hand, developed several systems based on natural navigation and guidance techniques. He studied a number of different bat species to understand the ultrasonic techniques used by the bats for navigation, guidance, and other echolocation and doppler measurements. Bats use different transmitter/transmission and receiver/reception techniques used for different purposes. For example, horseshoe bats wiggle their ears to utilize the doppler effect. Certain bats use chirp waveforms (which are used in man-made radar systems) for more effective processing, and some species of bats have nostrils that are set exactly 1/2 wavelength apart to form an interference pattern of a single forward directed lobe to beam outgoing sound waves. Based on these studies, Pye demonstrated the operation of the bat's processing by constructing several operational transmitter/receiver systems modeled, in form and function, on bats (Pye, 1984). Applications of this work include radar processing and clutter reduction, radio astronomy, navigation and guidance, and communication processing techniques.

Animals other than birds, bats, and fish are also the subject of investigation by bionics researchers. DARPA funded experiments with Nubian goats on simulated rough terrain in order to explore the ways in which natural systems select footholds (Van Voorhis, 1988). A computer simulation of rough terrain traversal was developed in parallel with the animal studies, and pertinent results from the animal experiments were integrated into the computer simulation. The goal of the experiments and developed systems is to further understanding of autonomous performance on rough terrain. Questions concerning techniques for choosing proper footholds, using past information on terrain to renegotiate trails, and sources of information both internal and external to the animal that are relevant to the problem are addressed and could lead to autonomous vehicle navigation and control on rough or alien terrain and path planning techniques for better exploration of planets by legged or wheeled vehicles.

Insects also provide amazing examples of navigational processing. A hunting spider can determine, using a special kind of receptor in the external skeleton and without any external directional clues, the range and direction through which it has moved--up to 0.75 meter (Waterman, 1989). Desert ants, crickets, and other insects may have comparable built-in mechanisms for reading sky polarization for use in navigation. The ant forages by taking a meandering exploration path away from its nest. At all times, however, the ant knows from dead reckoning where its unseen nest hole is and is able to return to it in a straight line using sky polarization. When displaced from their nest hole, the ant searches for the nest using a search pattern consisting of a series of exploratory loops centered about the starting point to which the ant repeatedly returns. The length of these radial explorations increases systematically, following a probability function while the direction varies randomly. Remarkably, this behavior is very similar to a United States Navy ideal search pattern devised for hunting for lost objects such as submarines. These kind of natural search patterns and techniques might lend themselves well to planetary exploration and methods for guiding rovers over a given region in search of desired features.

6.3.7 Sensory Processing

The previous sections straddle the fine line between sensing and sensory processing; indeed, the majority of the sections in information processing combine sensing and sensory processing. Animal systems, like man-made ones, must have both to function properly. While researchers may concentrate on sensor areas, there must be some processing done before the data becomes useful to a system. In this section we briefly review some of the work, concentrating more on the processing than on the sensors.

Vision is a good example of the need for processing sensor data for ultimate system use. Unlike robot vision, where many of the complexities of sensing the environment can be manipulated by tailoring the environment and using special imaging techniques, animal vision must somehow analyze time varying photometric data in its full complexity in real time (Ballard, 1985). Furthermore, biological systems use neural processing elements that are six orders of magnitude slower than silicon components. Yet humans can respond in a variety of ways to visual stimuli in a few hundred milliseconds. Vision researchers would do well indeed if they could embody the natural solutions to problems plaguing artificial vision. Ideas connected with animal vision are playing an increasingly compelling role in shaping computer vision research.

For example, for some tasks information can be processed in parallel--but for modest increases in complexity, the processing becomes sequential. Separation of data into two different levels of abstraction seems to be a fundamental design decision that allows the brain to do its job quickly. Ballard and Brown have incorporated findings like this into their own artificial vision system, and have achieved promising results.

New methods are being developed to analyze biological data and to construct hypotheses for further animal experimentation. These methods can be applied to acoustic imaging and pattern recognition in man-made systems. A range, cross-range ambiguity function and signal processing methods for time frequency data

representations are especially useful. These concepts lead to new design criteria for imaging systems and new insights into echo features for acoustic pattern recognition (Altes, 1987).

Since nature combines different sensor information (sensor fusion) for processing, a natural extension of bionics would lie in that direction. Typical techniques from nature that could lead to significant improvement of man-made systems include: multisensor integration, locally interacting maps, use of real world knowledge for parameter estimation, and distributed hypothesis testing such that hypotheses with different functional significance are tested at different levels or in different parts of the detector/ classifier (Altes, 1985).

Applications for these kinds of research: speech understanding, fault detection based on time varying sensor outputs from machinery or engines, binocular depth and distance perception, multispectral image analysis, synthetic aperture processing and ultrasonic imaging for fault detection in various materials, and the use of multiple sensor inputs for the decision process in a spacecraft or exploration vehicle.

In addition to processing specific sensor information, animals use sensory processing for applications such as communication. Strategies have evolved in animals for combating the problems of communication in a hostile environment (Richards, 1985). Richards compares man-made signals to animal signals and addresses the adaptations of the biological signals to combat problems such as channel degradation, interception, and interference. For example, the Carolina wren uses frequency hopping while communicating so that messages are understood even if large portions of the song are degraded. The reason for designing frequency hopping in communication systems is to avoid jamming. Richards also discusses firefly and fish communication processing. Extracting data from a noisy and changing environment is always a challenge when the source is separated by vast distances in outer space or if the signal is affected by interplanetary disturbances. Animate techniques may be helpful in addressing these kinds of issues in future communication systems

6.3.8 Neural Networks

The sensory processing discussed in the previous sections requires a structure in or on which the processing occurs. Most natural systems process data in the sensor, in the sensor to brain path and in the brain itself. Given the remarkable abilities of natural neural networks for processing, artificial neural networks offer great potential as powerful parallel computational devices. Nearly every researcher in the Bionics Workshop Sensors and Information Processing Working Group uses or has used neural networks as a research tool. They agreed that the potential for neural networks is tremendous; however, the current paradigms used in conventional neural networks (backprop, etc) were deemed insufficient. There was agreement that research in neural networks must address the biological neural network--how the brain's neural networks function--in order to allow neural networks to reach their full potential. The following represents a small sampling of the vast neural networks research currently under investigation. The emphasis of these examples is to show some of the work being performed in the bionics area.

The National Science Foundation organized a two day invitational workshop on the control of biological systems by neural networks. The participants decided on the following research priorities (Bekey, 1990):

1) New simulation tools for neural networks, including the ability to address system level topics.

2) More realistic neuron models, including the multinodal behavior of single neurons, presynaptic inhibition, frequency dependent effects, and other aspects of the behavior of living neurons. Models of greater complexity may be needed to account for the richness of behavior patterns observed in living systems.

3) New heterogeneous network architectures, containing models of a variety of neurons. Such architectures may be needed to allow for emergent behavior patterns, such as those in living control systems.

4) New architectures for engineering adaptive control systems based on biological prototypes. Such networks may yield improved control of engineering processes, as well as facilitating the development of prosthetic devices.

A recurring theme in recommendations made by the participants in this workshop as well as the bionics workshop is the need to form interdisciplinary research teams for work in neural networks.

In a vein similar to the conclusions of these two workshops, Freeman has proposed a model which overcomes shortcomings of particular neural network models; the model is based on simulations of the neural dynamics of olfactory pattern recognition in mammals. A hardware realization of the system described by their equations--the SPOCK--can be made to provide a fast, versatile, trainable, robust pattern recognizer in 1, 2 or higher dimensions. The SPOCK is an alternative to the Von Neumann digital computer architecture as a parallel hybrid device that incorporates digital memory to simulate retention and modification of the synaptic weights. It optimally combines the features of analog dynamics and the digital computer (Freeman, 1987). One can envision a workstation using this technique to process vast amounts of data collected in space for analysis. Analog dynamics can accomplish many processes which are difficult to implement digitally.

The fact that nervous systems of biological organisms are considerably more complex and heterogeneous than artificial neural networks seems to be responsible for much of the computational power of nervous systems. Artificial neural networks which incorporate biologically inspired heterogeneity contain a variety of neural elements with unique intrinsic properties connected in a carefully planned pattern. Data obtained from the neuroethological and neurobiological study of insect walking was used as the basis for constructing a locomotion controller for a six legged simulated insect (Chiel, 1989). The network was designed and perturbed to examine the robustness of the controller by studying its ability to generate statically stable gaits in the presence of a variety of sensory, central, and motor lesions. The artificial neural network for hexapod locomotion that they have constructed is extremely robust. The richness of the controller is due to its

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heterogeneity. They suggest that their network can serve as a useful guide for focusing a more mathematical analysis and interpreting its results.

Arbib, to help expand the concepts of computation to embrace the style of the brain, examined natural systems, such as how frog brains extract visual data which enables the frog to detour around a barrier to reach its prey and how the human neural network is involved in the control of skilled hand movements (Arbib, 1989). Applications include modeling neural networks to study how to best control a mobile robot or develop the next generation of machine vision systems. He suggests that the study of the brain defines a sixth generation of computers which will be characterized by melding into computer design the insights of brain research and cognitive science as catalyzed by developments in computer networking and parallel computation and such implementation technologies as optical computing. According to Arbib, the hardware of the brain offers nothing to technology in speed, but may offer ideas on connectivity and adaptability. The study of specific neural systems has many implications for the development of novel computer architectures. Arbib discusses three main issues he maintains are glossed over in backprop studies: complexity--is the network complex enough to encode a solution method; practicality--can the net achieve such a solution within a feasible period of time; efficacy--how can we guarantee that the generalization achieved by the machine matches our conception of a useful solution. He notes that the sixth generation computer must combine neural strategies based on the brain with other strategies that are better suited to tasks such as addition.

Another approach to understanding natural neural networks is to examine the actual physical structure of an animal's neural network. A study of montages, tracings, and reconstructions prepared from a series of 570 consecutive ultrathin sections shows that a rat maculas are morphologically organized for parallel processing of linear acceleratory information (Ross, 1988). Analyzing the physical structure of the rat provides a better understanding of how a natural system is constructed to process information. Applications for this particular network, in addition to general neural network processing, include advanced small accelerometers. Figure 6.16 shows gravity receptors that process information in a manner similar to parallel processing computers.

Kanerva approaches the neural networks area from a slightly different standpoint. He seeks to understand the functioning of animals in terms of their structure and materials, and to develop the technology that allows us to duplicate these functions (Kanerva, 1986). The language of an instinctive model of an animal is the language of sensation and action: sensory events are translated into actions. Kanerva presents a model of the organization of autonomous learning systems that includes connections to the world through sensors and effectors, memory for storing a model of the world based on experiences, and a central place between the two called a focus that holds a long vector representing the system's experience at any given moment. Learning is effected by storing temporal sequences of states of the focus in memory and recalling learned experiences. Performing learned actions means retrieving stored sequences from the memory into the focus. The memory can store experiences for later retrieval into the focus; these experiences contain information from sensory, motor, and internal (feeling) components. A system equipped with such a memory has the potential for planning actions and for learning

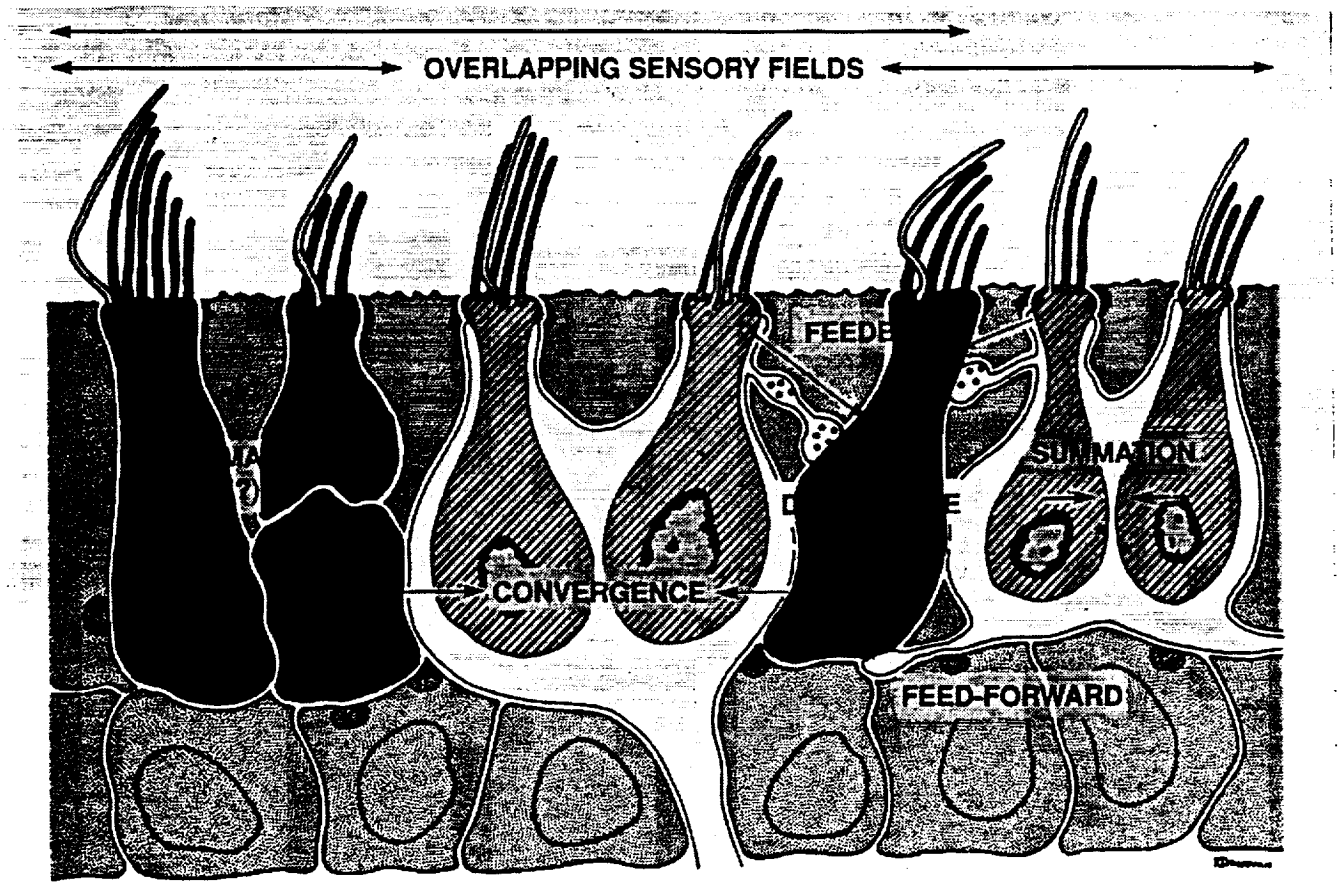

Figure 6.16: Cross-sections show that gravity receptors process information much like parallel processing computers (Ross, 1990).

new actions; however, much work needs to be done before engineering principles employed by nature become the standard for engineers. Some of the promising application areas include signal processing, combining information from multiple senses (sensor fusion), continuous feedback control, associative and experience control systems, and learning/control by analogy.

In a related paper, Flynn describes how to construct a computer memory that would allow the computer to recognize patterns and to recall sequences the way humans do: the sparse distributed memory (Flynn, 1988). Such a memory is remarkably similar in structure to a conventional computer memory and also to the neural circuits in the cortex of the cerebellum of the human brain. This model is an implementation of the above research.

There are countless other researchers investigating neural networks. Many are investigating networks or procedures whose connection with biology is tenuous at best. Others are interested in purely biological investigations. Many more are what we have termed bionic. While it is not possible to discuss all research being

explored in this area, just as it is not possible to discuss all work being done in a particular sensor area, hopefully the topics touched on here will provide a glimpse into the amazing potential of neural networks and computing. These network techniques may be applied to all the sensors we have explored in this section. Our exploration has included specific sensors for applications in vision, tactile, acoustic, olfactory, electromagnetic, and navigational systems. We also described investigations concerning the sensory processing of the data provided by the sensors and structures for accomplishing the processing in the form of neural networks.

The Sensors and Sensory Processing Working Group identified a score or so research possibilities that can advance the areas touched upon here. A host of applications were identified in this section; countless more abound in the area of information processing. As data collection methods improve and the sheer volume of data continues to increase drastically, the need for processing the information in real time continues to outstrip current technology. By incorporating the enormous capability of natural information processing with conventional techniques, the potential ability to process information and effectively apply it staggers the imagination.

6.4 Robotics

In time, most maintenance and repair of space structures as well as many exploration tasks will be performed by robots due to the high cost of manned extravehicular activity. Initially, these will be teleoperated robots, but the ultimate goal will be to allow these robots to perform most, if not all, routine tasks autonomously. The Flight Telerobotic Servicer is the first of these "worker" robots, but others to follow will help man to construct future space stations and lunar bases and to explore the surfaces of Mars and other celestial bodies.

Teleoperation and semi-autonomous and autonomous robotics are very active research areas for NASA and other technology organizations, but many technical challenges remain to be solved. There are several areas that bionics research may make significant impact in surmounting these technical problems. Several candidate areas are discussed in this section including innovative, dexterous manipulator design, legged locomotion systems, muscle-like actuators, and adaptive robust control.

6.4.1 Legged Locomotion

As NASA presses forward with a new exploration initiative, manned and unmanned surface rovers will undoubtedly play an important role by providing sufficient surface mobility to explore wider expanses of these new frontiers. The lunar rover from the Apollo era was a wheeled vehicle, as have been most concepts for planetary rovers. However, legged rovers (walking machines) will have the ability to traverse more irregular terrain thus allowing exploration of potentially more interesting geographical regions. NASA already has active programs, primarily through the Jet Propulsion Laboratory to develop such walking rovers. Research into the gaits and locomotor control systems of insects, crustaceans, and mammals have contributed to the design of research level walking machines developed by numerous investigators, and much is yet to be learned and applied through further study of these systems.

Robert McGhee was one of the early pioneers in the research in walking machines in the 1960s (Frank, 1968), and he spent much time analyzing photographs of the gait of a horse in developing his first such machine. Later, at Ohio State, he developed the OSU Hexapod, an insect-like vehicle (McGhee, 1984). McGhee and Kenneth Waldron then went on to build the Adaptive Suspension Vehicle for DARPA (Waldron, 1985). Waldron continues his interest in walking machines at Ohio State and recently worked with Martin Marietta Corporation to develop a concept for an agile walking robot (Figure 6.17) for planetary surface exploration (Speissbach, 1989).

Alexander has been a leading researcher in understanding the nature of gaits in the locomotion of animals (Alexander, 1984, 1989). While he has not directly developed walking machines, he is consulted by those who do. In recent years, Marc Raibert has made significant contributions to the development of dynamic balancing of walking machines (Raibert, 1983, 1986). Dynamic balance is a requirement for smooth gait of any walker, natural or artificial, with less than six legs. Cruse and others are studying the coordination of leg movement in various animal classes, and such research will undoubtedly apply to design of similar mechanisms to control walking legs in machines (Cruse, 1990).

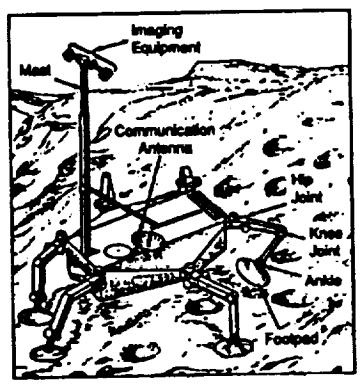

Figure 6.17: Insect-like hexapod robot concept for planetary exploration.

Some animals, such as starfish and centipedes, have continuously flexible legs that are well adapted to locomotion over rough surfaces. Wilson, et al have evaluated the overall structure and motions of such legs and employed these biological characteristics in two laboratory scale heaxapod robots which use internally pressurized, rubber legs (Wilson, 1989). These compliant legs may be more robust; less prone to tripping or damage from leg impact collisions. Wilson also has studied spiders that jump and nemertean worms that loop for their potential applications to unique walking machines (Wilson, 1984). Todd has also proposed the concept of conformal locomotion wherein a vehicle of variable geometry conforms to the objects it comes in contact with, gaining support and maneuvrability (Todd, 1989).

6.4.2 Neurocontrol of Complex Systems

Advances in computer technology have allowed significant progress in developing walking machines in recent years, yet the walking of an animal is much more versatile, elegant and effective. For navigation and control calculations, the agile walking robot proposed by Martin Marietta would require nine processors each operating at 1 million instructions per second. Conversely, the cockroach uses a microscopic processor consisting of only one million neurons to control all distinct systems, and this system is adaptable and displays rudimentary learning capability (Figure 6.18). Locomotion control in animals is mostly reflex. The central processor, the brain, makes basic direction and speed decisions, while the reflex system takes care of the low level details of sensing, actuation and coordination. Studies of biological systems with very low level central processing capability, such as the cockroach, may be the key to gaining necessary understanding of this type of distributed control system (Chiel, 1989).

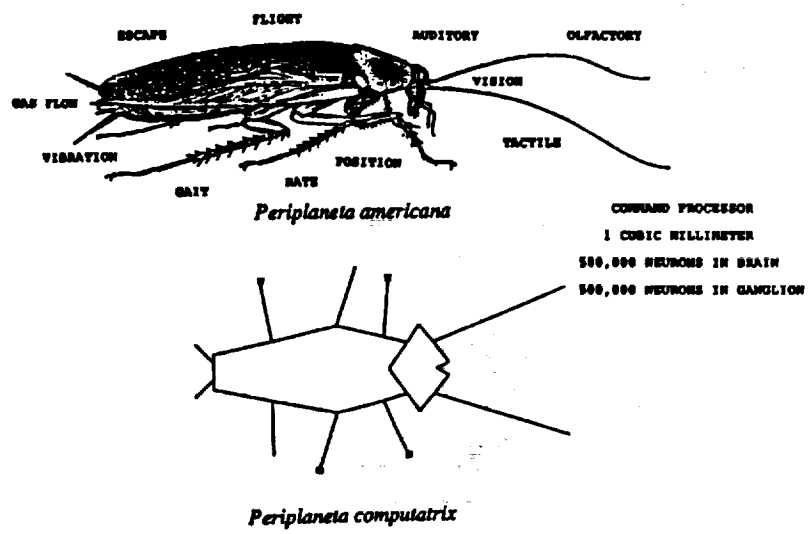

Figure 6.18: The cockroach is an example of a "primitive" system capable of processing input from multiple sensor pathways to control locomotion, search and escape behaviors.

The autonomous walking machine is one of many engineering systems for which man has been unsuccessful, to date, in developing automated systems for control. Neural networks are the essential elements for control of biological counterparts to these engineering systems (Daunicht, 1989). The existence of the brain is proof that such automated control systems can be designed; based upon parallel analog hardware, operating within a high degree of noise and nonlinearity, and achieving a high degree of robustness and stability. By duplicating, or even approaching, these capabilities of the brain, systems which were risky or impossible to control in the past may now become controllable. Significant research effort proceeds on this objective, and numerous theories are being investigated (Miller, 1990; Maren, In Press). Neurocontrol is an important field, not only because it may allow engineers to control previously uncontrollable systems, but also because of its contribution to understanding how the human mind operates. Werbos points out

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that how useful biological research is to reverse engineering (or true understanding) of the brain will depend on the success of efforts to deepen the collaboration between engineers and biologists (Werbos, In press).

6.4.3 Dexterous Manipulation

One of the goals of robotics research is to develop robotic devices capable of accomplishing dexterous manipulation in unstructured environments (Malecki, 1990). Achieving this goal will require improvements in sensing (see Sec. 6.3), control (see above) and end effector performance. Much of the recent research in dexterous end effector design has focused on multifingered hands such as the Utah/MIT Hand (Jacobsen, 1986) and the Jameson Hand. Design and control of these multifingered hands has benefited from the study of human hand motor control. Further benefits can be expected and researchers should be encouraged to seek to understand and apply how the human achieves dexterous manipulation.

However, biology may inspire other useful manipulator concepts than simply anthropomorhic hands. Depending upon the types of dexterous tasks required, insight may be gained from studying manipulation by insects, crustaceans, squids, elephants and other species. While some biological manipulators may not be as versatile as the human hand, they may very well be optimized for particular types of handling tasks. Nearly all present day robots are equipped with arms constructed of relatively rigid members connected by hinges or pivoted joints. Wilson, et al, have taken a novel approach to employ highly flexible, compliant manipulators that bend as an elephant's trunk or squid's tentacle (Wilson, 1986, 1989). Such manipulators consist of convoluted, orthotropic, rubber tubes that bend when subjected to internal pressure and are robust, fast acting and lightweight. Typical laboratory scale manipulators of this type have payload ratios in the range from one to ten.

6.4.4 Artificial Muscle Actuators

There is general agreement within the robotics community that we urgently need significant performance improvements in actuators for higher power to weight ratios, and lower volume to weight ratios. Many researchers view biological muscles a model actuators for robotics. Biological systems employ joint actuation systems in the form of linear actuators constructed of contractile material (muscle). A number of different laboratories have developed contractile hydrogels that exploit the volume-phase transition properties to contract in response to a variety of controllable means, such as light, temperature, electric field and pH (Tanaka, 1981, 1987; DeRossi, 1985; Suzuki, 1990). Using these materials, investigators have constructed "artificial muscles" with strength and reaction times comparable to human muscle (DeRossi, 1986; Caldwell, 1990). While hurdles remain in harnessing contractile gels into practical devices, this challenges mechanical engineers to design new mechanisms which take maximum advantage of this new linear actuation method. Clearly, the most widespread and diverse "machines" employing linear actuators for movement control are biological systems, and designers should learn from this systems as they attempt to design entirely new types of mobile machines.

An interesting marriage of this artificial muscle research and the research on hydrostat manipulators by Wilson and Wainwright (discussed above) has been

proposed by Frisch. He proposes to develop a class of artificial muscular hydrostats that can be used as robot end effectors; mimicking naturally occuring systems such as tentacles, trunks, and serpentines. The physical structure of a muscular hydrostat consists almost entirely of the actuator system itself. Figure 6.19 shows a cross section of an elephant trunk revealing the cross helical muscles, longitudinal muscles and radial muscles which form the trunk structure. Substantial weight savings and increased power to weight ratios will be inherent in such a structures. Challenges will be to develop generic mechano-chemical gels into useful fiber structures and provide means for activation of these structures. Biological systems will guide us in selecting artificial muscle fiber orientations, and selective activation could accomplish controlled movement with strength, flexibility and dexterity. Wilson has looked at the control of such flexible manipulators, but rigorous dynamics modeling and simulation will be required to understand the dynamics of such systems (Wilson, 1989). Neurocontrol, as discussed above, will undoubtedly be integral to successful real-time control of such a system.

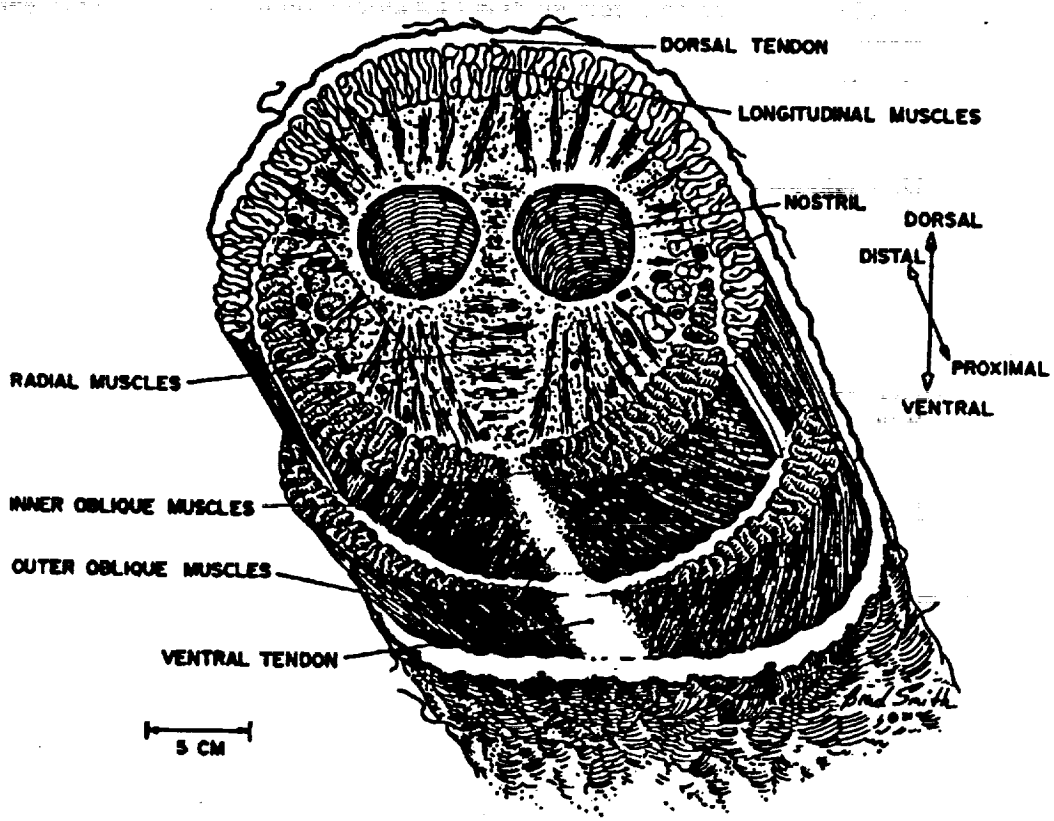

Figure 6.19: Cross-section of elephant trunk showing radial, longitudinal and oblique muscle orientations. (From Wilson.)

6.5 Life Support Systems

With the establishment of a new exploration initiative involving lunar bases and manned missions to Mars, NASA faces extreme technological challenges to safely support crews for extended durations. The high cost of transportation makes crew rotation and resupply very expensive; thus, self sufficiency becomes a necessity. Closed loop life support must provide air, water, and food, while removing and recycling wastes and contaminants. Power generation must be sufficient for environmental control and operations. Constraints of weight, volume and power consumption will drive new advances in technology to meet these demands.

Perhaps the most direct improvement to closed loop life support systems, as well as to most other spacecraft systems, is to make more efficient use of the primary source of available energy: sunlight. Current technology relies upon photovoltaics to produce electricity from solar energy, or in some cases, to convert the solar energy to thermal energy. Photoconversion processes, on the other hand, can yield stored chemical energy at high theoretical solar conversion efficiencies (Figure 6.20). The basic physical phenomenon which allows the green plant to be the best converter of solar quanta that exists today is the fact that it has evolved a system of photoelectron transfer, which involves the transfer of an electron across a phase boundary. Photoconversion research may lead to the next generation of fuel and chemical producing solar energy technologies (Seibert, 1986), and should be of particular interest to NASA in the development of self sufficient space vehicles or colonies.

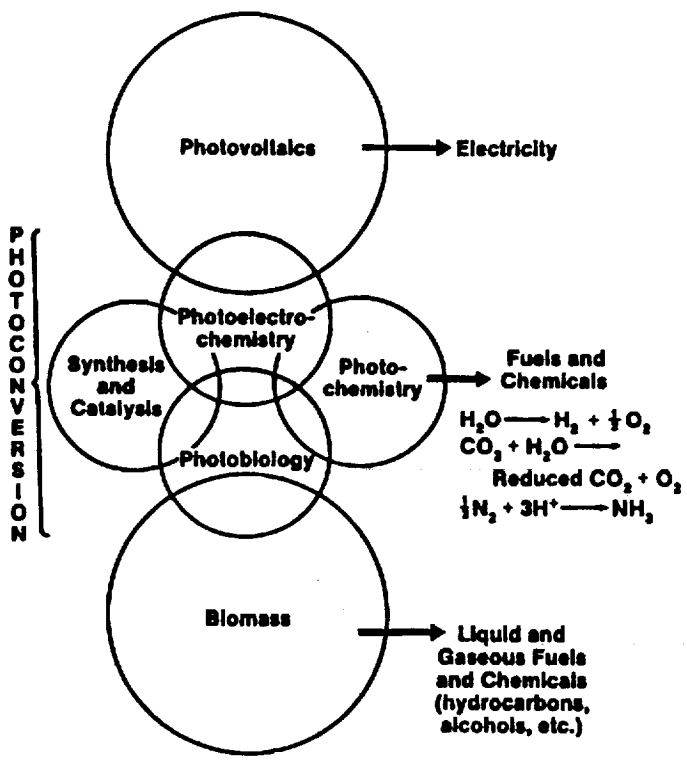

Figure 6.20: Photoconversion processes are aimed at producing fuels and chemicals directly from simple substrates using light-driven process (from Seibert, 1986).

One approach to the efficient utilization of solar energy is the development of devices that mimic natural photosynthesis. The Department of Energy has two divisions that support fundamental research into photosynthetic processes. The Division of Energy Biosciences supports a program to understand biological phenomena relating to how organisms transform and use energy. The Division of Chemical Sciences supports a program in solar photochemical energy conversion whereby, fuels or electricity may be produced by visible light excitation of small molecules or solids. Together, research supported by these programs is developing the fundamental understanding of photosynthesis necessary to develop artificial photoconversion systems (Gust, 1989).

The initial events of photosynthesis consist of a sequence of subnanosecond electron transfer reactions between chlorophyll, pheophytin, and quinone molecules that are positioned at critical distances and orientations relative to one another within a large protein reaction center. To understand the mechanism by which high quantum yield photochemical charge separation occurs, Norris, Wasielewski and others at Argonne National Lab, are studying the ways in which these molecules interact in hopes of developing stable derivatives of these photosynthetic pigments for use in artificial photosynthesis (Norris, 1983, 1985).

Calvin, et al at the Lawrence Berkeley Laboratory are also attempting to devise a synthetic system for storing energy from visible light (Calvin, 1987). First, there is a photo-induced electron transfer process across a phase boundary, mimicking natural photosynthesis, followed by a stabilization of the initial products. These products are then catalytically converted to hydrogen and oxygen, or to reduced compounds and oxygen if carbon dioxide is used as a substrate. For such a system to succeed, advancement is needed in three areas: increase of the useful fraction of the total solar spectral irradiance; improvement of the quantum yield of the initial photochemical reaction; and determination of soluble catalysts for the final conversion on both sides of the process.

The Solar Energy Research Institute (SERI) is also funded to develop model systems that mimic the primary photosynthetic processes. The goal is to understand the specific properties of protein membranes that facilitate electron transfer and stabilize the resulting redox products in natural photosynthesis. While all of this work remains in the research state, it warrants NASA's attention as these photoconversion processes have great potential on thermodynamic grounds, and the implications for self-sufficient space missions are significant.

Another promising area of photoconversion research is for future production of hydrogen via the biological approach to decomposition of water. Weaver, et al have published a review of the photobiological production of hydrogen (Weaver, 1980). Photoproduction of hydrogen by intact cells was first observed in algae by Gaffron in 1940 and in photosynthetic bacteria by Nakamura in 1937 (Gaffron, 1940; Nakamura, 1937). Hydrogenase or nitrogenase are two necessary enzymes that catalyze hydrogen metabolism. Prospects for near and mid term applications rest mainly with systems using photosynthetic bacteria; however, long term research should emphasize cell-free systems based upon the hydrogen production pathway found in green algae.

The main drawback of plant chloroplasts or blue green algae for hydrogen production is the inactivation of the photosynthetic quantum capture system upon prolonged exposure to solar radiation, and that the oxygen produced during hydrogen evolution inactivates the hydrogenase enzyme. The purple membrane of Halobacterium halobium

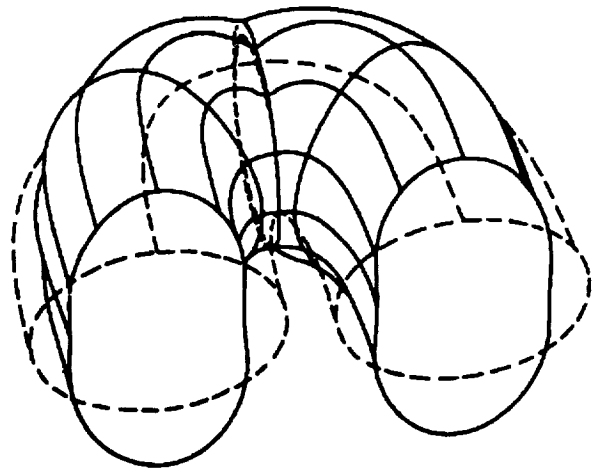

Figure 6.21: Comparison of deformed [solid] and undeformed [dashed] guard cells.

probably represents the simplest biological solar energy conversion system. Light absorbed by bacteriorhodopsin, a small protein whose chromophore is retinal, directly leads to the transport of protons across the cell membrane. The resulting chemiosmotic potential can be used to produce ATP. Halobacterium halobium, however, lacks the hydrogenase enzyme essential for the production of hydrogen. Khan and Bhatt have achieved successful hydrogen production by combining H. halobium and E. coli as a source of hydrogenase (Khan, 1989).

Another biochemical process utilized in nature that may impact development of biologically based life support systems is the use of carrier molecules for the separation and/or concentration of selected chemicals. SERI has completed a study for the Johnson Space Center on electrochemical transport of carbon dioxide (DuBois, 1990). Current manned space missions relay on LiOH as the carbon dioxide absorbent, a method which will be unacceptable for long duration for long duration flights because of the requirement for large amounts of expendables. The approach suggested by SERI utilizes an electrochemically active carrier molecule to pump carbon dioxide. Such carrier molecules are found in desert plants which conduct transpiration at night as a means to preserve water. Since photosynthesis is halted at night without sunlight, the plant requires a different binding mechanism to extract carbon dioxide from the air. Corn plants have also been found to use this approach. During peak growth, corn plants are photosynthesizing so rapidly that they locally deplete the carbon dioxide and, thus, require a more efficient binding mechanism to extract carbon dioxide from the depleted air. The SERI study demonstrated the feasibility of using redox active carriers to pump CO_2 over the pressure range needed for regenerative CO_2 removal. However, the quinone carriers are air sensitive. Other carriers have been shown to be stable to oxygen and water; thus, it should be possible to develop carriers that are highly efficient, stable to oxygen and water, and that are long lived. Moreover, this concept of using carrier molecules can be generalized for use in removing other things from the air, through development of specific carriers for that molecule.

Another example of the use of carrier molecules is that an artificial gill developed by the Aquanautics Corp. (Stover, 1989). Aquanautics originally acquired technology from Duke University for the Hemosponge, created by binding hemoglobin to a polyurethane foam. However, they turned to the oxygenation system used by fish to develop a more efficient system to extract oxygen from seawater. They designed a circulating system modeled after the flow of blood through the gill membranes and the release of oxygen to the tissue. They have studied over 200 carrier molecules and have developed a proprietary carrier similar to heme, the iron-containing molecule in hemoglobin. The oxygen release mechanism of these carriers is controlled electrically rather than by pH. An Aquanautics study also found it feasible to design a system that would extract oxygen from the Martian atmosphere, even though it contains only 0.3% oxygen.

Another interesting factor in the control of plant transpiration is the role of the stomata. These tiny, variable aperture pores on the surfaces of higher land plants control the inflow of carbon dioxide from the air, as well as the outflow of water lost to the atmosphere. The width of the stomatal aperture is a function of the hydrostatic pressure in the guard cells, which form the stomata, and in the surrounding epidermal cells. Cooke, et al used the finite element method to analyze an elliptical torus model of the guard cell (Figure 6.21) to show that the pore opening results from deformation of the guard cell out of the plane of the leaf surface and concomitant decrease in cross section within the plane (Cooke, 1976; Upadhyaya, 1988). This is controlled by a multilinear function of the pressures within the guard cell and the adjacent cells. Thus, the stomata serves as a miniature, hydrostatically-controlled valve and perhaps, can serve as a model for design of miniature fluid valves which are lightweight and easily controlled with minimal power requirements. Active membranes could be developed in which pore size is controlled in response to process feedback variables. This potential application is mentioned here due to the commonality with the above discussion on photosynthesis, but, in fact, such a miniature valve may have applications in many others areas for control of low pressure fluids.

Environmental control for spacecraft requires detection of trace quantities of undesirable organics that may contaminate the air or water systems. The earlier contaminates can be detected, the faster the system can automatically respond to remove the contaminates or correct the process to prevent their generation. Thus, rapid, accurate biochemical sensors will play a crucial role.

The biological analogy is that of biochemical or olfactory sensors in biological systems. Certain species have sensory capabilities far surpassing any man-made sensors; canine olfactory sense can detect concentrations down to 10^{-18} molar, and the silk worm moth can detect single molecules of the female moth pheromone. Other biological systems, while not more precise, demonstrate superior discrimination capabilities through sophisticated sensory processing using neural networks. Examples of current research are discussed in the section on Information Processing. Suffice it to say here, that obvious benefits will be realized through better understanding and application of the principles governing both the primary receptor events, and the neural processing of multisensor data for chemical pattern recognition.

A final area we would like to address in this section is that of physiological deconditioning resulting from the microgravity experienced during spaceflight. Adverse

physiological effects to the cardiovascular, metabolic, osteoregulatory, and immune systems have been well reported, although research on these effects is hampered by the small number of flight research opportunities and the shortcomings of available animal and/or ground-based models.

A unique biological system has been identified that appears to have important implications to the research and possible prevention of the effects of microgravity on calcium metabolism. Floyd and Nelson have conducted research into the metabolism of black bears during denning (Floyd, 1990; Nelson, 1987). These bears do not hibernate, but rather during denning they remain alert, maintain near normal heart rate, cardiac output and temperature, and expend 4000 kilocalories per day. Yet, they do not eat, drink, urinate or defecate, and most relevant to NASA, do not lose bone mass despite being inactive and recumbent for 4 to 5 months. This last phenomenon is not known to exist elsewhere in nature. The researchers postulate that denning bears produce an osteoregulatory substance that allows continued differentiation and activation of osteoblasts despite reduction in mechanical loading to the skeleton. Identification and isolation of such a substance not only could serve as a countermeasure to loss of bone mass in microgravity, but could also have therapeutic implications in osteoporosis, and in bone loss by paralyzed and bedridden individuals.

Perhaps there are other unique species that have developed similar adaptations to their physiological regulatory mechanisms that may have application to the regulatory systems altered by exposure to spaceflight conditions. Researchers in these fields should continue their search for improved animal models, as well as searching for biological systems which seem to demonstrate capabilities that may be applicable to countermeasures.

6.6 Aeronautics

At NASA's direction, this study has focused on the potential contributions of bionics research to space technology. However, any treatment of the biological systems of relevance to NASA must include a discussion of the fluid mechanics and drag reduction mechanisms utilized by birds and fishes, and their potential applications to aeronautics. Even small contributions to drag reduction, for example, can yield sizable reductions in fuel consumption and have substantial financial impact.

Several important texts/articles warrant referencing that provide a good overview of the great deal of work in this field. Holst and Kuchemann in 1941 argued that there remains a great deal to learn from studying the flight of birds and encouraged the foundation of an interdisciplinary field of flight biophysics (Holst, 1980 [translation]). Hertel's text, Structure-Form-Movement, is a classic and gives brief treatment to a wide array of biological mechanisms in flight and swimming (Hertel, 1963). A number of important papers were presented at the Symposium on Flying and Swimming in Nature in 1974 (Anon., 1974). Most recently, the article on drag reduction in nature by Bushnell and Moore (Bushnel, 1991), provides a useful overview of the various drag reduction mechanisms displayed in natural systems.

Further study of the fluid mechanics of birds and fishes will have the potential to contribute to drag reduction, high lift devices, quiet operation, high efficiency surfaces, separation control, and anti-fouling mechanisms.

To research drag reductions in nature presumes that adaptations have evolved to improved efficiency or speed and reduce the energy costs of flight. The most significant type of drag is "form drag" which is particularly troublesome when flow separation occurs. Laminar flow is much more separation prone than turbulent flow. Thus, nature employs roughness at various surface regions to stimulate turbulent flow. Vortex generators, such as the leading edge combs of owls and shark dermal denticles, are an alternative approach to transferring momentum to the wall region for separation control. Flow visualization experiments by the U.S. Air Force revealed that leading edge combs of owls produce a stationary span-wise vortex that delays flow separation at high angles of attack (Anderson, 1973). Its application to a high lift device for aircraft has been considered. Fighter aircraft designers are adapting the shark nose configuration as a result of studies which indicate that this nose shape produces vortices which are more effective in separation control than conventional axisymmetric noses.

Friction drag reduction in nature is accomplished widely by the use of surface additives, either polymers, surfactants or bubbles. Most fish slimes, which consist of mucopolysaccharides, proteins, and usually, surfactants, exhibit significant drag reduction behavior (above 50% for polymers). Another additive is that of anti-fouling compounds to prevent biofouling of marine surfaces (Baier, 1986). Such anti-fouling compounds may have applications in other marine exposure applications, or in process systems where microbial fouling may be a problem, such as in a closed loop life support system.

Shark dermal denticles have also been shown to contribute to reduction in friction drag (Bechert, 1986; Raschi, 1986). Figure 6.22 shows a three dimensional array of riblets proposed by Bechert following his analysis of corresponding staggered riblets on hammerhead and great white sharks. These ridges, which are lined up with the flow, are of a size and shape similar to NASA-developed riblets, which have been shown to achieve a 5-10% reduction in drag. These riblets have been used on racing yachts, in crew races, and experimentally, on aircraft (Bushnell, 1991).

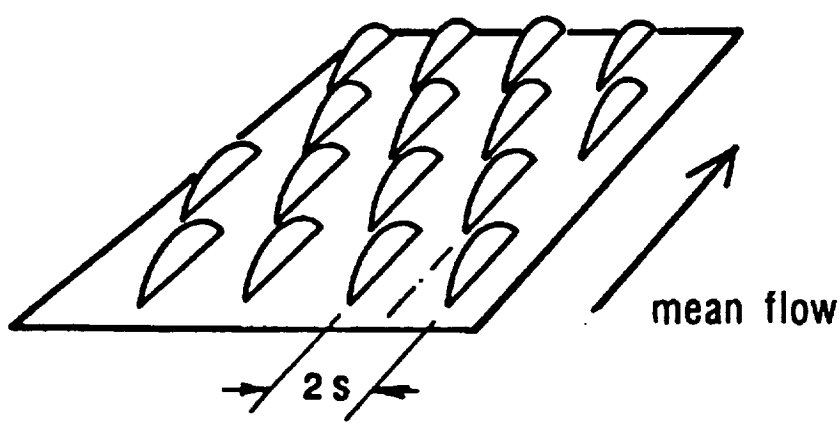

Figure 6.22: Short three-dimensional riblets in a staggered array.

Drag-due-to-lift is the third significant source of drag, reduction of which is accomplished by reducing or making use of the tip bleed flow on a lifting surface. Techniques used in nature to reduce drag-due-to-lift include increased chord length (albatross), use of tip sails or tip feathers (condor), swept-back tapered tips (many species), serrated trailing edges (shark, humpback whale, many birds), and leading edge bumps (humpback whale, hammerhead shark). Van Dam and others have shown that swept-back tapered tips reduce drag due to a vertical distribution of the lift vector (van Dam, 1987). Van Dam has analyzed computer models and conducted wind tunnel testing at NASA Langley to demonstrate the comparative lifting efficiency of lunate and crescent wings. Interestingly, the results of both van Dam's work and NASA's riblets research were employed in Dennis Connor's "Stars & Stripes" successful America's Cup races. (Figure 6.23.) Other tests at NASA Langley have shown the benefits of trailing serrated edges. Bushnell indicates that viable drag-due-to-lift reduction techniques are of utmost importance in aircraft applications.

From a military standpoint, it is desirable that aircraft and submarines operate in such a way as to avoid detection. One mode of detection is sound, thus, there is a desire to produce "quiet" planes and submarines. A solution to silent flight is found in nature in the flight of strigiform birds including owls. These species have the following wing features: leading edge combs, trailing edge fringe, and a soft, porous upper surface. The Air Force has studied the quiet flight of owls and proposed design to use these features in piloted sailplanes (Kroeger, 1972). More recently, quieter submarines have been achieved by placing fillets at major surface intersections (Bushnell, 1991). Such fillets are displayed on most predatory fish species.

NASA aerodynamics specialists should be encouraged to consider the aerodynamic/hydrodynamic drag reduction mechanisms existing in natural systems. The emergence of theoretical fluid dynamics initially led engineers to turn away from nature for design ideas. Now, however, our theoretical understanding and experimental capabilities have advanced sufficiently that we can reveal some of the subtle fluid dynamic principles incorporated into natural flying and swimming organisms. Even small, incremental improvements based upon such subtle design principles can have significant impact on the fuel consumption and financial cost of flight operations.

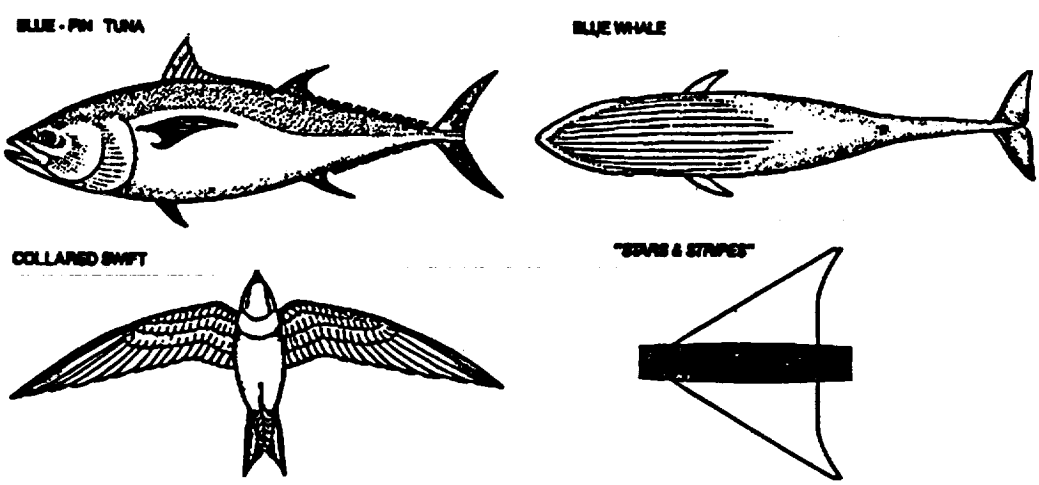

Figure 6.23: Swept-back wings and fins provide greater lift; engineers redesigned the wings on the keel of the "Stars & Stripes".

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7.0 CONCLUSIONS AND RECOMMENDATIONS

The goals of this study were to document the engineering contributions from the field of bionics and to identify opportunities for accelerated research which may provide innovative solutions, based on design principles derived from nature, to aerospace problems. Our study has uncovered a wealth of engineering contributions from the field of bionics. Specific examples of past contributions and current research are mentioned throughout the report.

Biological systems are very useful design analogs to current and future technological systems due to unique features resulting from the long process of evolution. Through natural selection, evolutionary pressures have resulted in biological systems (be they structural, sensory, neural or motor) that conserve material and energy. The resulting small, lightweight, energy efficient (and frequently multifunctional) systems should be of obvious interest for aerospace designs where these are critical design parameters. The performance of biological systems is robust and adaptable, and this characteristic feature is typically not environment dependent. As biological research progresses, there is evidence that many basic principles are employed and adapted by many species to meet their specific functional requirements. It is these scientific principles which we seek to understand through bionics research; thus we adapt these principles to our engineering applications (even extraterrestrial) rather than mimic nature directly.

The present study has consisted of a literature survey, a survey of researchers, and a workshop on bionics. These tasks have produced an extensive Annotated Bibliography of bionics research (282 citations), a Directory of bionics researchers, and a workshop report on specific bionics research topics applicable to aerospace. To provide organization to this highly interdisciplinary field and to serve as a guide for interested researchers, we have also prepared a taxonomy or classification of the various subelements of natural engineering systems. Finally, we have synthesized the results of the various components of this study into a discussion of the most promising opportunities for accelerated research within the areas of materials, structures, sensors, information processing, robotics, autonomous systems, life support systems, and aeronautics.

The Aerospace Applications of Bionics Workshop was extremely successful in exploring possible research topics applicable aerospace technology. It also served to initiate many areas of interdisciplinary discussion that will, hopefully, be expanded in the future to include a wider array of researchers both in and outside of NASA. The workshop participants were emphatic in their conclusion that there is tremendous potential for technical advancements realized through the study and understanding of the engineering principles employed in natural systems.

Each of the working groups at the workshop generated reports which identified certain design principles in biological systems and research opportunities to further understand and apply these principles. The Materials and Structures Group reported on five design principles in biological materials: (1) use of large, nonlinear deformations as accommodation to force, (2) use of novel architectures for functionality, (3) processing of precision microstructures, (4) multifunctionality, and (5) adaptive response to changes in external environment or internal condition. Investigation of these principles in analogous biological systems should lead to potentially fruitful concepts that may be implemented within current or projected fabrication capabilities.

The Sensors and Information Processing Group reported that the area of sensors and information processing has functional impact on almost all NASA mission areas. They con-

cluded that significant additional research is needed into biological information processing in order to understand the principles of neural organization. In the area of sensors, this group espoused the high degree of miniaturization in biological transducing mechanisms for all sensory pathways. Such miniaturization will have obvious weight saving and efficiency benefits for space applications.

The Mechanics and Dynamics Group focused their attention on the problems to be addressed in developing improved robots. Artificial (contractile gel) muscles offer the potential to produce high response actuators with high power to weight ratio. The problem in implementing these fibers is one of architecture, and analysis of biological muscles may offer insight into design of effective actuator mechanisms employing this new technology. Similarly, hydrostatic actuators modeled after hydrostats, squid tentacles or elephant trunks may yield lightweight, compliant actuators.

Finally, the Biochemical Systems Group proposed that NASA consider artificial photoconversion systems based upon the primary electron transfer reactions in natural photosynthesis as a potentially more efficient means to utilize solar energy. While such systems will require long term research, continuing support may be warranted as these systems may allow direct synthesis of most expendables needed for a space vehicle or space colony. This group also provided a good deal of information on biomolecular electronics; molecular electronic devices, based upon natural membrane phenomena, will yield much faster and more robust sensors and processors.

A common recommendation from all working groups is the need for multidisciplinary investigator teams performing bionics research. Bionics is inherently a multidisciplinary science, and research must proceed in parallel to understand the biological design principles. The processes involved in bionics research can be divided into four stages in which researchers:

- Select features of living systems which exceed present technological capabilities,
- Discover and derive principles and processes responsible for their superiority,
- Develop models and methods to describe biological systems in terms useful to design engineers, and
- Demonstrate the feasibility of translating this knowledge into dependable and efficient hardware.

Such multidisciplinary research does not follow usual disciplines and organizational boundaries, but instead combines previously disparate elements or disciplines. This research must be fostered if it is to proceed in such a way as to assist NASA in advancing its technical objectives. Interdisciplinary communication must be encouraged as well as means provided to address specific technical needs of NASA. The bionics workshop is a first step in this direction; NASA should consider both internal and external means to support interdisciplinary concepts.

This study has identified numerous opportunities for accelerated research in bionics with applicability to aerospace problems. Many of these areas offer true breakthrough potential as the biological systems far surpass current technology in robustness and adaptability. Critical evaluation of the opportunities of most interest to NASA will require greater consideration of NASA's requirements, more focused evaluation of the biological analogues, and clearer definition of the research steps required. We recommend that NASA support future workshops, more focused in scope, in which NASA personnel will explore, with leading biologists and bionics researchers, the current knowledge of biological system performance, potential capabilities

offered by a bionics system over current technology, and the key research steps needed to understand the biological system and apply these principles in synthetic systems.

As evidenced by the extensive annotated bibliography and bionics directory, there is a great deal of research currently underway. It is recommended that NASA coordinate its efforts with other agencies supporting research in this field. These include ONR, AFOSR, DOE, NSF, and others. Many of NASA's technical objectives are complementary with those of other agencies, and cross communication, or even collaboration and co-funding, between agencies should be encouraged. Collaboration with foreign researchers should also be encouraged where appropriate. Leading bionics research efforts can be found in many countries, including England, Germany, Italy, Japan and the Soviet Union.

This study has produced overwhelming evidence that research into natural systems engineering principles can offer breakthrough potential in advancing space technology. The research opportunities mentioned will hopefully stimulate aerospace engineers to consider these natural systems as they seek solutions to difficult technical problems for future space exploration. As this research will cross disciplinary boundaries, NASA should maintain a focused initiative to foster and support relevant bionics research. However, this initiative must be closely coordinated with the principal technical disciplines so that the research efforts will provide maximum contribution to the new technologies required for future space systems.

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Wilson, J.F., Wainwright, S., et al.; A continuum model of elephant trunks., J. of Biomechanical Engineering (In Press).

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

ANNOTATED BIBLIOGRAPHY

Biochemical Systems

Moore, John, JR.; The MIT Marine Industry Collegium: Novel applications of marine biopolymers., MITSG-89-7 Opportunity Brief 54, Workshop held 13 Apr. 1989.

Polymers produced by marine plants and animals have been long valued as food and industrial ingredients. Recent developments in biotechnology, enzyme technology, and food and biochemical engineering have lead to new applications for these marine biopolymers. In the biomedical field, research is under way to develop a process for the encapsulation of mammalian cells prior to a transplantation operation. Within the food industry, marine biopolymers have always played an important role, such as stabilizers, and gelling ingredients, etc. Several research projects were undertaken to devise new applications for marine biopolymers in the food industry. These include: chitosan fibers, films and globules; encapsulation of biologicals with chitosan; fluorescence sensor for food and oil deterioration; stabilization of alcohol oxidase by entrapment in alginate beads; complex marine biopolymer coacervate capsules in plant technology; and, microencapsulated liposomes (the use of alginates for drug delivery systems).

Schnur, Joel M., Rudolph, Alan S.; Technological applications of biologically derived microstructures, IEEE Engineering in Medicine and Biology Society 10th Annual International Conference, 1988, p 0996.

Phospholipids are an important example of a class of molecule that have the ability to self-organize into complex assemblies. These molecules comprise a major fraction of biological membranes. The specific arrangement of phospholipids in biological membranes and the matrix these lipids provide for membrane proteins, play a role in important functional membrane properties such as energy transduction and molecular recognition. One of the goals of technological development in the area of lipid based self-assembly is to impart similar fuctionality into a designed microstructure. The study of the relationship of phospholipid molecular structure to assemblies of increasing size and complexity may lead to applications in such diverse areas as electronic materials, drug delivery, improved composites, and advanced biosensors.

Stover, D.; Artificial Gill, Popular Science, 146:121-123, April 1989.

Scientists at Aquanautics Corp. are developing an oxygen extraction system that mimics the oxygenation system of fish. They have studied how fish blood passes through the gill membrane, becomes oxygenated, and releases the oxygen to the tissues. They have researched over 200 carrier molecules synthesized molecules that resemble natural heme occurring in blood. These oxygen carriers are placed in a fluid as part of a circulating system to extract oxygen from seawater and release to an oxygen supply. They have conducted a study for NASA showing it to be feasible

to extract oxygen from the Martian atmosphere even though it contains only 0.3% oxygen.

Tributsch, Helmut; Solar Bacterial Biomass Farm for Space Vehicles, Astronautics and Aeronautics, vol. 20 (6), June 1982.

An unusually adaptive bacteria exploiting solar power and iron compounds lends itself to an automated spacecraft fluid-flow system to produce food and other useful materials. By combining modern solar-energy technology with bacterial mechanisms to build up valuable proteins and carbohydrates from inorganic substances, mankind could create a new biological living space, which nature itself was not able to open up, and develop an artificial branch of agriculture for extreme environments.

Biochemical Systems, Adhesives

Waite, J. H.; Nature's underwater adhesive specialist, Chemtech, pp 692-697, November 1987.

The author describes the adhesive strategy of the sea mussel which is dependant on anchorage for survival. In sticking to a surface, the mussel uses it foot to first squeeze out all water, then create a vacuum, and finally to inject an adhesive foam. The permanent foam is ideally suited for this situation, offering good compressive and tensile strength, insulating properties, and efficiency of material utilization. This approach to adhesive joint formation may solve important problems in underwater (or possibly vacuum) adhesion. The polyphenolic protein has been commercialized by Biopolymers, Inc. as a biocompatible adhesive for cell and tissue culture.

Biochemical Systems, Biochemical Sensors

Huve, J. L.; Chemoreception and detection of micropollutants by means of a telemetric bionic detector, Oceanis (France), 10:191-204, 1984.

The feasibility of using rainbow trout as a biological detector for micropollutants in freshwater ecosystems was studied. Experiments used the electrical activity of the olfactory bulb of the trout to detect micropollutants. An FM transmitter coupled to two electrodes implanted in the bulb of the fish is used to send signals to a computer. The experiments were carried out with groups of pesticides, herbicides, polychlorobiphenyl and organo mineral molecules. Results suggest that the system can act as a real time alarm, but requires development to act as an analytical indicator of micropollution.

Ito, Hiroyuki, Morton, Thomas H., Vodyanoy, Vitaly; Small odorant molecules affect steady state properties of monolayers, Thin Solid Films 180: 1-13, 1989.

An important step in odor perception is the interaction of odorant molecules with the cell membrane of an olfactory neuron. If the receptor site is a protein, interaction between odorant and receptor produces an alteration of the protein structure,

which may in turn cause changes in the structural arrangement of surrounding lipids. Alternatively, the membrane itself might act as a receptor, with limited participation of membrane-bound proteins. Not enough is known at present to permit a choice to be made between these alternatives, nor is it clear that they are mutually exclusive. Many other possibilities for the mechanism of olfactory transduction can also be envisaged, and there is as yet, no basis for ruling out any of them.

Morton, Thomas, Nachbar, Robert B.; A Gas Chromatographic Model for the Sense of Smell., J. Theor. Biol. 89: 387-407, 1981.

Computer simulation of an olfactory detector has been developed using a chemical kinetic scheme originally proposed by McNab and Koshland for bacterial chemotaxis. This model describes response as a function of two opposed reactions, both of which are activated by odorant. One reaction turns on response, while its opponent shuts it off. Net response to various stimulus profiles is compared to psychophysical experiments, with particular attention paid to stimulating magnitude estimation and odor adaptation results.

Sugawara, M., Kataoka, M., Odashima, K.; Biomimetic Ion-Channel Sensors Based on Host-Guest Molecular Recog. in Langmuir-Blodgett membranes., Thin Solid Films, Part III (of 3): 129-133, 1989.

Biomimetic 'ion-channel sensors' based on host-guest molecular recognition were constructed by incorporating several kinds of receptor molecules in Langmuir-Blodgett (LB) molecular assemblies deposited directly on glassy carbon electrodes. The receptors used were valinomycin, bis(crown ether)s, macrocyclic polyamine and cyclodextrin polyamine. The binding of charged stimulants (metal ions, inorganic and organic anions) to these receptors induced a marked increase (or decrease) in the ion permeability of the membranes, as detected by cyclic voltammetry using (Fe(CN)*SUB*6)*SUP*4*SUP* minus or (Ru(bpy)*SUB*3) *SUP*2*SUP* plus as marker ion. Such a mode of response, corresponding to model 'channel opening (or closing)', can be explained on the basis of the charge-charge interaction involving the stimulant, marker ion and lipid.

Valleton, Jean M.; Information Processing in Biomolecule-Based Biomimetic Systems. From macroscopic to nanoscopic scale, React Polym, 12(2): 109-131, April, 1990.

This paper deals with information processing in biomolecule-based biomimetic systems (i.e., artificial systems in which a biomolecule is involved, and whose purpose is to mimic biological functions). Several approaches are presented, based on structures ranging from the macroscopic to the nanoscopic scale. The first part is devoted to the biosensing fuction: the basic principle, the possible transducers, the main applications. The second part presents integrated information on processing functions in macroscopic structures: active transport, biological clocks, mathematical operations, information storage and control functions. In the third part, the evolution of this field toward the nanoscopic scale is described, with the presentation of some

methods of creating nanoscopic structures (adsorbed and chemically bound monolayers, bilayer lipid membrane (BLM) and Langmuir-Blodgett techniques), and their application in the field of biosensors. Finally, new trends in information processing by nanoscopic systems are discussed.

Biochemical Systems, Bioelectronics

Govil, Girjesh, Phadke, Ratna S., Sonawat, H.M.; An approach to biomolecular electronics and bioengineering based on coenzymes chained to solid supp., Journal of Molecular Structure 179: 165-175, 1988.

The possibility of attaching coenzymes to graphite surfaces through molecular wires in a manner such that an efficient electron transport chain is established between the bioactive molecule and the solid support has been considered. The covalent link used in these studies prevents the active molecules from diffusing away in the aqueous environment and improves their stability and efficiency. This opens the way to employing the molecules gainfully in biomolecular electronics and bioengineering. Potential applications of the chained coenzyme systems could arise in the field of biosensors, biobatteries, synthesis of value-added compounds and biomolecular electronics.

Haarer, D.; How to tailor molecular electronics or why is nature taking the soft approach?, Angew. Chem. Int. Ed. Engl. Adv. Mater. 28(11): 1544-1547, 1989.

The author's opening statement characterizes the scope of this brief article: 'The more we are able to understand the efficiency of biological systems, the more our mind is tempted to design Molecular Devices whose efficiency is comparable to the efficiency which nature has achieved during its evolutionary path.' He presents a theory as to why nature uses large units like phycobilisomes and bacteriorhodopsin to perform electronic functions. These point toward a principle of low densities of excited states or low charge carrier densities accomplished through the use of ionic environments, hydrogen bonded environments and environments in which Van der Waals interactions dominate and through the use of bulky proteins to separate active sites.

Hong, F. T.; Control of electric signals in a thin film-based molecular optoelectronic system, IEEE Engineering in Medicine & Biology Society 10th Annual International Conference, 1988.

Both the Langmuir-Blodgett (LB) technique and the artificial bilayer membrane (BLM) technique have been proposed as methods of assemblying molecular electronic devices. Electric signals can be elicited from these types of layered structures with embedded macromolecular pigments. The photoelectric responses to a short light pulse are highly variable in their characteristic relaxations. In an attempt to understand the factors responsible for this variability, we have found equivalent circuit analysis to be useful in linking the observed photoresponses with the underly-

ing physicochemical processes. This approach allows investigators to manipulate and to predict the relaxation time course of the photoelectric signal over a wide range of experimental conditions.

Hong, F. T.; Relevance of light induced charge displacements in molecular electronics; design principles., J. Mol. Electronics, 5(3): 163-185, 1989.

Three different systems of light transducing membranes are examined: the photon-sensing visual membranes, the photon-converting photosynthetic membranes of purple phototropic bacteria and higher plants, and the purple membrane of Halobacteria halobium. In these membranes the primary event in response to a light pulse is a rapid charge movement that can be detected as a displacement current. A scheme of coupled consecutive charge transfer reactions allows a unified perspective on these processes to be gained and a general strategy for analyzing and interpreting the displacement photosignals to be plotted. It is demonstrated that a combined electrochemical and equivalent circuit analysis has considerable power in predicting the time course of the photosignal and is relevant to the design of membrane-based molecular optoelectronic devices.

Powers, L.; The Ultimate in Microelectronics: Biomolecules, IEEE Engineering in Medicine & Biology Society 10th Annual International Conference, 1988, p 0995.

Biological microstructures perform a variety of chemical and electrical functions: switches, proton pumps, power supplies, receptors, effectors, and transducers. Although these processes are not executed rapidly by comparison with solid state electronics, they are highly efficient. The underlying principles here are parallel processes and feedback control, and the mechanisms involve electron tunneling, diffusion within or adjacent to the matrix, charge separation across a highly resistive low capacity medium, energy stored in chemical bonds, and near-thermodynamic equilibrium pools for electron transport. Thus, a detailed understanding of the structure-function relationship using a host of structural and spectroscopic techniques is paramount to design of molecular based electronic architecture.

Schick, G.A., Lawrence, A.F., and Birge, R.R.; Biotechnology and molecular computing., Trends in Biotechnology, 6(7): 159-163, 1988.

Carbon-based molecular machines are in sight for the next generation electronics industry. In that nature has been producing and maintaining molecular machines for millions of years, the biological sciences may hold the keys to tomorrow's computer science disciplines. This article reviews some contributions that natural systems may make, and some general concerns that have yet to be resolved in realizing molecule-based devices.

Biochemical Systems, Bioluminescence

Anoshin, A. I.; Possible usage of bioluminescence in the DUMAND project, 18th Int'l Cosmic Ray Conference, 8:174-176, 1983.

The possibility of using marine luminescent organisms (MLO), capable of producing a flash in response to external irritation, as a track detector of ionizing particles is investigated analytically. It is shown that a large-volume track detector can be designed using MLO with light emittance several orders of magnitude higher than that of conventional scintillators and Cerenkov counters. Such detectors could be used in EAS studies and in the DUMAND project.

McElroy, William D.; Firefly luciferase-structure and function, NTIS# AD-A198292, UCSD-88-5722, 1988.

In order to better understand the enzymatic structure and function of firefly luciferase, the cDNA encoding this protein was recently cloned. In this report we present the extension of our earlier work with the cloning of several luciferases from a bioluminescent click beetle (Pyrophorus plagiophthalamus). The luciferases of this beetle produce bioluminescence of different colors. We isolated 13 cDNA clones which were capable of producing luminescence in E. coli of four different colors: green, yellow-green, yellow, and orange. The amino acid sequence of these luciferases are approximately 96 percent identical with each other, but are less than 50 percent identical with the firefly luciferase.

Rosson, Reinhardt A.; Bioluminescence for detection of trace compounds, NTIS#: AD-A213458, 1989.

The purpose of this investigation is to demonstrate the feasibility of bioluminescent testing for detection of toxic compounds and to develop an inexpensive photodiode based light detection system for field measurement of low level bioluminescence. Progress in the following areas is reported: (1) detection of carcinogens using cloned lux genes in various strains of E. coli; (2) stabilization and immobilization of E. coli biosensors by lyophilization; and (3) development and fabrication of a portable photodiode light detection system.

Sanchez, Hugo; A novel electroluminescent molecular diode: a quantum electronic model of bioluminescence, Journal of Molecular Electronics 5: 221-226, 1989.

Voltage-current characteristics of the firefly Photuris vermontica luminescent luciferin enzyme-catalyzed system (LECS) were obtained. From these measurements, a quantum electronic model was developed for calculating the activation energy (or energy gap) between the LECS electron donor-acceptor energy levels in it excited states. Using this activation energy and Planck's law of radiation, the wavelength of the LECS luminescence spectra was calculated and compared with that obtained by optical methods. It was found that there is good agreement between these two wavelengths. The fundamental results of this work open up a novel way of studying luminescence in biological systems using principles of semiconductor physics and statistical mechanics. Further, it is shown experimentally that the Photuris vermontica chemiluminescent LECS behaves like a solid-state light-emit-

ting diode, implying that new synthetic molecular luminescent devices can be fabricated using the LECS electronic properties.

Biochemical Systems, Metabolism

Floyd, T., Nelson, R.A., Wynne, G.F.; Calcium and bone metabolic homeostasis in active and denning black bears., Clincal Orthopedics 255: 301-309, 1990.

Decreased mechanical use of the skeleton results in osteoporosis in all species that have been studied including humans. The unique metabolic adaptations of denning bears, however, suggest that these animals have evolved osteoregulatory mechanisms to protect against osteoporosis. After four months of skeletal inactivity and without urination, serum calcium remained unchanged and bone mass, bone formation and mineral apposition were unchanged over summer values. Such an osteoregulatory mechanism could have substantial potential therapeutic applications for humans on earth and in spaceflight. The authors have submitted a proposal to NASA.

Nelson, R. A.; Black bears and polar bears-still metabolic marvels., Mayo Clinic Proceedings, 62:850-852, Sept. 1987.

In this editorial, the author discusses research on denning bear metabolism. Denning bears do not eat or drink, continue to burn 4,000 kcal per day, and do not urinate. By degrading urea, nitrogen is recycled to produce plasma proteins. The net effect of prolonged starvation is that the bear loses only fat while gaining a little protein. Also, bears do not experience increased losses of calcium as do bedridden patients or astronauts in space. Polar bears assume a hibernation-like metabolism during the summer and fall while maintaining physical activity. They ignore food, and survive on fat reserves.

Biochemical Systems, Photoconversion

DuBois, Daniel L.; Advanced Electrochemical Carbon-Dioxide Transport Study, Final Report on Contract No. T-5985M, Prepared for NASA, Johnson Space Center, Houston, TX.

This report describes the results of research on a new concept for the regenerative removal of CO2 from enclosed environments. The basis of the concept is the utilization of electrochemically active molecules to pump CO2 selectively from low pressures to high pressures. This report contains a brief review of existing technologies for CO2 removal with an emphasis on the potential efficiencies of the various processes. A thermodynamic model has been developed to allow estimations of efficiencies to be made for redox active carriers with different binding constants. Criteria are then presented for the synthesis of redox active carrier molecules. These criteria are then followed by selected examples of the syntheses and characterization of carrier molecules. The screening techniques used for the evaluation of potential CO2 carriers are described. The measurement of equilibrium binding constants of the carriers in different oxidation states is described and their use in estimating potential

efficiencies is discussed. Finally, a summary of the most promising kinds of carriers is given with an overview of what was accomplished in the course of this research and what remains to be done for such carriers to be useful for NASA purposes.

Khan, M.M.T. and Bhatt, J.P.; Light dependent hydrogen production by halobacterium halobium coupled to Escherichia coli., Int. J. Hydrogen Energy 14(9): 643-645, 1989.

One of the promising areas of research for future hydrogen production is the biological approach to the decomposition of water. A single species of protein, bacteriorhodopsin, present within the purple membrane of Halobacterium halobium has been shown to function as a light driven proton pump which creates an electrochemical gradient across the plasma membrane. In this paper, the authors report their observations on the rate of hydrogen production by 22 different strains of H. halobium isolated from the brine obtained from the Salt Farm of CSMCRI in the presence of E. coli as source of hydrogenase.

Seibert, Michael; Photoconversion - a future energy technology option, ASES '86, Boulder CO, June 11-14, 1986, Proceedings of the 1986 Annual Meeting American Solar Energy Society.

Photoconversion provides a means to produce fuels and chemicals directly from abundant resources such as water, carbon-dioxide, and nitrogen in solar light-driven processes. Thus, photoconversion research could lead to the next generation of fuel- and chemical-producing solar energy conversion technologies. Given a continuation of present progress, photoconversion processes could be in a position to provide a basis for new renewable energy technology options during the next decade and a half.

Biochemical Systems, Photosynthesis

Boxer, Steven G.; Energy Transfer and Photochemistry in Biomimetic Solar Conversion, Annual Report. Gas Research Institute Rpt# GRI-88/0248, 1988.

This research program aims at developing methods for studying electron transfer reactions and electron transfer in biomimetic solar energy systems. Photosynthesis is a model for efficient implementation of a number of the steps in inorganic-based gaseous fuel synthesis reactions. Key steps to understand are the nearly perfect channeling of absorbed light energy to photosynthetic reaction centers and the efficient charge separation that takes place at the reaction centers. One objective of the research is to synthesize artificial systems in which efficient energy and electron transfer take place in a controlled environment analogous to that of natural photosynthesis. Model systems capable of efficient energy and electron transfer are being developed to do so. New methods for manipulating electron transfer reactions are being developed and applied to study natural and artificial photosynthetic systems. The author discusses new techniques using electric field induced fluorescence anisotropy to study the electron flow in natural photosynthetic reaction centers. He suggests that the results may have potential applications in solar conversion systems.

Other possible applications: using photosynthesis techniques to generate products, possibly from raw materials on nonterrestrial surfaces.

Calvin, Melvin; Artificial Photosynthesis, Journal of Membrane Science 33: 137-149, 1987.

The principal factor enabling green plants to convert incoming visible quanta into some stable chemical form long enough to do secondary chemical reactions for storage involves the separation of charge across a phase boundary (e.g., membrane-water). The positive charge, or hole, ultimately is used to generate oxygen from water by electron withdrawal, and the negative charge is ultimately used to reduce carbon dioxide. In our synthetic system, at least in its first phase, we are concerned with the conversion of the negative charge to hydrogen (later to reduce carbon dioxide) and the positive charge to oxygen or possible some oxidized products otherwise difficult to obtain. The first step requires not only the stabilization of the excited state to some extent but, more importantly, the stabilization of the produced charge separation. The final result of this effort will be to produce a device in which the reduction and the oxidation steps are contained either in separate parts of the device in which the reduction and the oxidation steps are contained either in separate parts of the device or separated by a membrane which keeps the ultimate reduction and oxidation productions from back reacting.

Gust, D. and Moore, T. A.; Mimicking photosynthesis., Science, 224: 35-41, April 7, 1989.

Recent work in artificial photosynthesis is reviewed. Relatively simple molecular dyads that mimic certain aspects of photosynthetic electron transfer and singlet or triplet energy transfer are described. The use of the basic principles of photoinitiated electron transfer to engineer desirable properties into the more complex species of multicomponent molecular devices is illustrated by examples.

Norris, J.R., Bowman, M.K., Thurnauer, M.C., Wasielewski, M.R.; Structural and Mechanistic Studies of Natural and Artificial Photosynthesis, DOE R&D Report DE83 010745, 1983.

One approach to the utilization of solar energy is the development of devices that mimic natural photosynthesis. This brief report covers work at the Argonne National Laboratory to better understand the primary steps that occur in the natural photosynthetic process. The emphasis is on the structural and mechanistic details that appear to be crucial to the design of artificial solar energy devices.

Norris, J.R., Gast, P.; Bridging the gap between natural and artificial photosynthesis, Journal of Photochemistry, 29:185-194, 1985.

Considerable effort has been expended to develop artificial models that mimic various aspects of natural photosynthesis. The most direct and complete bridge be-

tween natural and artificial systems would be provided by the detailed structure of a functioning photosynthetic reaction center protein complex. When sufficient structural knowledge is available, a better understanding of the dynamics and functions occurring in the primary act of photosynthesis will be possible in a straightforward manner, particularly with the recent development of single crystals of reaction center proteins derived from photosynthetic bacteria. Consequently, single crystals of protein reaction centers from photosynthetic bacteria currently serve as the best fiduciary system for the development of model systems that use light energy to produce charge separation.

Petke, J.D., Maggiora, G.M.; Development of preliminary design characteristics for biomimetic solar energy conversion systems, J. Chem. Phys. 84 (3), 1 February 1986.

In photosynthetic organisms the initial chemical reaction following absorption of light is an electron transfer (ET) reaction occurring within ten picoseconds. The resultant radical pair is sufficiently stable against charge recombination to permit charge separation over larger distances through additional ET steps. Ultimately, the oxidants and reductants produced are utilized as chemical energy sources for subsequent biosynthetic processes.

Bionics, General

Antomonov, Y. G.; Biological cybernetics: results and prospects., Cybernetics 18(5): 670-679, 1982.

Bionics is the field of research studying the principles of design and functioning of biological systems with the purpose of creating new machines, instruments, and mechanisms with similar characteristics. Results of theoretic and applied biocybernetics are important for the advance of bionics studies. A graphic example of this influence is the recent intense interest in artificial intelligence and robotics. The increasingly profound understanding of the functioning of the brain and the motor system of the organism makes it possible to develop engineering systems such as transport robots and automatic readers, and to improve such systems.

Bernard, E. E., Kare, M. R.; Biological Prototypes and Synthetic Systems, Plenum Press, New York, 1962.

Proceedings of the Second Annual Bionics Symposium, Cornell University, 1961. The symposium gives more emphasis to biological contributions than previous bionics meetings. Topics are wide ranging from specific studies of biology to development of more general models of natural systems. Of particular interest is the final chapter on biomimesis by McCulloch.

French, M. J.; Invention and Evolution: Design in nature and engineering., Cambridge University Press, Cambridge, 1988.

This book is about design for function in both engineering and nature. It draws out general principles and shows how similar problems have led to similar solutions, both millions of years ago in evolution and by engineers in our present time. Analogies abound. More than one-half the text is a designer's eye look for what the designer needs from basic physics.

Gamow, R. I.; Harris, J. F.; What engineers can learn from nature., IEEE Spectrum, August 1972, pp. 36-42.

Following a brief introduction to bionics with a few examples, the authors discuss their research into phototropism of a fungus, Phycomyces, which shows extraordinary light sensitivity with a dynamic range of over one billion. Also discussed is the infrared receptor membrane of snakes and the optics of insect compound eyes.

Gerardin, L.; Bionics., Translated from French, World University Library, McGraw-Hill, New York, 1968.

This book traces the origin of the science of bionics from 1960 and argues for its recognition as a new science. Its relation to cybernetics is discussed. Specific topics include communication systems; sensory systems (chemical sensing by silk worm moths, natural vision systems, snake infrared sensing); migration and navigation; natural radar systems (bat and dolphin echolocation, electromagnetic field disturbances); adaptive systems and biological memory.

Gibbs, K. M.; Bionics and Related Research: A Report Bibliography., ASTIA Report, AD 294150, January, 1963.

This bibliography includes reports catalogued by ASTIA from 1953 through 1962. However, it takes a very liberal definition of the term bionics. A vast proportion of the citations listed deal with adaptive systems, pattern recognition and character recognition, automata theory, and neuromuscular transmission.

Grassmann, P.; Bionics: Limits and Perspectives, Naturwissenschaften, 77(7): 305-9, July, 1990. In German.

Bionics, based on analogies between living beings and technical systems, neglects fundamental differences, e.g., on the one hand, technology uses high temperatures, a means closed to all living beings and, on the other hand, the cells of all organisms have a high degree of autonomy. The first fact makes it possible to construct airplanes three or four powers of ten heavier than the heaviest birds, whereas the second fact enables each cell to reproduce itself, to restore lost limbs or even the whole organism, far beyond the reach of technology. The symbiosis of organisms and technical installations (biotechnology) or, on a higher level, of mankind and environment, may be a guiding star for future development.

Halacy, D. S.; Bionics: The Science of Living Machines., Holiday House, New York, 1965.

The author defines bionics as the art of solving problems by discovering, recognizing and applying techniques developed by living things for the solution of similar problems. The book is a thorough accounting of the many accomplishments of the new field of bionics in the early 1960s and preceding years. Even some of the earliest attempts to mimic nature are described. Areas covered include fluid dynamics, sensors, thinking machines, bioelectricity, and man-machine systems.

Horgan, J.; Roboticists aim to ape nature., IEEE Spectrum (USA). 23(2):66-71, Feb. 1986.

The way in which bionics is affecting research and development in robotics is discussed. It is pointed out that mimicry itself is not the goal; rather, researchers hope that in building artificial analogues to biological systems they will discover principles that will advance both engineering and biology. Most profoundly, bionics is dissolving barriers between the science of the living and the artificial. The result may be the formation of a discipline that, by treating biological and technological systems as being alike in a fundamental way, advances both. The success achieved in a number of research projects is surveyed.

Lenihan, John; Biological design - a neglected art., Australas Phys Eng Sci Med 9(2):57-60, Apr-Jun 1986.

This paper considers the philosophical problems facing the adaptation of bionics to design. It is pointed out that Western society has a tendency to become hostile to technology again today as it has at various times in the past. The author feels that the biological engineering community can resolve this conflict by using its knowledge of science and technology, not to disparage or discourage enthusiasm for a style of living which seems closer to nature, but to achieve a better understanding of the principles and achievements of natural design, so that we may practice and apply them in the increasingly artificial (and therefore unnatural) world that we have created. Systems based on biological design will almost always be more efficient and should be more acceptable in a world that is so increasingly disenchanted with conventional ideas and achievements of progress.

Maguerre, H.; Bionics: Plants as Light Guides, Elektronik (West Germany), 39(12): 79-81, June 8, 1990. In German.

Explains how fibers in living plants act as color selective light guides to guide external illumination from receptors to the roots. Plants can sense color, intensity and angle of light incidence and respond. In particular, they can detect time of day and length of days, and respond.

Marteka, V.; Bionics, J. B. Lippincott Company, Philadelphia, 1965.

A cursory overview of the emerging field of bionics in 1965. Includes a Foreword by Sidney Galler, Office of Naval Research, who is said to have begun this new field in 1951 through the ONR program on biological orientation (although the term 'bionics' was not adopted until 1960. Most interesting overviews included the studies by the Navy, Air Force, and NASA of circadian rhythms; the studies by D.R. Griffin and others of bat echolocation; studies by Schevill, Kellogg, and Norris of dolphin echolocation; research into frog vision that led to development of a laboratory model vision system by the Air Force in 1963; a vision system incorporating the crab's eye's ability to sharpen images; a new ground speed indicator based on two facets of the beetle's eye; and attempts by General Electric to incorporate knowledge in human vision psychophysics into the Visilog, a vision system for moving vehicles to recognize and avoid obstacles.

Smirnov, S. N.; The problem of the objective foundation of bionics., JPRS Report 49644, 20 January 1970, translated from Voprosy Filosofii, Russian, No. 11, 117-128, 1969.

This article gives a philosophical discussion of the question whether bionics should be considered a integral, transitional science or a new approach to solving problems. The origin of bionics lies as a new approach to the solution of engineering problems. The author concludes that bionics is not merely the idea of using biological principles in engineering, but the idea of applying the laws of constructional homomorphism and isomorphism of functionally identical systems in engineering creativity.

Umetani, Y.; Biomimetic viewpoint in robotics., Proc. 1985 International Conference on Advanced Robotics, Tokyo, Sept. 1985.

It is suggested that in the development of a robot equipped with improved functions and performance, most scientists and engineers might have encountered difficulties when trying to design the robot by determining or selecting among available technologies from the very initial stages of conceptualizing a general idea or creating concept. There are two possible methods for designing the robot; one is to create a robot utilizing the sophistication of existing robotic technologies, while the other is to model a robot to be designed from the biological point of view. The paper treats robotics from the latter point of view. 'Biomimetic' means almost the same thing as 'bionic'.

Vogel, Steven.; Life's Devices, Princeton University Press, Princeton, NJ, 1988.

This fairly non-technical text describes how living things bump up against nonbiological reality. Physical factors, such as gravity, flowing water, compressibility of air and the behavior of diffusing molecules, form both constraints which the evolutionary process must contend and opportunities upon which it might capitalize. This book deals with enormously diverse examples of the mechanics at the interface between

living things and their environment. It is an easy to read text for the general reader, and can also serve as an introduction to biomechanics.

von Gierke, H. E.; Bionics - Its role and future in support of Astronautics, Aerospace Medical Research Lab Rpt# AMRL-TR-68-153, 1968.

This paper was presented at the Technical Symposium on Bioastronautics and the Exploration of Space, June 24-27, 1968. The author provides an overview of the contributions and potential of the field of bionics, including how it differs and relates to biophysics, cybernetics, and bioengineering. Bionics, from the engineering viewpoint, is basic research into biological systems with the goal to contribute to the design of better technological systems based on biological prototypes. It's purpose is to study the superior capabilities of biological systems to discover and formalize the principles responsible for the specific superiorities and then to apply these principles toward design of an advanced technology. Specific examples discussed briefly include: drag reduction in birds and fish, modeling of visual system processing, development of an analog artificial ear and speech recognition systems, and pattern recognition systems. The capabilities and approaches which allowed life to originate, to survive, and to develop on this planet over millions of years are basically the same capabilities needed to assist man and his man-made environment to survive, to explore, and to conquer the new environments of space. The most promising road to success in this venture would be to take full advantage of the biological approaches developed during evolution.

___; International Workshop on Intelligent Materials., Workshop Proceedings, March 1989, Society of Non-Traditional Technologies, 308 pages.

This conference discusses the trend toward smart materials and includes discussion of biomimetic processing of ceramics and composites, the design of molecular assemblies to attain intelligent materials, structural design of biomimetic composites, control of two-dimensional protein molecules for bioelectronics, biomimetic approaches to tactile perception, mechanochemical devices using polymer gels, and integrated micromotion systems.

___; From animals to animats: Simulation of adaptive behavior, Conference Proceedings, Paris, Sept. 24-28, 1990. To be published by MIT Press/Bradford Books.

This international conference was held in Paris, Sept. 24-28, 1990, and deals with the relatively new field of animats, or simulated animals. The term artificial life has also been used. Papers deal with a variety of subjects related to simulation of adaptive behavior exhibited by animal species.

Control Systems

Anderson, T.L. and Donath, M.; Animal behavior as a paradigm for developing robot autonomy, Robot. Auton, Syst. (Netherlands), 6(1-2): 145-168, 1990.

The authors review relevant research in the area of animal behavior and propose a number of primitive reflex behaviors which are then used to develop several useful emergent behaviors. These emergent behaviors were demonstrated on an actual robot which demonstrated that behavioral control strategies may provide a powerful strategy for robust operation in dynamically changing, unstructured environments.

Hogan, N.; Control of contact in robots and biological systems., NATO Advanced Research Workshop on Robots and Biological Systems, Tuscany, Italy, June, 1989.

This presentation discussed one fundamental aspect of manipulation to illustrate how a comparative study of robotics and biological movement control can yield deeper insights into both fields. Mechanical interaction with objects is a prerequisite for manipulation, yet stable control of contact has proven surprisingly difficult for robotics. The subtlety of this problem is disguised by the ease with which humans manipulate. The fundamental cause of contact instability is identified, and necessary and sufficient conditions for preserving stability of contact are presented.

Kuperstein, Michael; Adaptive Control of Visually Guided Grasping in Neural Networks., AFOSR Final Report TR-90-0420, March 1990.

Based on a theory of neural computing in biological systems, a new robotics system capable of adaptive control of multijoint arms and a new visual system capable of recognizing handwritten numbers have been developed. Such systems can be used for tasks that exceed advisable human limits for error-free repitition, strength, speed, or risk. Unlike current systems that must be hand crafted by engineers for specific tasks of recognition or control, these new systems demonstrate that general-purpose solutions are feasible. One new product that offers visually guided control of multijointed robotic arms leans to reach for objects by actively looking and moving. Learning results in a sensorimotor map suitable for reaching an object anywhere in view. Robots that learn this way can save programming time because sensorimotor maps are different for arms that differ in the number or position of joints, for example. The new system overcomes such programming chores by using a general-purpose structure. This structure, a "topography" in the current parlance of neural networks, can be adapted readily to many robotic arms now in use.

Information Processing

Kaliaev, A. V., Galuev, G. A.; State of the Art and Development Prospects of Neurocomputer Technology., Elektronnoe Modelirovanie, 12: 14-19, 1990. In Russian.

A neurobionic approach to creating data processing systems is considered. Three possible ways of development are discussed: creating neurocomputers serving as general-purpose computers, employing neurocomputers as coprocessors for general-purpose computers, and designing neurocomputers as parallel neurolike structures. Several types of neurocomputers developed mainly in the U.S.A. and Japan are

described and future trends in this field are indicated along with possible application areas.

Kato, I., Ohteru, S., Shirai, K., Narita, S., Sugano, S., Matsushima, T.,et; The Robot Musician 'WABOT-2' (WAseda roBOT-2), Robotics 3:143-155, 1987.

The robot musician WABOT-2 can converse with a person, read a normal musical score with his eye and play an average tune on an electronic organ. the WABOT-2 is also able to accompany a person singing while he listens to the person singing. This paper describes a full-scale anthropomorphic robot, and its various systems: Limb Control, Vision, Conversation, and Singing Voice Tracking.

Levashov, O. V.; Computational Models of Sensory Systems., Itogi Nauki i Tekhniki, Seriia Bionika, Biokibernetika, Bioinzheneriia, Vol. 6: 3-151, 1989. In Russian.

Recent research (primarily from 1983 to 1988) on the simulation of information processing processes in the sensory systems of living organisms is reviewed, with particular emphasis placed on the simulation of visual-system processes. This work presents a systematic exposition and analysis of stereovision models and algorithms, issues involved in the simulation of visual spatial-frequency analysis, and problems in the simulation of higher levels of shape recognition. Neutron-network models for visual, auditory, and tactile perception are considered, with particular attention given Hopfield networks, which are of central importance to the development of neurocomputers.

Richards, Douglas G.; Biological Strategies for Communication, IEEE Communications Magazine, Vol. 23, No. 6, June 1985.

This article discusses the structure of typical examples of animal signals in the acoustic, radio frequency, and optical modalities, compares them to manmade signals, and addresses the adaptations of the biological signals to combat problems such as channel degradation, interception, and interference.

Sochivko, V. P.; Essays on Marine Bionics, Report Number FSTC-HT-23- 965-70.

An introductory text on a wide range of topics in bionics. Chapter 5 surveys biological control structures, their useful properties for applications, and cybernetic approaches to analyzing systems of control. Chapter 6 provides a basic introduction to the mathematics of pattern recognition, and mentions problems in acoustical processing.

Zinner, H.; Information Bionics: Progress of Research and its Importance to Future Technology., NTIS Report No. MBB-Z-0274-89-PUB., 39 pages, October 16, 1989. In German.

This article tries to estimate the future development of information bionics and its effects. When bionics were created, interest focussed on information bionics - as the

science of the recording, storing and processing of sensory information. Information bionics has received the most promotion due to defense technology and shows the greatest progress. MBB have set their priorities accordingly and they are the ones who have gathered the most practical experience in the field of information bionics. This article discusses some of the positive effects of translating information bionic concepts into technologies such as: 1) information and communications technology, 2) robotics and automation, 3) computer technology, 4) defense technology.

Information Processing, Biomolecular Computing

Conrad, Michael; Neuromolecular Computing: Mechanisms and Architectures, IEEE Engineering in Medicine & Biology Society 10th Annual International Conference, p. 1015, 1988.

The contrasting capabilities of biological systems and digital computers suggest radically different modes of information processing. The difference is connected to a fundamental tradeoff among programmability, computational efficiency, and evolutionary adaptability. Biological systems operate on the efficiency-adaptability side of this tradeoff. Biomolecular geometry (computing by shape) replaces electronic logic in this domain. We describe a brain model that accommodates a hierarchy of processes built on top of shape-based molecular computing, including electrochemical processes in single neurons and collective processes in neural networks. The model serves as a new computer architecture capable of recruiting molecular mechanisms for novel forms of computing.

Conrad, Michael; Biomolecular information processing: Biotechnology paves the way for new approaches to computing, IEEE Potentials, vol. 6 (3):12-15, Oct. 1987.

In the nineteenth century, the synthesis of the biological compound urea by organic chemists established that living organisms were not always necessary to produce organic materials. Today, the challenge is to use organic materials to form a molecular computer that can process information in a lifelike manner. The desire to do so stems in part from important and difficult problems that face today's computer scientist. Three of the most challenging areas are effective pattern recognition in ambiguous environments, efficient utilization of parallelism, and learning from experience.

Draganescu, M.; The present status and prospects in bio-electronics and molecular electronics., Electroteh. Electron. Autom., 32(1):10-21, March 1988.

Premolecular electronics (electron tubes, transistors, micro-electronics, photonics and superconductivity electronics) will be followed by molecular electronics, the link between them being a functional view of electronics, by conventional functions and functions of artificial intelligence and robotic functions. Bioelectronics defined as 'bionics applied to electronics' contains domains such as biosensors, biochips, macro-

molecular or chemical-molecular electronics, neurobionics (neutral networks) and molecular electronics (in two alternatives), all examined briefly.

Hong, F. T. and Conrad, M.; The bacteriorhodopsin membrane as a prototype molecular electronic device., In Molecular Electronic Devices, F.L. Carter, R.E. Siatkowski, H. Wohltjen (Editors), Elsevier Science Publishers B.V., 1988.

The light sensitive macromolecule, bacteriorhodopsin, isolated from Halobacterium halobium, has five properties that make it attractive as a molecular electronic device. First, the molecule is stable. Second, it is fast acting. Third, it undergoes a cyclic photoreaction that allows for its regeneration. Fourth, it can be arranged is a precise way in Langmuir-Blodgett films. Fifth, it is amenable to gradual evolutionary modification through recombinant DNA and protein engineering techniques. The authors show that by using pulsed light inputs, the waveform and magnitude of the signal are predictable. It should be possible to exploit these interactions to produce a device that recognizes patterns by means of spatiotemporal integration of signals.

La Brecque, Mort; Molecular Electronics, MOSAIC Volume 20 (1):16-23, Spring 1989.

With the hype removed, efforts to design electronic devices made of single molecules are settling in for the long, productive haul. Biochips are in the barrel too. Electronic devices that can assemble themselves without any outside assistance are luring some researchers to the promise of proteins.

Information Processing, Neural Networks

Arbib, Michael A.; Schemas and Neural Networks for Sixth Generation Computing, Journal of Parallel and Distributed Computing 6: 185-216, 1989.

The study of animal and human brains suggests overall architectural principles for "sixth generation computers." This article is designed to help expand our concepts of computation to embrace the style of the brain, depending on the constant interaction of concurrently active systems, many of which express their activity in the interplay of spatio-temporal patterns in manifold layers of neurons. A survey of related work in computational neurobiology and neural engineering supports predictions about the form of future computing.

Bekey, George A.; NSF Workshop on Bio-Control by Neural Networks, IEEE Control Systems Magazine, 1(3):279, September 1990.

In the view of a number of investigators, there is an increasing dichotomy between engineering research in artificial neural networks and physiological research on neural control mechanisms. In order to determine the state of the art in both the biological and engineering view of neural networks, to isolate the major difficulties that hinder communication and block progress in the field, and to identify those areas where focused research might be most beneficial, the National Science Founda-

tion sponsored a small invitational workshop on May 16-18, 1990 in Alexandria, VA. This paper describes the workshop, and what was presented there.

Braham, R. and Hamblen, J. O.; The design of a neural network with a biologically motivated architecture., IEEE Transactions on Neural Networks 1(3): 251-262, 1990.

This paper describes an associative neural network whose architecture is greatly influenced by biological data. The data reflects the current knowledge of the anatomy and psychophysics of the visual system of cats and primates. The proposed network is significantly different in architecture and connectivity from other existing models and emphasizes high parallelism and modularity.

Chiel, H. J., Beer, R. D.; A Lesion Study of a Heterogeneous Artificial Neural Network for Hexapod Locomotion, Case Western Reserve University Technical Report TR 89-108, 1989.

The authors use data obtained from the neuroethological and neurobiological study of insect walking as the basis for constructing a locomotion controller for a six legged simulated insect--the American cockroach. They stress that their primary goal is not to construct a detailed model, but rather to use ideas from biological nervous systems to design heterogeneous artificial neural networks. Though the model is inspired by biological data, it is not constrained by it. They maintain that biology can serve as a guide for studying the function, robustness, and dynamics of heterogeneous artificial neural networks. The authors describe their model of the insect, their neural network model (which is intermediate in complexity between biological neurons and those typically used in artificial neural networks), and the biologically inspired locomotion controller. They then study the effect of sensory, central, and motor lesions on robustness and find the system to be quite robust. They then analyze the relative importance of the mechanisms of robustness. They draw conclusions about the robustness and function of the artificial neural network and conclude that the way in which the net functions causes it to be quite robust; the rich dynamics of the controller are due to the heterogeneity of the network. The authors plan to extend their research in several directions, including constructing a robot whose locomotion is controlled by the described network.

Daunicht, W. J.; Control of Manipulators By Neural Networks, IEE Proceedings, Pt. E, 136(5):395-399, September 1989.

The author discusses neural networks in the context of robotic manipulator control. He describes the need to use parallel processing/neural networks to avoid some of the drawbacks in the computationally intense manipulator control mechanisms. Biological neural networks are described, including elements, connections, and properties. Artificial neural network schemes are described with comments on the relationship of the nets with biological nets and in conjunction with the nets' effectiveness in controlling manipulators. While no equations or figures are given, the author does a good job describing different types of neural networks. He sum-

marizes and discusses the drawbacks and advantages to parallel processing and neural networks in manipulator control.

Dawes, R.L.; BIOMASSCOMP: A Procedure for Mapping the Architecture of a Living Neural Network into a Machine, IEEE First International Conference on Neural Networks. IEEE June 1987.

This paper describes an experimental design for the mathematical engineering of an artificial neural network architecture by the optimum transfer of structure from a functioning biological neural network. This method exploits the recent convergence of neurocomputing technology and parallel multielectrode sampling and stimulation of living neural tissue, and it provides the mathematical framework for dynamic, real-time intercommunication between natural and artificial neural networks.

Roitblat, H.L., Moore, P.W.B., Nachtigall, P.E., Penner, R.H., Au, W.W.L.; Natural echolocation with an artificial neural network., International Journal of Neural Networks, 1(4):239-248, October, 1989.

A dolphin was trained to recognize targets using echolocation. Echoes from signals emitted by a dolphin and by an artificial transponder were recorded and later recognized using counter propogation and back propogation artificial neural networks. The first experiment investigated the ability of a counterpropogation network to learn to identify four targets on the basis of the spectral distribution returned in the echo from the objects. Echoes for this experiment were collected in a quiet test pool using a simulated dolphin click as the source. These patterns were classified with 100% accuracy. These data compared well with those obtained from a real dolphin, which recognized (94.5%) correct these same targets in a noisy natural environment. Echoes from three of these stimuli were subsequently collected in two additional experiments while the dolphin performed an object recognition task. Under these conditions, using the echoes employed by the dolphin, both the counterpropogation and the backpropogation networks were 100% accurate on a training set and 97% accurate on a novel set of echoes. These results suggest that neural networks of various sorts may be promising computational devices for automated sonar target recognition and for the modelling of cognitive and perceptual processes in dolphins.

Taylor, J.G.; Living neural nets, New Developments in Neural Computing, Ed. Taylor and Mannion, IOP Publishing Ltd, England, pp 31-51, 1989.

Some of the subtleties of single neurons and their learning rules and of living nerve nets and their connectivities are discussed. Principles and implications for neural modeling are deduced, and a general mathematical framework outlined. Why bother about the complexity of living neural nets? First of all artificial neural nets are not yet at the stage that their abilities can be usefully be compared to those of our own brains. Secondly, it may be helpful to look more closely at the living system to see if we can extract more clues to resolve the problems raised in the preceding paragraph and bridge the gap between unthinking artificial nets and thinking brains. Thirdly

our own brains provide a solution to the problem of constructing a thinking neural net.

Werbos, P. J.; Neurocontrol and Related Techniques, In Handbook of Neural Computer Applications, ed. by Maren, A.J., Academic Press, In Press.

The term neurocontrol refers to the use of neural networks directly to output signals to control motors, actuators, etc. This chapter discusses the current state-of-the-art of neurocontrol and a few related issues, such as the problem of modeling the environment to be controlled and the relation to conventional control theory and expert systems. Neurocontrol can enable the automated control of systems which could not be controlled in the past either due to the physical cost of implementing a known control algorithm or due to the difficulty of finding such an algorithm for complex, noisy, nonlinear problems. Potential applications are discussed in the areas of vehicles and structures; robots and manufacturing; teleoperation; and communications and computation systems. The chapter concludes with a discussion of biological parallels and the need for future research and experimentation.

Information Processing, Neural Processing

Byrne, John H.; Analysis and Synthesis of Adaptive Neural Elements, Final Report # AFOSR TR 87-1567, 1987.

The overall goal of this research is to provide insights into the adaptive capabilities of individual neurons, which will lead to the development of machines having some of the information processing capabilities of the nervous system. The research is designed to examine the adaptive cellular components of a simple biological system (the marine mollusc Aplysia) that displays basic attributes of intelligence. Single identified sensory and interneurons that have demonstrated capacities for associative conditioning were investigated in three research directions: 1) particular ionic conductances and second messenger systems causally involved in adaptive cellular behavior were examined via experimental studies. 2) Experimental studies were made on the neural control of feeding behavior, identifying motor neurons which generate feeding movements and command neurons which drive the motor neurons. 3) A single cell neuronal model for associative learning based on modern cell biological principles was developed and computer simulated. The author states that it is too early in the research to comment on specific applications of this research, but eventually the results will be relevant to aspects of artificial intelligence. The neural networks portion of this paper is pertinent to this project because the neural model is directly based on biological system research.

Caulfield, H.J.; Holographic mapping for perception, SPIE Vol. 1136 Holographic Optics II: Principles and Applications (1989).

In this short article, the author demonstrates that optics is well suited for implementing some neural network tasks. One example is the process of neural reconciliation of different sensory maps in an owl brain.

Farhat, Nabil H.; Optical computing based on neuronal models, Final Report, 15 Sep. 1985 - 15 Feb. 1988.

The ultimate goal of the research work carried out under this grant is understanding the computational algorithms used by the nervous system and development of systems that emulate, match, or surpass in their performance the computational power of biological brain. Tasks such as seeing, hearing, touch, walking, and cognition are far too complex for existing sequential digital computers. Therefore new architectures, hardware, and algorithms modeled after neural circuits must be considered in order to deal with real-world problems. Neural net models and their analogs represent a new approach to collective signal processing that is robust, fault tolerant and can be extremely fast. These properties stem directly from the massive interconnectivity of neurons (the logic elements) in the brain and their ability to perform many-to-one mappings with varied degree of nonlinearity and to store information as weights of the links between them, i.e., their synaptic interconnections, in a distributed non-localized manner. As a result signal processing tasks such as nearest neighbor searches in associative memory can be performed in time durations equal to a few time constants of the decision making elements, the neurons, of the net.

Freeman, Walter J., Eisenberg, Joe, Burke, Brian; Hardware simulation of brain dynamics in learning: the SPOCK, IEEE Int. Conf. on Neural Networks, 1987.

There is a paramount need in modern computation for devices for pattern formation and pattern recognition that are fully parallel, self-organizing, and amenable to construction using VLSI techniques. Most existing pattern recognition devices are based on serial computational architectures. They use algorithms of feature extraction and comparison or correlation of such features stored in memory. Their shortcomings include the lack of robust ability to generalize from incomplete, noisy, or distorted features into a whole pattern, and excessive time for search to report on a novel pattern not in memory. The model described is designed to overcome these shortcomings. It is based on simulations of the neural dynamics of olfactory pattern recognition in mammals. The simulations are done on a digital computer, and with a hardware realization of the system described by the equations that serves to simulate EEG space-time dynamics in real time.

Haun, J. E., Nachtigall, P. E.; Artificial Intelligence and Bionics Workshop., NTIS#: AD-A150463 NOSC-TR-1003, 1984.

This report summarizes the results of the Artificial Intelligence and Bionics Workshop, hosted by Naval Ocean Systems Center, and sponsored by the Office of Naval Research. The goal of the workshop as stated in the overview that was sent to the participants is summarized as follows: This workshop will investigate possible ap-

plications of current knowledge of animal sensory, cognitive and motor abilities to discover new directions or issues in the continuing effort to build intelligent systems. It has been organized to foster a productive dialogue between scholars in artificial intelligence and biological intelligence, including such areas as neurophysiology, sensory processes, information capture and transfer, cognitive processing and biomechanical implementation. Our effort will be to explore useful biological models in the further development of artificial intelligence. The Sensors Working Group recommended concerted study of biological sonar signal processing of bats and dolphins, passive electromagnetic detection systems of elasmobranches, olfactory modeling for chemical detection, and, in the long term, peripheral, syntactic, and central processing. Speech recognition was given significant treatment as were the possibilities of developing artificial muscles and autonomous robotic systems.

Hecht-Nielsen, R.; Neural analog processing., SPIE Proc. Robotics and Industrial Inspection, 1983, p. 180-189.

This paper presents a bionic approach to pattern classification entitled Neural Analog Processing (NAP). NAP systems are based upon information processing principles discovered by neural modelers, but are not themselves neural models. To set the stage for a discussion of how NAP systems work, the theory of a particular type of local-in-time template-matching classifier - the Generalized Nearest Neighbor (GNN) classifier - for general time-varying patterns (imagery, spectra, tactile signals, etc.) is reviewed. The definition and function of the fundamental NAP structure - the slab - is then presented and it is shown that a GNN classifier can, in principle, be implemented using slabs. The embellishments necessary to allow NAP systems to be realized in hardware are then described. Finally, a summary of NAP system characteristics is presented.

Ivanov, Muromskiy K.A.; Neurobionics: development and prospects., Sov. J. Autom. Inf. Sci. (USA). 20(5):51-5, Sept.-Oct. 1987.

The main developmental stages and future prospects of neurobionics, a new branch of bionics, are surveyed.

Jelimek, J.; Bionics and robotics., Vyber Inf. Organ. Vypocetni Tech. (Czech.) 6:807-10, 1985.

Possible applications of the results of bionic research in robotics are discussed. The research areas discussed include: bionic sensors, neural networks and brain models, mechanisms of learning (artificial intelligence), biocommunication, biocontrol, bioelectric phenomena, biomechanics and bioarchitecture.

Kanerva, Pentti; Parallel Structures in Human and Computer Memory, RIACS Technical Report 86.2 (NASA-TM-89402), 1986.

This paper discusses a computer memory, the sparse distributed memory, that would allow a computer to recognize patterns and recall sequences the way humans do.

The first section summarizes conventional computer memory. Next, parallel processing is discussed. The sparse distributed memory is then discussed as a generalization of the computer memory, with emphasis placed on the sensitivity to similarity. The neurophysiological parallels of this model are discussed, including the neuron, synapse, dendrite, Purkinje cells, and the cerebellar cortex. The "focus", an analogy to a moment of a human individual's experience, is then discussed. Applications of the sparse distributed memory to the frame problem of artificial intelligence and robotics is discussed. Finally, conclusions supported by the model concerning human memory are presented. This paper provides a good explanation of the sparse distributed memory concepts; this technique is similar to a Hopfield net in the autoassociative mode, but is not based on energy minimization techniques. An addendum notes that in October 1985 a project which ultimately will result in a hardware prototype was begun. In February 1988, a Computer Systems Laboratory report (CSL-TR-87-338) provides detailed information about a sparse distributed memory prototype involving this author. In May 88 the author published RIACS Tech report 88.14 which delves deeper into the SPM model, expanding on this paper, but with less biological detail.

Pellionisz, Andras J.; Sensorimotor Operations: a Ground for the Co-Evolution of Brain Theory with Neurobotics, Neurocomput, IEEE Int. Conf. on Neural Networks, 1987.

In this paper a program is laid down to propose that sensorimotor operations could serve as a common ground on which Brain Theory, Neurobotics and Neurocomputers will co-evolve, and that tensor geometry can serve as the common mathematical language that unites them.

Ross, M. D.; Morphological evidence of parallel processing of information in rat macula., Acta Otolaryngol (Stockh.) 106(3-4): 213-218, Sep-Oct 1988.

Study of montages, tracings and reconstructions prepared from a series of 570 consecutive ultrathin sections shows that rat maculas are morphologically organized for parallel processing of linear acceleratory information. Type II cells of one terminal field distribute information to neighboring terminals as well. The findings are examined in light of physiological data which indicate that macular receptor fields have a preferred directional vector, and are interpreted by analogy to a computer technology known as an information network.

Ross, M.D., Meyer, G., Lam, T., Cutler, L., and Vaziri, P.; 3-D components of a biological neural network visualized in computer imagery. II. Macular neural net, Acta Otolaryngol (Stockh.) 109(3-4): 235-244, Mar-Apr. 1990.

Computer-assisted reconstructions of small parts of the macular neural networks show how the nerve terminals and receptive fields are organized in three dimensional space. This biological neural network is anatomically organized for parallel distributed processing of information. Processing appears to be more complex than

in computer-based neural networks, because spatiotemporal factors figure into synaptic weighting. Serial reconstruction data show anatomical arrangements which suggest that 1) assemblies of cells analyze and distribute information with inbuilt redundancy to improve reliability; 2) feedforward/feedback loops provide the capacity for presynaptic modulation of output during processing; 3) constrained randomness in connectivities contributes to adaptability; and 4) local variations in network complexity permit differing analyses of incoming signals to take place simultaneously. A companion article on the computer visualization of the associated receptor fields can be found in Acta Otolaryngol (Stockh.) 109(1-2); 83-92, Jan-Feb 1990.

Schwartz, Eric; Computing with Neural Maps: Application to Perceptual and Cognitive Functions., AFOSR Final Report TR-89-1826, October, 1989.

A new technique of image processing has been developed for computing the distances of objects in stereo images. The resulting computer algorithm is very fast, compared with existing techniques, and is suitable for parallel processing of entire images. This technique is based on an interpretation of the neuroanatomy of the brain. Previous attempts to provide computer vision systems with more humanlike abilities have produced stereo algorithms that are slow, prone to misinterpretation, or effective only in severely constrained visual environments. This new stereo-matching algorithm is already being used to help align pairs of cameras in robotic systems so that the cameras are centered on exactly the same point in the scene. The algorithm works by matching image data from small corresponding regions of left- and right-eye views. Depth for each region is computed using a technique for spatial cross-correlation based on Cepstrum analysis. The algorithm was inspired by a curious fact about the way the brain represents visual images. Images from the left and right eyes are broken into strips and interlaced before projection to the brain's visual cortex.

Sokolov, E. N., Shmelev, L. A.; Neurobionics: Organization of neurallike elements and systems - Russian book., Moscow, Izdatel'stvo Nauka, 1983, 280 p. In Russian.

Current theories concerning the informational properties of the nerve cell, the organization of neural nets, and sensory and control systems of the brain are reviewed. A general theory of the organization of systems of neurallike elements is elaborated. Attention is given to neurallike structures for the analysis of auditory, visual, and tactile-vibratory signals, and for motion control (e.g., robot manipulators constructed of neurallike elements). Finally, the design of artificial neurobionic informational systems is considered with attention given to a spectral analyzer, computing structures, and vibrometry based on the neurobionic principle.

Information Processing, Sensory Processing

Adamson, K., Donnan, G., Black, N.D.; Simple Transformation Rules in Application of Transputers to the Physiological Processing of Speech, North-Holland Microprocessing and Microprogramming 24: 397-402, 1988.

Two physiological based models are considered; the human basilar membrane and the human vocal tract. These models are of direct interest in the design of speech recognition systems, natural sounding speech synthesizers, and the development of acoustic prostheses for example, artificial cochlear implants. Attention is directed at structural aspects of the models, as expressed in their digital filter form, and in particular the transformation of the structure expressed therein into a software equivalent and eventually a hardware implementation.

Altes, Richard A.; Further Development and New Concepts for Bionic Sonar. Volume 3--New Concepts and Experiments, Naval Ocean Systems Center (NOSC) Technical Report 404, Vol 3. October 1978.

This report documents theoretical studies of models for echolocation signal processing of dolphins and some bats and the testing of the effectiveness of these models for detecting and classifying small objects in introduced noise and reverberation. This volume (the third of three) investigates potential uses of binaural (two receiver) sonar systems. The effective beamwidth for a two receiver array is computed by using a range ambiguity function. Effective beamwidth decreases as array size and bandwidth increase, so a trade off can be made between array size and bandwidth. Binaural systems may also be used to estimate cross range velocity. Expected error for velocity estimation is computed for surveying certain range, bandwidth, receiver separation and SNR parameters. Section 3.3 discusses theoretical and experimental issues concerning several dolphin, bat, and moth species. The author concludes the volume with a discussion on the use of extremely wide bandwidths used by dolphins and some bats for target classification and interference suppression, as well as several other conclusions concerning analysis techniques.

Altes, Richard A.; Detection and Classification Phenomena of Biological Systems, Adaptive Methods in Underwater Acoustics, 537-554, H.G. Urban, ed. D. Reidel Publishing Co., 1985.

Adaptive signal processing methods are compared with detection/classification models inferred from experiments on animal sensory systems. Attention is drawn to existing signal processing and pattern recognition strategies that appear to be most relevant to biology. Some of the detection and classification of man-made systems, e.g., multisensor integration with locally interacting overlaid maps, use of real-world knowledge for constrained parameter estimation or deconvolution, and distributed testing, such that hypotheses with different functional significance are tested at different levels or in different parts of the detector/classifier. The author's goals are to obtain insight into biological sensory systems by examining them in the context of adaptive signal processing and to obtain new signal processing ideas by analyzing animal sensory systems. He considers nine basic properties of biological sensory systems and draws conclusions on how implementation of the biological systems may have high pay-off in man-made systems.

Altes, Richard A.; An interpretation of cortical maps in echolocating bats, J. Acoust. Soc. Am., Vol. 85, No. 2, February 1989.

Target parameters such as reflectivity, range, velocity, and angular position are represented by ordered maps of tuned cortical neurons in insectivorous bats. It is suggested that the response of each neuron in such a map is determined by a hypothesis test conditioned on a particular value of the mapped parameter. The interpretation of cortical maps presented in this article, together with interpolation and sequential likelihood ratio testing via neuronal tuning curves and local interactions between neurons, is similar to the interpolative probability field used by Kuczewski for multi-target tracking with engineering models of neural networks.

Arbib, Michael A., Overton, Kenneth J., Lawton, Daryl T.; Perceptual Systems for Robots, Interdisciplinary Science Reviews, Vol. 9, No. 1, 1984.

This review presents a sampling of recent research on the design of perceptual systems for robots, with special emphasis on pattern recognition based on an array of touch sensors, and optic flow techniques for depth extraction and navigation based on a sequence of visual images. It not only presents specific work in machine vision, machine touch and robotics, but also illuminates what we believe to be general principles for the design of perceptual systems for an animal, or human, as well as for a robot.

Baird, Bill; Bifurcation Analysis of a Network Model of Rabbit Olfactory Bulb with Periodic Attractors Stored By-, IEEE Int. Conf. on Neural Networks, 1989.

The spatio-temporal dynamics of pattern recognition are investigated in a network model of the rabbit olfactory bulb where time varying spatial patterns have been stored by an error correction algorithm. Such patterns appear in the EEG during inspiration through a bifurcation from a homogeneous steady state and suffice to predict the animal's response in conditioning experiments. The model may be considered a nonsymmetric variant of the model of continuous analog neural dynamics used by Hopfield. In an effort to obtain mathematical insight into the intrinsic mechanisms and capabilities of this type of system, application is made of the numerical and analytic tools of bifurcation theory - both center manifold theory and the newly emerging singularity theory of bifurcations with symmetry. The intent is to explicate novel design principles that may underlie the superior performance of biological systems in pattern recognition.

Ballard, Dana H.; Behavioural constraints on animate vision, Imag. Vis. Comput. (UK). vol. 7, no. 1, pp 3-9, Feb. 1989 Fourth Alvey Computer Vision Conference. Alvey, Manchester, UK.

The computations involved in vision are so expensive that little thought has been given to integrating visual computations with visual behaviours in real-time. However, recent hardware advances such as pipeline computer architectures are making this integration possible. Preliminary results suggest that the combination is very advantageous. Perhaps unexpectedly, visual computation is less expensive when considered in the larger context of behaviour.

Ballard, Dana H., Brown, Christopher M.; Vision: Biology challenges technology, Byte 10(4):245-261, April 1985.

The underlying intent of this article is to show that ideas connected with animal vision, contrary to many earlier expectations, are playing an increasingly compelling role in shaping computer-vision research. Animal brains incorporate hierarchical representations as a fundamental design principle. Furthermore, it seems likely that the biological system has also solved the parallel-computation problem that is emerging as the issue for formal vision studies. The form follows that of an overview of computer-vision research.

Brown, Christopher; Gaze controls cooperating through prediction, Image and Vision Computing, Vol 8(1):10-17, Feb. 1990.

Animate vision systems, biological or robotic, employ gaze control systems to acquire and stabilize objects on their retinae, and in some animals to foveate (centre) objects. Our goal is to guild robust control behaviour from cooperating lower-level visual reflexes. Predictive control strategies can cope with time delayed, multi-rate and interacting controls. Solutions are explored through simulation incorporating ten primitive gaze control capabilities, more or less comparable to subsystems in primate gaze and head control. Versions of several of the subsystems have been implemented on a binocular robot. Smith prediction is the basic control strategy, using kinematic simulation of agent and optimal filtering to predict world state.

Burton, G.J., Haig, N.D., Moorhead, I.R.; A Self-Similar Stack Model for Human and Machine Vision, Biological Cybernetics 53:397-403, 1986.

A new model is proposed that not only exhibits the major properties of primate spatial vision but also has a structure that can be implemented efficiently in a machine vision system. The model is based on a self-similar stack structure with a spatial resolution that varies with eccentricity. The structure of the model allows efficient hierarchical search to be made and it naturally embraces the concept of "attention area". Exploitation of this model has already confirmed these properties and has also revealed its robust ability to control the focus and gain of machine vision systems. (see Clement, Haig, Moorhead 1989 for follow-up)

Clark, James J., Ferrier, Nicola J.; Modal Control of an Attentive Vision System, 1988 IEEE International Conference on Computer Vision.

A vision system for use in a mobile robot system, or in a fixed multi-tasking industrial robot requires attentive control. Attentive control refers to the process by which the direction of gaze of the visual sensors are determined, along with the determination of what processing is required to be applied to the sensed images based on the goals of the robot and the tasks it is performing. This paper describes the implementation of a motion control system which allows the attentive control of a binocular vision system. Attentive inputs to the system specify the type of visual feedback that the

oculo-motor control system will use. The MDL language developed by Brockett is used to communicate between the attentive planner and the motion controller.

Clement, R.A., Haig, N.D., Moorhead, I.R.; Coordination in transputer and biological image processing, IEE Colloquium on 'Transputers for Image Processing Applications' 13 Feb. 1989.

The authors describe a computer vision system for active perceptual tasks such as camera focusing and positioning, and object recognition. Their approach has been to utilize principles which have been shown to work in animal visual systems. The design, which is implemented in transputers, is an active vision system that,instead of analyzing incomplete images, will look around to seek the most revealing images.

Daugman, John G., Kammen, Daniel M.; Image Statistics, Gases, and Visual Neural Primatives, IEEE First International Conference on Neural Networks, 21-24 June 1987.

The subject of this paper is early vision and the parsing operations which both natural and artificial signal processing mechanisms must perform in order to encode, usefully and efficiently, the structured sea of information present in the visual image. Both biological and formal neural networks enter at several distinct points: in the specification of the primitives of early vision which can be inferred from actual neurobiologically recorded receptive field profiles, and also in the competitive interactions which, in our image processing simulations of these processes for compact data structures needed in early vision and bandwidth-limited telecommunications, make possible severe factors of image compression. The algorithms implemented in this work exploit the statistical correlations inherent in meaningful image structure, as Daugman and Kammen suggest efficient neurobiological or artificial vision systems do, to obtain severe image compressions which maintain superior transmission of information.

Eeckman, Frank H., Colvin, Michael E., Axelrod, Timothy S.; A Retina-like Model for Motion Detection, International Joint Conference on Neural Networks, 18-22 June 1989, IEEE (cat. no. 89CH2765-6).

A model is presented for motion detection based on anatomy and physiology of biological retinas. They give a summary of some of the salient features of the vertebrate retina. They describe the model and point out analogies to biological retinas. The model tracks better than thresholding algorithms followed by Kalman filtering. Its implementation in VLSI is conceptually straightforward.

Eisenberg, Joe, Freeman, Walter J., Burke, Brian; Hardware Architecture of a Neural Network Model Simulating Pattern Recognition by the Olfactory Bulb, Neural Networks 2: 315-325, 1989.

The authors designed, built and tested an electronic neural network which replicates many features exhibited by the olfactory bulb. The electronic design is a digi-

tal/analog hybrid approach, utilizing the speed and flexibility of random access memory (RAM) for the initial storing and further modification of synaptic strengths, while still preserving the analog computational power of neural networks. A simple "learning" algorithm is implemented to show qualitative agreement to experimental results.

Griswold, N.C., Yeh, C.P.; A New Stereo Vision Model Base upon the Binocular Fusion Concept, Computer Vision, Graphics, and Image Processing 41:153-171, 1988.

A new model for stereo vision has been proposed which is more closely based upon the mechanisms of the human vision system than previous models. The method is computationally efficient and the results indicate accuracies which are tolerant to noise. An example of a computer generated image and gray level image was given for this model. It can be shown that, if the surfaces obey some assumptions as to smoothness, the relative depth can be used to reconstruct the surface structure. We expect our results to be important for satellite repair, space station docking, and robotics.

Griswold, N.C., Yeh, C.P.; A Stereo Model Based Upon Mechanisms of Human Binocular Vision, SPIE Vol. 635 Applications of Artificial Intelligence III, 1986.

Recent progress in the study of the brain mechanisms of vision has opened new vistas in computer vision research. This paper investigates this knowledge base and its applicability to improving the technique of computer stereo vision. Specific features of the human visual system are described in terms of function. A stereo vision model in conjunction with evidences from neurophysiology of the human binocular system is established herein. The engineering advantages resulting from each feature of the human binocular system are discussed along with their implementation in a computationally efficient algorithm for computer vision systems. This algorithm has been tested on both computer generated and real scene images.

Grossberg, Stephen, Marshall, Johnathon A.; Stereo Boundary Fusion by Cortical Complex Cells: A System of Maps, Filters and Feedback Networks, Neural Networks 2: 29-51, 1989.

A neural network model of multiple-scale binocular fusion and rivalry in visual cortex is described and simulated on the computer. The data structure generates complex cell receptive fields which multiplex input position, orientation, spatial frequency, positional disparity, and orientational disparity, and which are insensitive to direction-of-contrast in the image. The self-similarity property across spatial scales enables the network to exhibit a size-disparity correlation, whereby simultaneous binocular fusion and rivalry can occur among the spatial scales corresponding to a given retinal region. The output patterns of the model complex cells are designed to feed into the model hypercomplex cells at the first competitive stage of Boundary Contour System network, where they trigger a process of multiple scale emergent binocular boundary segmentation. The modeling results are compared

with psychophysical data about binocular fusion and rivalry, as well as with the cepstrum stereo model of Yeshurun and Schwartz. The results indicate that analogous self-similar multiple-scale neural networks may be used to carry out data fusion of many other types of spatially organized data structures.

Grossberg, Stephen, Rudd, Michael E.; A neural architecture for visual motion perception: group and element apparent motion, International Joint Conference on Neural Networks, 1989.

This work further develops a neural network model of motion segmentation by the visual cortex that was outlined in a previous paper. We illustrate the model's properties by simulating on the computer data concerning group and element apparent motion including the tendency for group motion to occur at longer ISIs and under conditions of short visual persistence. The phenomena challenge recent vision models because the switch between group and element motion is determined by changing temporal but not spatial display properties. The model clarifies the dependence of short-range and long-range motion on spatial scale. The model also clarifies how motion after-effects may be generated and how preprocessing of motion signals is joined to long-range cooperative motion mechanisms to control phenomena such as induced motion and motion capture. The total model system is a motion Boundary Contour System (BCS) that is computed in parallel with the static BCS of Grossberg and Mingolla before both systems cooperate to generate a boundary representation for 3-D visual form perception.

Hunt, B.R.; Prospects for artificial neural systems in vision computations., SPIE Vol. 758 Image Understanding and the Man-Machine Interface, 1987.

This is an extended abstract which sketches a brief justification of different approaches to vision, and a possible outline for the structure of a "combined or eclectic approach."

Hutchinson, James, Koch, Christof, Luo, Jin, Mead, Carver; Computing Motion Using Analog and Binary Resistive Networks, Computer, Vol. 21 (3), March 1988.

This article describes motion computation using CMOS VLSI networks to map out cost functions of early vision. These networks share several features with biological neuronal networks. Specifically, they do not require a system-wide clock, they rely on many connections between simple computational nodes, they converge rapidly, and they are quite robust to hardware errors. Real-time performance, low power consumption, robustness, and small spatial dimensions make these circuits attractive for a variety of deep space missions.

Jacobson, Lowell, Wechsler, Harry; Multipurpose Low-Level Visual Processing, Proceedings of the seventh International Conference on Pattern Recognition, Montreal, Canada, 7/30-8/2, 1984

A new computational theory for (invariant) image processing is advanced in this paper. The theory employs a spatial/spatial-frequency representation which approximates the CL-conformally mapped WD of a gray-level image, and it is consistent with recent findings on human visual processing, coming from both neurophysiology and psychophysics. The theory allows for different tasks to be dealt within the same framework. Tasks described in this paper include invariant recognition of objects, analysis of time-varying imagery and texture analysis.

Jarvis, R. A.; Some Observations on the Human Visual Perception System and Their Relevance to Computer Vision Resea, NTIS PB-277 938, Dec. 1977.

This paper presents a number of observations concerning the properties of the human visual perception system considered to be of relevance in designing computer vision systems.

Jayawant, B.V.; Tactile sensing in robotics, J. Phys. E: Sci. Instrum. 22:684-692, 1989.

Tactile sensing in human beings is a very complex process and when used for object recognition, or object orientation, it is in conjunction with arm and wrist movements, as well as with other sensory systems. This paper examines the extent of established knowledge in this field and goes on to assess the likely requirements of robotics, automated assemble and manufacture by way of tactile sensors. Some of the currently known and interesting 'tactile sensor' developments are reviewed.

Jobson, Daniel J.; Spatial Vision Processes: From the Optical Image to the Symbolic Structures of Contour Information, NASA Technical Paper 2838, November 1988.

The significance of machine and natural vision is discussed together with the need for a general approach to image acquisition and processing aimed at recognition. An exploratory scheme is proposed which encompasses the definition of spatial primatives, intrinsic image properties and sampling, two-dimensional edge detection at the smallest scale, construction of spatial primitives from edges, and isolation of contour information from textural information. Concepts drawn from or suggested by natural vision at both the perceptual and the physiological level are relied upon heavily to guide the development of the overall scheme.

Johnson, J.D., Grogan, T.A.; Neural network controlled visual saccades, SPIE Vol. 1076 Image Understanding and the Man-Machine Interface II (1989).

This paper discusses research on a computer vision system controlled by a neural network capable of learning through classical (Pavlovian) conditioning. Through the use of unconditional stimuli (reward and punishment) the system will develop scan patterns of eye saccades necessary to differentiate and recognize members of an input set. By foveating only those portions of the input image that the system has found to be necessary for recognition the drawback of computational explosion as the size of the input image grows is avoided. The model incorporates many features

found in animal vision systems, and is governed by understandable and modifiable behavior patterns similar to those reported by Pavlov in his classic study.

Kuyk, Thomas K.; Using Depth Recovery in Humans, NTIS# AD-A201 278, AAMRL-TR-88-035, 1988.

This program investigated the relevant information content contained in a physiologically based model of the human visual system with regard to the efficient extraction of depth through stereopsis. The significance of this approach is that it models not a visual system but rather an experimentally verified model of the primate visual system. This is critical to the effective application of human information processing techniques to specialized or intelligent image processing systems. Applications are discussed.

Maher, Mary Ann C., Deweerth, Stephen P., Mahowald, Misha A., Mead, Carver; Implementing Neural Architectures Using Analog VLSI Circuits, IEEE Transactions on Circuits and Systems, Vol. 36(5), May 1989.

Biological systems routinely perform computations, such as speech recognition and the calculation of visual motion, that baffle our most powerful computers. Analog VLSI technology allows us not only to study and simulate biological systems, but also to emulate them in designing artificial sensory systems. A methodology for building these systems in CMOS VLSI technology has been developed using analog micropower circuit elements that can be hierarchically combined. Using this methodology, experimental VLSI chips exhibit behavior similar to that of biological systems, and perform computations useful for artificial sensory systems.

Malecki, Gerald S., Hollerbach, John M.; International Workshop on Dextrous Manipulation and Teleoperation, European Science Notes Information Bulletin (ESNIB) 90-01, Connie R. Orendorf, Ed., pp 39-48, 1990.

An international workshop on dextrous manipulation, sponsored by the Office of Naval Research, was conducted at Oxford University, U.K., August 7-10, 1989. The purposes of the workshop were to review recent research findings in biological motor control and robotics, and to discuss the potential convergence of these two lines of scientific inquiry toward the development of new theories and models for sensing, grasping, coordinated movement, and manipulation.

Markus, M., Muller, S.C., Plesser, T., Hess, B.; On the Recognition of Order and Disorder, Biological Cybernetics, 57:187-195, 1987.

This paper compares several algorithms for the recognition of ordered and disordered images. The authors favor an "autodifference function" (ADF). The ADF is not only a more reliable computer algorithm, but is also a more plausible biological mechanism.

Mead, Carver; Analog VLSI and Neural Systems, Addison-Wesley Publishing Company, 1989.

The author states that this book is the result of studying nervous systems of animals and applying the organizational principles to develop silicon neural systems. The first four chapters discuss basic electronics, thermal motion, transistor physics, and neurons. Static and dynamic functions are then discussed. Following these discussions, which deal with natural and engineering aspects, four system examples are given: the seehear, which converts visual signals to auditory signals, the optical motion sensor, the silicon retina, and the electronic cochlea. In each example, the natural mechanisms and functions are discussed, followed by the implementation of those functions in VLSI.

Meyers, Richard C.; Extrema Coding: Perception-Based Signal Processing, Speech Technology, Vol 4, No. 3, Sept./Oct. 1988.

A new speech coding scheme models the human sensory perception mechanism to achieve information reduction in audio communications and signal processing. With Extrema Theory of Perception and Extrema Coding, XSI has taken one more step towards a better understanding of how information in our environment is processed by the human sensory system. This understanding is the cornerstone of XSI's proprietary technology which electronically simulates parts of the human sensory system to achieve low complexity, low real-estate, real-time signal processors. The domain of possible XCSP applications is quite broad. Any application where the human sensory system is the last link in the communication chain is a potential candidate.

Minnix, Jay L., Inigo, Rafael M., McVey, Eugene S.; A New Sensor for Machine Vision, Nineteenth Asilomar Conference on Circuits, Systems & Computers, November 6-8, 1985, Pacific Grove, CA.

A machine vision sensor structured like the human retina is proposed. This sensor uses the peripheral structure of the retina, the preprocessing in hardware, and the logarithmic conformal mapping into the cortex to significantly reduce computational time. Each of these three features of the biological vision system is discussed in detail and has qualities that are useful in machine vision applications. The structure of this sensor is discussed, pointing out advantages and disadvantages of several designs. The results obtained from simulations are described providing favorable indications for the use of this sensor.

Miyake, Sei, Inui, Toshio; Neural Computation Research for Vision, R. Trappl (ed.), Cybernetics and Systems '88, 1007-1014.

In neural net research, parallel processing is an essential principle of computation. It is now necessary to study the practical applicability of neural network models to real images using parallel processing computers. In this paper, the relation between

neural network modeling and parallel processing computers is discussed. Also a neural network model of the human retina is simulated using a NCUBE hypercube parallel computer.

Nabet, Bahram, Darling, Robert B.; Implementation of optical sensory neural networks by simple discrete and monolithic circuits, International Neural Network Society meeting, Boston, September 1988.

An extremely simple, all analog, and fully parallel implementation of a neural network, which was originally derived to account for the nonlinearity and mean luminance dependence observed in many biological visual systems is presented. The network performs a wide variety of useful computational tasks which can be predicted with a system of first-order differential equations. Good agreement has been found between this model and circuit implementations of the network.

Narathong, C., Inigo, R.M., Doner, J.F.,McVey, E.S.; Motion-Vision Architectures, 1988 IEEE Computer Vision and Pattern Recognition Conference.

One of the most difficult problems in a video tracking system is the speed required for real-time operation. In this paper, a fast tracking algorithm to determine displacements of points (pixels) on object surfaces between frames, a sequence of image frames representing a time-varying scene is described. The algorithm was developed in conjunction with research on sensors for machine vision with biological vision features. This algorithm is easily implementable by parallel architecture, and combines many good features of various algorithms presented in the literature. The combination of the algorithm and the biological visual system sensor with two planes configurations has solved the 3D motion problem.

Overington, Ian; Some important observations concerning human visual image coding., SPIE Vol. 594, Image Coding (1985), pp 158-167.

During some 20 years of research into thresholds of visual performance we have required to explore deeply the developing knowledge in both physiology, neurophysiology and, to a lesser extent, anatomy of primate vision. Over the last few years, as interest in computer vision has grown, it has become clear to us that a number of aspects of image processing and coding by human vision are very simple yet powerful, but appear to have been largely overlooked or misrepresented in classical computer vision literature. The paper discusses some important aspects of early visual processing. It then endeavours to demonstrate some of the simple yet powerful coding procedures which we believe are or may be used by human vision and which may be applied directly to computer vision.

Peiss, C. N.; AGARD Lecture Series on Bionics., Technical Report # ORNL-C-4-66, 1966.

The Advisory Group for Aerospace Research and Development (AGARD/NATO) sponsored a lecture series on Bionics in 1965. This report defines the differences between cybernetics and bionics with the latter to mean the analysis of the ways in which living systems actually work, and, having discovered nature's tricks, the embodiment of them into hardware. The term "bionics" was coined in 1960 by Maj. Jack Steele. Specific abstracts include: Bionics Principles (von Forester), Neural Sensory Systems (Fessard), Central Organization of Neural Systems (Varju), Neural Motor Systems (Paillard), Information Processing and Control (Augenstein), Learning and Stimulus Analyzing Systems (Sutherland), Bionics in Practical Systems (McCulloch), and Bionics in the Military Program (Keto). The last of these is given the most treatment focusing largely on sensory processing systems (vision, hearing, and tactile), but including the neural system (the artron, or artificial neuron, system used to develop a maze runner) and electro-mechanical devices (the artificial muscle and myoelectric servo control).

Porat, Moshe, Zeevi,Yehoshua Y.; The Generalized Gabor Scheme of Image Representation in Biological and Machine Vision, IEEE Transactions on Pattern Analysis and Machine Intelligence Vol. 10 (4) July 1988.

Since the rationale of our approach is to learn as much as possible from biological visual systems and implement this knowledge in computational vision by machines, it is interesting to note that both physiological findings and psychophysical aspects of adaptation and masking indicate that the biological processing is based on matching localized frequency signatures having a form reminiscent of Gabor operators. Indeed, preliminary studies reveal interesting possibilities of pattern analysis based on these operations. A scheme suitable for visual information representation in a combined frequency-position space is investigated through image decomposition into a finite set of two-dimensional Gabor Elementary Functions.

Rose, Gary, Heiligenberg, Walter; Temporal hyperacuity in the electric sense of fish, Nature, Vol. 318:178-180, 14 November 1985.

It has recently become evident that sensory thresholds for certain tasks are lower than those expected from the properties of individual receptors. This perceptual capacity, termed hyperacuity, reveals the impressive information-processing abilities of the central nervous system. Here we demonstrate that an electric fish, Eigenmannia, can detect modulations in the timing (phase) of an electric signal at least as small as 400ns. This hyperacuity results from a nonlinear convergence of parallel afferent inputs to the central nervous system; subthreshold inputs from particular areas of the body surface accumulate to permit the detection of these extremely small temporal modulations.

Shemlon, Stephen, Dunn, Stanley M., Liang, Tajen; Progressive Knowledge Use in Incremental Segmentation, SPIE Vol. 1095 Applications of Artificial Intelligence VII (1989).

The segmentation problem in image processing still falls short of an optimal solution. Obtaining a suitable segmentation requires domain specific knowledge. The optimal insertion of this knowledge in the segmentation process is the major issue. The complex human visual system first extracts reliable intrinsic information from the input and then applies knowledge stepwise at each stage of visual processing from the retinal to the cognitive levels. A near optimal segmentation scheme should approximate this approach. In this paper a segmentation algorithm based on the above approach is presented.

Tzanakou, Evangelia; Neural Aspects of Vision and Related Technological Advances, Proceedings of the IEEE, Vol. 76(9):1130-1142, September 1988.

Examines the physiological aspects of the visual systems of animals and humans and several models that explain or try to explain physiological or psychophysical data. Theory and experiment complement each other and neural networks are used for more complicated and sophisticated designs. Both digital and analog implementations are discussed and some projections to future applications are also mentioned. Extensive references.

Watson, Andrew B.; A perceptual components architecture for digital video, J. Optical Soc. of America, A: Optics and Imaging Science, 7:1943-1954, Oct. 1990.

A Perceptual Components Architecture for digital video partitions the image stream into signal components in a manner analogous to the human visual system. These components consist of achromatic and opponent color channels, divided into static and motion channels, further divided into bands of particular spatial frequency and orientation. Bits are allocated to individual bands in accord with visual sensitivity to that band, and in accord with the properties of visual masking. This architecture is argued to have desirable features such as efficiency, error tolerance, scalability, device independence, and extensibility.

Yao, Yong, Freeman, Walter J.; Pattern Recognition in Olfactory Systems: modeling and simulation, International Joint Conference on Neural Networks. IEEE June 1989.

An attempt has been made to understand the natural design principles that underlie the superior performance of biological olfactory systems in pattern recognition. We express these principles in mathematics, learning algorithms, and neuromorphic hardware. A diagram of the olfactory system and its mathematical model are presented to show how to implement the system by software and electronic hardware. Its capability for pattern classification is verified in an input driven model olfactory bulb under an input correlation learning rule.

Yeshurun, Yehezkel, Schwartz, Eric L.; Cepstral Filtering on Columnar Image Architecture: A Fast Algorithm for Binocular Stereo Segmentatio, IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 11(7), July 1989.

Many primate visual cortex architectures have a prominent feature responsible for the mixing of left and right eye visual data: ocular dominance columns represent thin strips of alternating left and right eye input to the brain. In the present paper we show that such an architecture, when operated upon with a cepstral filter, provides a strong cue for binocular stereopsis. We suggest that this provides a fast algorithm for stereo segmentation, in a machine vision context. The present algorithm achieves this goal by using local context, in parallel, to arrive at a "one shot" measurement of the disparity vector.

Young, Richard A.; Simulation of Human Retinal Function with the Gaussian Derivative Model, IEEE Conference on Computer Vision and Pattern Recognition, Miami Beach, Florida, June 1986

A new operator for early machine vision was developed after study of the primate retina. A machine implementation of the new operator provided partial deblurring, noise suppression, excellent color segmentation, and efficient and complete information transmission to higher processing levels.

Young, Richard A.; The Gaussian derivative model for spatial vision: I. Retinal mechanisms, Spatial Vision, Vol 2(4):273-293, 1987.

A machine vision system was constructed to simulate human foveal retinal vision, based on Gaussian derivative filters. It provided edge and line enhancement (deblurring) and noise suppression, while retaining all the information in the original image.

Locomotion

Todd, D.J.; Mobile robots: the lessons from nature., NATO Advanced Research Workshop on Robots and Biological Systems, Tuscany, Italy, June, 1989.

The author states that locomotion is the hallmark of the animal world, and it is when we make mobile robots that we seem to be emulating nature most closely. Many principles derived from the observation of legged animals have consciously or unconsciously been incorporated into the design of legged robots. The paper lists a number of additional design ideas drawn from nature which seem to have potential for future legged robots.

Locomotion, Ambulation

Abe, Minoru, Kaneko, Makoto, Tanie, Kazuo, Nishizawa, Shoichiro.; Study on hexapod walking machine using an approximate straight-line mechanism., Kikai Gijutsu Kenkyusho Shoho 39(4):195-208, July 1985.

It can be interpreted that human walking on irregular terrain is realized by a basic leg motion pattern to proceed on flat plane and a supplemental leg motion pattern to adapt to the irregular terrain. In order to apply this idea to the walking machines, the authors have been studying walking machines which can adapt themselves to an irregular terrain by a basic leg motion pattern and a supplemental leg motion pattern. This paper discusses the design criteria of leg system to produce the basic leg motion pattern, and also discusses the fundamental mechanism of hexapod walking machine using an approximate straight-line mechanism. (Edited author abstract) 10 refs. In Japanese.

Alexander, R. McN.; The gaits of bipedal and quadrupedal animals., Int'l Journal of Robotics Research 3:49-59, Summer 1984.

The gaits of reptiles, birds, and mammals are reviewed. It is shown that mammals of different sizes tend to move in dynamically similar fashion whenever their Froude numbers are equal. The gaits of turtles appear to reduce unwanted displacements to the minimum possible for animals with slow muscles. The patterns of force exerted in human walking and running minimize the work required of the muscles at each speed. Much of the energy that would be required for running is saved by tendon elasticity.

Alexander, R. McN.; Three uses for springs in legged locomotion, International Journal of Robotics Research, 9:53-61, 1990.

Use of springs in legged robots, especially robots designed to run fast, is studied. Pogo stick-like springs and return springs are shown to be able to save energy and reduce fuel consumption and unwanted heat production while foot pads can moderate the force at impact of the foot on the ground and improve road holding by preventing chatter. The external kinetic energy of an animal or vehicle is distinguished from the internal kinetic energy associated with movement of component parts.

Beletshii, V. V.; Biped walking: Model problems of dynamics and control --- Russian book., Izdatel'stvo Nauka, 1984, 288 p. In Russian.

A theoretical description of the process of biped walking is presented. A model theory of walking is applied to various technical systems (robots, exoskeletons, and pressure suits), and to biped locomotion as it occurs in nature (man, birds, and dinosaurs). An analytical investigation is provided in the form of a numerical study of the physical characteristics of biped walking including its rhythmic, kinematic,

dynamic, and energetic elements. Models are also developed to describe the processes of stabilization and control of biped locomotion.

Brooks, Rodney A.; A Robot that Walks; Emergent Behaviors from a Carefully Evolved Network, NTIS# AD-A207 958, AIM-1091.

Most animals have significant behavioral expertise built in without having to explicitly learn it all from scratch. This paper suggests one possible mechanism for analogous robot evolution by describing a carefully designed series of networks, each one being a strict augmentation of the previous one, which control a six-legged walking machine capable of walking over rough terrain and following a person passively sensed in the infrared spectrum. The experiments with an actual robot ensure that an essence of reality is maintained and that no critical disabling problems have been ignored.

Cruse, Holk.; What mechanisms coordinate leg movement in walking arthropods?, TINS 13(1): 15-21, 1990.

While this article is strictly a review of current knowledge of biology on this subject, its motivation is displayed in the abstract which deals with the challenges in construction of walking machines. The walking of an animal is much more versatile and seems to be more effective and efficient than that of robots. Thus it is useful to consider the corresponding biological mechanisms in order to apply these to the control of walking legs in machines. This paper summarizes recent developments in the study of biological control mechanisms.

Easton, Thomas A.; A Biological Model for Multilegged Robot Control, Robotics Age, vol. 6 (11):26-29, Nov. 1984.

This article describes a concept for a multilegged robot steering mechanism called HORNS, a Heuristically Orienting Navigation System. The HORNS concept models animal reflexes to create a robot that can steer itself automatically. The model simplifies the problem of robot motor control to its essentials. The ultimate control becomes simply attentiveness, so that any decision to move will move the robot toward whatever holds its attention. It requires only that the robot have suitable sensors for joint or eye movement, plus circuitry that allows signals from these sensors to affect appropriate motor control centers. The result is that the central computer or outside controller has much less controlling to do.

Hanamoto, B. and Martin, L.; Locomotion in nature, Part I: Quadrapeds., Technical Report 9464 (LL 111), Land Locomotion Division, USATACOM, Nov. 1966.

Parker, Claude B.; Locomotion in Nature Part II: Modifications of the Fly Foot for Human Needs, NTIS AD039668, USATAC trn. 10016, January 1968.

A search was undertaken to find out what work had been done and was available concerning the natural capability of flies and similar insects to walk on smooth inverted surfaces. The results show two general schools of thought on the physiological structure responsible for the special capability of the fly: (a) a gluing mechanism, and (b) suction cups. At present there exists insufficient data to closely duplicate the fly foot for man's needs. A general fly foot concept is outlined for use on a future walking machine, such as is being built for the land locomotion division under contract by General Electric Corporation. Possible adaptations of the fly foot are suggested in other fields.

Raibert, Marc H., Sutherland, Ivan E.; Machines That Walk, Scientific American Vol. 248(1):44-53, Jan. 1983.

Many machines imitate nature; a familiar example is the imitation of a soaring bird by the airplane. One form of animal locomotion that has resisted imitation is walking. So far we have built two machines. One has six legs and a human driver; its purpose is to explore the kind of locomotion displayed by insects, which does not demand attention to the problem of balance. The other machine has only one leg and moves by hopping; it serves to explore the problems of balance.

Song, Shin M., Waldron, Kenneth J., Kinzel, Gary L.; Computer-aided geometric design of legs for a walking vehicle., Mech Mach Theory 20(6):587-596, 1985.

The mobility of the legged vehicle is brought into consideration in the leg design. A study of the mobility of a six-legged vehicle shows that a large walking envelope is required for each leg linkage. In order to satisfy this requirement, the original four-bar leg was modified into a seven-bar leg by mounting another four-bar linkage on the coupler of the original four-bar linkage. Also, a different type of leg linkage based on pantograph mechanism was designed. A comparison of the leg performance of both types of leg is made and the pantograph leg is found to be more effective.

Spiessbach, A. J., et al.; Semi-autonomous design concepts for a Mars rover, AIAA, Aerospace Sciences Meeting, Jan. 9-12, 1989, 9 pages.

Working for the Jet Propulsion Lab., the authors have developed a concept for an agile walking robot equipped with six articulated legs like those of an insect. Each leg would continually feel the ground before applying weight to it; if unexpected objects are encountered or the foot fails to touch ground, it would seek an alternative foot placement within a 20 cm placement. The rover would use a laser ranging imager to help select foot placement as well as to plan paths. With current technology, such a semi-autonomous vehicle would require nine processors each capable of one million instructions per second. The six leg configuration offers greater speed and stability than four legs. This work is also referenced in NASA Tech Briefs, December 1990, p. 52.

Waldron, Kenneth J.; The Mechanics of Mobile Robots, Proc. 1985 Int'l Conf. on Advanced Robotics, Tokyo, pp 533-543.

The interaction of the mechanics of a mobile platform with control and sensing hardware and software is important to performance in robotic applications. In this paper the basic principles involved will be reviewed, and new material on comparative characterizations will be presented. The application of those principles to a specific example: the Adaptive Suspension Vehicle, will be presented.

Locomotion, Flight

Anderson, G.W.; An experimental investigation of a high lift device on the owl wing, NTIS AD-769 492, March 1973.

A study was made of the aerodynamic function of the comblike fixtures found on the leading edge of owl wings. Microphotographs of an owl's wing showed the comb to resemble a row of spanwise twisted airfoils oriented to form a cascade. Smoke flow visualization experiments were run using flat plate and cambered airfoils with combs in a low speed three-dimensional wind tunnel. Results showed that the leading edge comb produced a stationary spanwise vortex that delays flow separation at high angles of attack. The high lift device was related to the vortex lift phenomena observed on delta wing aircraft. The comb's small relative size, simple structure, and lack of moving parts may make it attractive for aircraft use.

Borin, A. A., Kokshaiskii, N. V.; Evaluation of the energy efficiency of bird flight., Akademiia Nauk SSSR, Doklady 277(2):489-493, 1984, In Russian.

The energy efficiency of bird flight is defined as a quantitative measure of the conversion of bird muscle energy into the work of flight. The energy efficiency of bird flight is compared with the flight performance of a number of aircraft (ranging from the human-propelled Gossamer Condor to turbojet aircraft), and it is concluded that birds do not have any extraordinary advantages over aircraft with respect to energy efficiency.

Bushnell, D.M., Moore, K.J.; Drag reduction in nature., To appear in Annual Review of Fluid Mechanics, Vol. 23, 1991.

One source of inspiration for alternative drag reduction approaches is a renewed study of Avians and Nektons, i.e., fliers and swimmers in the natural world. This paper provides a review of the literature on various biological means of drag reduction. Topics included are surface and body geometries to reduce friction drag (including shark denticles which are similar to artificial riblets); use of surface additives; use of vortex generators and three dimensional, asymmetric body design to reduce form drag; and swept-back tapered tips, serrated trailing edges and leading edge bumps to reduce drag due to lift. He concludes that there is much to be gained from continued study of natural hydro- and aerodynamics.

Holst, Erich V., Kuchemann, Dietrich; Biological and Aerodynamic Problems with the Flight of Animals, NASA-TM-75337, May 1980.

This article discusses the biological and aerodynamic considerations related to birds and insects. It is noted a wide field is open for comparative biological, physiological and aerodynamic investigations. Considerable mathematics related to the flight of animals is presented, including approximately 20 equations. The 15 figures included depict the design of bird and insect wings, diagrams of propulsion efficiency, thrust, lift and angles of attack and photographs of flapping wing free flying "wing only" models which were built and flown. This is a translation of Biologische und aerodynamische probleme des tierfluges, Die Naturwissenschaften, 24/25: 348-362, 1941.

Kroeger, R.A., Gruschka, H.D., and Helvey, T.C.; Low speed aerodynamics for ultra-quiet flight., Technical Report # AFFDL-TR-71-75, March 1972.

A combined aerodynamic, acoustic, and bionic study to discover novel mechanisms to reduce the noise associated with aircraft flight. The strigiformes order of birds were selected as possessing characteristics of silent flight. Three potential mechanisms producing the potential for acoustic quieting were discovered: 1) vortex sheet generators, 2) compliant surfaces, and 3) distributed wing porosity.

Sorokodum, E. D.; Structure and methodological problems in the study of the locomotion of flying and swimming animals, Uspekhi Sovremennoi Biologii 96:466-475, Nov.-Dec. 1983. In Russian.

van Dam, Cornelis P.; High Angle-of-Attack Aerodynamic Characteristics of Crescent and Elliptical Wings, NASA-CR-184992.

Force and moment data and flow-visualization results indicated that the crescent wing model with its highly swept tips produces much better high angle-of-attack aerodynamic characteristics than the elliptic model. Leading-edge separation-induced vortex flow over the highly swept tips of the crescent wing is thought to produce this improved behavior at high angles-of-attack. The unique planform design could result in safer and more efficient low-speed airplanes.

van Dam, Cornelis P.; Efficiency characteristics of crescent-shaped wings and caudal fins, Nature, Vol. 325, pp 435-437, 29 January 1987.

This steady-flow analysis of lift and drag characteristics of crescent-shaped wings indicates that aerodynamic efficiency is improved as a result of increased backward curvature. The combination of high induced efficiency and large wing span results in low drag from lift for a given loading. This may help explain why fast marine animals and efficiently flying birds have evolved long crescent-shaped lifting surfaces.

Locomotion, Swimming

Bechert, D. W., Bartenwerfer, M., Hoppe, G., Reif, W.-E.; Drag reduction mechanisms derived from shark skin., Proc. 15th ICAS Congress, London, September 7-12, 1986, Volume 2:1044-1068.

A theory of viscous flow on surfaces with small longitudinal riblets is developed. Various riblet shapes immersed in a viscous Couette type shear flow are analyzed, and it is shown that the height by which the riblets protrude into the boundary layer flow is of crucial importance. This protrusion height cannot be increased beyond a certain level for all conceivable straight riblet configurations. Fairly detailed flow data on various riblet configurations are given, including sawtooth, bladelike, scalloped, and convex riblet cross sections. The analytical calculations are confirmed by electrolytical analogy experiments. Staggered short riblets are suggested for circumventing the limit on riblet protrusion height. Electrolytical analogy experiments are used to show that the protrusion height of shark skin may be increased to more than twice the value of conventional straight riblets. It is demonstrated that the skin of fast sharks clearly exhibits the suggested short staggered riblets.

Devillers, J.F., Leriche, M.A.; Direct measurements of hydrodynamic forces on a flapping wing., Arch. Mech. (Poland). 38(5-6):577-84, 1986.

Presents results of an experimental investigation of the forces exerted by water flowing around an oscillating wing for a variety of parameters defining the movement of the obstacle. Special care was taken in order to achieve precise and reproducible results. This investigation was prompted by the need for more accurate results necessary to validate new theoretical and numerical models as well as by the desire of mechanically reproducing, in a bionic way the movements of aquatic or aerial animals.

Hertel, Heinrich.; Structure-Form-Movement., Reinhold Publishing Corp., New York, 1963.

The author's stated purpose is for this book is to inspire new interest in living nature through a unified perception of biology and technology. The book offers superb illustrations and discussion of bioengineering analogies across a broad spectrum of organic and artificial mechanisms and structures. In depth attention is given to the dynamics of animal movement, particularly the flight of birds and insects and swimming of fish and dolphin.

Logvinovich, G.V., Pyatetskii, V.E., Pershin, S.V., Karandeeva, O.G.; Hydrodynamic Problems of Bionics, Trans. of Mono. Bionika, Kiev, N4 p3-120, 1970.

The combined study of problems of hydrodynamics and biology of aquatic animals not only expands and deepens man's knowledge of nature but also enables him to utilize the results obtained in technology. Since a living organism in the course of evolution adapts optimally to the conditions of its environment, a knowledge of its system should lead to new technological achievements. This volume contains some results of investigations conducted on these problems.

Raschi, William G., Musick, John A.; Hydrodynamic Aspects of Shark Scales, NASA Contractor Report 3963, 1986.

A variety of structural mechanisms, such as scombroid scale corselets and scale ctenii are of particular interest to those studying drag reduction. Ridge morphometrics on placoid scales, from 12 galeoid shark species, were examined in order to evaluate their potential value for frictional drag reduction. The results indicate that the ridge heights and spacings are normally maintained between the predicted optimal values proposed for voluntary and burst swimming speeds throughout the individual's ontogeny.

___; Proceedings. Symposium on Swimming and Flying in Nature., NTIS AD-A020 007, July 1974.

This is a collection of papers on different topics in swimming and flying. Examples include various mechanisms for propulsion, drag reduction, lift utilization, energy transfer between organisms. Applications are especially in aeronautics, since this symposium was organized for the Office of Naval Research.

Materials

Douglas, K., Clark, N.A.; Biomolecular/solid-state nanoheterostructures., Appl. Phys. Lett. (USA), 56(7): 692-694, 1990.

The authors demonstrate a fabrication process for making composite biological/solid state heterostructures of nanometer dimensions. In this process individual protein molecules selectively self assemble onto a 1.2 nm thick tantalum-tungsten oxide film which has been patterned into a screen-like lattice with holes of a 22 nm periodicity by parallel nanometer molecular lithography. Self assembly is accomplished by preferential electrostatic bonding of the protein molecules to selected sites on the solid state lattice.

Gunderson, S.L., Naranyan, R., and Schiavone, R.C.; Overview of three biotechnology areas for development of advanced composite materials and structures, Proc. American Society for Composites, Fifth Technical Conference, June 12-14, 1990, pp. 165-175.

This paper examines research in the areas of biomimetics, biosynthesis, and bioprocessing as they relate to composite materials. In this context, biomimetics is defined as the study of natural systems and structures for novel designs and material utilization that could improve the versatility and performance capabilities of synthetic materials and structures. Brief descriptions and references are provided for wood, insect exoskeleton, mollusc shell, and bone. They reference a patent by Chaplin of a composite structure based on the helical winding angle of cellulose fibrils in the wood cell. They find the fiber-matrix interface in insect cuticle to be superior to man-made composites and believe the microfiber bridging to improve shear strength and toughness. They cite novel toughening mechanisms in mollusc shells that may apply to ceramic or metal matrix composites.

Rothschild, K. J.; Biophysical study of archaebacteria biomembrane and possible application in biomaterials., NTIS AD-A210-174-9-XAB, Boston Univ. Annual Report, Jul. 1988 - June 1989. 7 pages.

The objective of this project is to study the structure and molecular basis for structural stability in archaebacterial membranes. Another objective is to study the utilization of these membranes in the production of new materials which are fabricated on the nanometer scale. A method of using these crystalline membranes as two dimensional masks for nanometer molecular lithography has been developed.

Vincent, Julian.; Materials Technology from Nature., Met Mater (Inst Met), 6(1): 7-11, January, 1990.

The materials from which animals and plants are constructed are highly sophisticated, yet made from very few and very common components. They are of interest in a wide variety of disciplines, the aim being to understand, model and use them. The medical significance of such studies is well known; less well known but developing is the idea of biomimetic and 'intelligent' materials.

Wainwright, S.A., Biggs, W.D., Currey, J.D. and Gosline, J.M.; Mechanical Design in Organisms., John Wiley & Sons, Inc, New York, 1976.

This book deals with the interface between mechanical engineering and biology and reviews biological structural materials and their mechanically important features. Five chapters are devoted to a unified discussion of the properties of materials in general and the structure and properties of biomaterials in particular. They investigate organisms in their environment and point out the insights that may be gained from the study of the mechanical aspects of their lives. The underlying theme is that function at any particular level of biological integration is permitted and controlled by structure at lower levels of integration. The author concludes that organisms and their component materials are as precisely adapted to mechanical situations as they are to many other physiological and biochemical situations.

Materials, Biomineralization

Berman, A., Addadi, L. and Weiner, S.; Interactions of sea urchin skeleton macromolecules with growing calcite crystals., Nature, 331(6156): 546-548, 1988.

The authors grew crystals of calcite in the presence of acidic glycoproteins extracted from within the mineralized hard parts of sea urchin tests. As a control they used analogous proteins from the calcitic layer of a mollusc shell which are known to be nucleators of calcite when adsorbed on a rigic substrate, but inhibitors in solution. The authors show that the sea urchin, but not the mollusc macromolecules selectively adsorb onto specific calcite crystal planes and with continued crstal growth are occluded inside the solid phase. These synthetic crystals fracture with a conchoidal cleavage similar to that observed in sea urchin calcite. Thus intracrystalline proteins

may be responsible for this phenomenon in biology and the manner in which they affect the mechanical properties of the crystals may also have intersting implications to the material sciences.

Berman, A., et al.; Intercalation of sea urchin proteins in calcite: study of a crystalline composite material., Science, 250: 664-667, November 2, 1990.

Sea urchin skeletal elements are composed of single crystals of calcite. Unlike their synthetic counterparts, these crystals do not have well-developed cleavage and are consequently much more resistant to fracture. This phenomenon is due in part to the presence of acidic glycoproteins occluded within the crystals. It is proposed that the presence of macromolecules concentrated at the mosaic boundaries that are oblique to cleavage planes is responsible for the change in fracture properties. These results may be important in the material sciences, because of the unusual nature of this material, namely, a composite based on the controlled intercalation of macromolecules inside single crystal lattices.

Birchall, J. D.; The importance of the study of biominerals to materials technology., In: Biomineralization, edited by Mann, S., Webb, J. and Williams, R.J.P., VCH Publishers, New York, 1989

Biology does not waste energy manipulating materials and structures that have no function, and it eliminates those that do not function adequately or economically. The structures that are observed in nature work and their form and microstructure have been refined over millions of years. The task of modern materials technologists is to develop, within a very short time scale, materials the microstructure of which is such that they perform a function efficiently. It is as well, then, to look for fresh insights to biology and at the wisdom encapsulated in the materials it uses.

Calvert, P. and Mann, S.; Synthetic and biological composites formed by in situ precipitation (Review)., J. of Materials Science, 23: 3801-3815, 1988.

Many advanced materials employ second phase particles to impart special properties. Many biological materials are also composite with particles reinforcing a polymer matrix. In biological materials the particles are grown in situ within the polymer matrix, and under control of the matrix. This paper discusses the principles governing such processes and the potential for the production of highly structured composite materials by this route.

Mann, S. and Calvert, P. D.; Biotechnological horizons in biomineralization, Trends in Biotechnology, 5(11): 309-314, Nov. 1987.

Organisms which deposit bioinorganic solids (biominerals) may have important future potential in biotechnology and materials science. Two main themes are described; the direct use of unicellular organisms in the production of novel materials for medical implants, catalytic, magnetic and electronic devices; and

second, the mimicking of biomineralization mechanisms in ceramic technology and in the control of crystal growth. In the latter area, attempts to mimic the densely packed, laminar microstructure of inorganic materials have resulted in high strength, tough materials such as macro-defect-free cement from ICI. Interest has been expressed in the design of dredging machinery based on studies of mineralized teeth of limpets and chitons.

Mann, Stephen.; Crystal engineering: the natural way., New Scientist, March 10, 1990, pages 42-47.

This overview article describes efforts by materials scientists to mimic biomineralization in the laboratory. Within cells the genetic machinery exerts control over crystal growth to produce exquisite and complex structures. These often consist of high quality single crystals even though the complex architecture may include pores and curved edges. In particular, the author is investigating different forms of iron oxide in biological environments since iron oxides are used for catalysts and magnets. For example, magnetotactic bacteria use iron oxide magnetite as a magnetic sensor, while limpets use iron oxide goethite for abrasive teeth. The author and others have used Langmuir films to control the orientation of crystal structures. Eventually, they hope to grow new forms of single crystals or organized composites.

Materials, Biosynthesis

Dougherty, Elizabeth; Bio-Derived Materials, R&D Magazine, June 1990.

Researchers are taking nature to a new level by synthesizing genes to create materials for applications from artificial skin to nonlinear optics.

Kaplan, D.A., Valdes, J.J., Skurnick, I., Gendason, P.; Biotechnology: Opportunities to Enhance Army Capabilities, STR Technical Report 89-3, AD-A216 756, 1989.

This report describes the potential impact of biotechnology on operational enhancements in all phases of Army missions. By employing the protein and genetic engineering techniques of biotechnology, significant advances can be achieved in a wide spectrum of materials, processes and systems. Highlights of this documents include: bioprocessing of high performance fibers (e.g. spider silk), lightweight, lower cost ceramics, ultrasensitive chemical and biological sensors, self assembling biomaterials, reactive materials for degradation of chemical and biological agents, and materials or coatings to provide protection against directed energy or capable of mimicking local natural signatures to provide camouflage protection.

Lombardi, S.J., Fossey, S., Kaplan, D.L.; Recombinant spider silk proteins for composite fibers., Proceedings of the American Society for Composites, Fifth Technical Conference, June 12-14, 1990, 184-187.

The use of genetic engineering for polymer synthesis provides many opportunities for control of chain composition, sequence, size, reactivity and stereochemistry. Silk proteins represent an unusual class of structural fibers with interesting mechanoelastic properties. Some types of spider silk exhibit improved mechanical properties when compared with the silkworm silk. Therefore, spider silk was cloned and expressed in a bacterial host system. Research on selectively modifying composition at the genetic level to effect structural and functional changes in fiber properties is continuing. Applications in the material sciences are expected due to the versatility and properties of this class of fibers.

Oci, T.; Designing of biopolymers discussed., Japan Report: Science and Technology (JPRS-JST-86-006) p 35-47, 1986.

The properties and structural principles of configuration of the biopolymers are described. Of the representative biopolymers, nucleic acids and proteins, proteins have diverse and varied functions and structures. The present state of knowledge regarding the process of biosynthesis, the formation of a three-dimensional configuration following peptide chain synthesis, and the three-dimensional structure of a protein, and what sort of designing is feasible based on that knowledge are discussed.

Pool, R.; Making new materials with nature's help., Science 250:1389, December 15, 1989.

This brief article describes the highlights from a special symposium at the fall meeting of the Materials Research Society entitled "Materials Synthesis Utilizing Biological Processes." Specific researchers and topics mentioned include: Paul Calvert (bioceramics), Mark Alper and Mark Bednarski (organic molecules for biosensors), Joseph Cappello (synthetic protein polymers), Stephen Mann (thin films of organic crystals), Dan Urry, (artificial muscle fibers), Richard Blakemore (magnetotactic bacteria).

Schiavone, Rebecca.; Potential Applications of Biotechnology to Aerospace Materials., AFOSR Report No. TR-87-0168, Nov. 1986.

This is a report of a workshop held in Dayton, OH which uncovered five areas of interest and possible benefit to the aerospace materials community. These include: (1) use of biological organisms to recover strategic metals and produce fine powders; (2) use of biological organisms for novel chemical approaches to produce specialty chemicals or materials; (3) use of biological molecules for electric and optical properties; (4) use of biological organisms for degrading materials or waste products; and (5) examination of natural products for structure/property relationships and novel

design concepts. The summary report recommended the following specific applications: biomining using bioleaching or bioabsorption; bioelectronics using biomaterials with highly non-linear optical properties for molecular computing, optical storage, laser hardening and high-speed A to D conversion; biodegradation for paint stripping aircraft; and biosynthesis of new chemicals and materials.

Ulrich, Donald R.; Prospects for Sol-Gel Processes., Journal of NonCrystalline Solids, 121(1-3): 465-479, May 1, 1990.

As the science of sol-gel materials develops with the new understanding of synthesis and processing, structure development, and structure-property relationships, opportunities are presented for research into new emerging areas. Examples are composite waveguides for third-order nonlinear optical applications (all optical) and ion laser intracavity glass optics for ultraviolet photonics. The coupling of partial densification and pore structure development with laser physics will create new opportunities for optical device design. The implications for bioprocessing and biomimetics to enhance sol-gel processes and structures for creating multi-functional materials is assessed.

___; Biotechnology Aided Synthesis of Aerospace Composite Resins., Proceedings of the American Society of Composites, Dayton, OH, Aug. 25-26, 1987.

This report is a collection of papers presented at a special symposium organized by the American Society for Composites and sponsored by AFOSR. It includes both Air Force and industry perspectives on the current and future needs in aerospace matrix resin chemistry. Several papers discuss potential applications for biosynthesis of various resin materials. The results of the group discussions are not included in this report.

Materials, Composite

Chaplin, C. R., Gordon, J.E., and Jeronimidis, G.; Composite Material., U. S. Patent No. 4,409,274, Oct. 11, 1983.

The inventors describe a composite structural panel of high strength and toughness that can be inexpensively formed with current corrugated paperboard equipment. This is accomplished by bonding structural reinforcing fiber to a corrugated medium at an approximately 15 degree orientation angle relative to the medium flute axes. In the patent, the inventors state that this work resulted from the study of failure modes of natural wood. Under tensile stress, the helically wound cellulose cell walls collapse inward, severing the lignin matrix bond, and facilitating significant axial extension as the helical fibrils straighten and shear. From these observations, the inventors suggest a fiber reinforced composite with an optimum helix angle of 15 degrees to balance toughness with strength and stiffness.

Currey, J. D.; Shell form and strength., The Mollusca, Vol 11:183-210, 1988.

The author presents the mechanical properties of the materials of mollusc shells and indicates which features of their structure give them their mechanical properties. The relation between architecture and mechanical properties is discussed, as is the relation to the selective forces, such as predation, cost of material, etc.

Gunderson, S. and Schiavone, R.; The insect exoskeleton: a natural structural composite., Journal of The Minerals, Metals and Materials Society, 41(11): 60-62, 1989.

The authors study the structure and materials of the insect exoskeleton, or cuticle, specifically the bessbeetle. The structure closely resembles man-made fiber reinforced composites with each section consisting of highly ordered unidirectional plies of fibers embedded in a protein matrix. Successive layers of fibers are offset by a small angle resulting in a dual helicoid arrangement. In addition, in some areas there are small trabeculae observed bridging from one layer to the next, with an air space between, and these are believed to improve impact damage tolerance. The observed design may offer insight into design of synthetic composites.

Jeronimidis, George.; Engineering aspects of natural composite materials., Presented at BIOTECH '86: Online Publications, Pinner, UK, 1986, pp. 153-157.

Composites in nature are based on relatively few chemical substances but vary widely in mechanical properties through "design". Special mechanisms are used to achieve structural safety at minimum metabolic cost. Controlled interactions between subunits and gradual transition from molecular building blocks to macroscopic structure point to an integrated approach which is successful and which modern technology may well use for inspiration.

Sarikaya, M., et al.; Seashells as a natural model to study laminated composites., Proc. American Society of Composites, Fifth Technical Conference, June 12-14, 1990, pp. 176-183.

The microstructure and mechanical properties of the nacre section of abalone shell were studied as a model for the fabrication of laminated ceramic-metal composites. The unusually high toughness values for the shell are attributed to the unique microstructure consisting of alternating layers of aragonite and organics with thicknesses of 0.25 micrometer and 20 nanometer, respectively. Laminated cermets were fabricated to mimic this design and the resulting cermets demonstrated a 40% increase in fracture toughness and strength. Present research is directed at reducing the thickness of the laminates to submicrometer levels to maximize the benefit of the laminations.

Materials, Crystals

Sleytr, Uwe B, Dietmar, Pum, Margit, Sara; Application potentials of two dimensional protein crystals., Microelectron Eng 9(1-4):13-20 May 1989.

This article gives an overview of the structure, chemistry, self-assembly and technical application of crystalline bacterial cell surface layers (S-layers). These supramolecular structures represent ideal model systems for learning how nature accomplishes producing and maintaining nanometer structures. Studies have clearly shown that these protein crystals are of great interest as templates or patterning elements for nanometer fabrication. Applications discussed include specific filtration problems such as particle counting in the electronics industry, substrates for enzyme or immunoassays for biosensors, and controlled release systems for drugs. As the architecture and function of more complex biological systems, particularly membranes, becomes better known, novel concepts should influence the design and fabrication of molecular machines and electronic devices.

Materials, Surface Coatings

Baier, R.E. and Meyer, A.E.; Biosurface chemistry for fun and profit., Chemtech, March, 1986, 178-185.

This overview article covers some of the work of these investigators and other over the years. They have studied many biosurfaces including those of porpoises and killer whales, oral mucosa, and blood vessel endothelium. The outermost aspect of these surfaces is a thin, amorphous layer of glycoproteinaceous materials that have a remarkably low surface energy, less than 30 dynes/cm. Various physical and chemical analytical techniques have shown that the same closely packed cluster of methyl groups is used for surfaces contacting blood and seawater. This knowledge has been used and applied to produce thromboresistant vascular grafts, cell culture vessels, and anti-fouling films for periscope windows. This technology may have application in preventing biofouling in closed loop life support systems and on space vehicle or systems exposed to the marine environment, such as expended solid rocket motors.

Mechanisms

Caldwell, D.G. and Taylor, P.M.; Chemically stimulated pseudo-muscular actuation, International Journal of Engineering Science, 28(8): 797-808, 1990.

Polyelectrolyte gels are synthesized as a structural materials for a chemically stimulated muscle-like actuator to be used in a robotic arm. The work sought to determine the feasibility of producing a new power system with an excellent power/weight ratio. The static and dynamic mechanical properties were studied, especially those affecting crosslinking, component ratio, and environmental conditions. Comparisons of the relative abilities of natural and artificial muscle are made with secial reference to those properties having a bearing on the use of this type of actuator in robotic applications.

Piotrowski, George.; Nature's lessons for creative machine design., Mechanical Engineering 106(3): 50-54, 1984.

The design of the human locomotor system is evaluated in this article with the purpose of improving machine designs. The concept of biological designs can be equally well adapted to such fields as heat transfer, chemical processing, information transfer and processing, and many others.

Shiga, T., Hirose, Y., Okade, A., Kurauchi, T.; Bending of a High Strength Polymer Gel in an Electric Field., Kobunshi Ronbunshu, 46(11): 709-713, 1989. In Japanese.

Deformation of a high strength poly(vinyl alcohol) hydrogel which contains poly(sodium acrylate), PVA-PAA gel, in an electrolyte solution under the influence of an electric field was studied. The PVA-PAA gel was prepared by repeatedly freezing and thawing a mixture of a PVA aqueous solution and a PAA aqueous solution. The PVA-PAA gel bends to the cathode side when subject to the influence of a d.c. electric field. This bending occurs through swelling on the anode side of the gel. The bending speed depends on the field intensity and on the concentration of an electrolyte in the solution. The bending force is about 1kPa. Two biomimetic machinery systems putting to use the PVA-PAA gel driven by an electric field were designed.

Wilson, James F.; Robotic Mechanics and Animal Morphology, NATO ASI Series, vol. F11, Robotics and Artificial Intelligence, edited by M. Brady et al., pp.419-443, 1984.

The wealth of information on animal structure and motion could well assist the engineer in robotic design. The viewpoint herein is that of continuum mechanics. To limit the scope, data for three species were studied: the jumping spider, the nemertean worm and the squid. The important geometric characteristics of their skeletal support systems which allow for appendage extension, bending and twisting motions were reviewed and summarized. With knowledge of available anatomy it is visualized that purely mechanical analogs to muscles can be designed without using the complex biological and electrochemical action. For instance, simple pressurized tube manipulators capable of length change, bending and twisting have already been patented but have yet to be exploited for use in robotics.

Mechanisms, Manipulators

Grupen, R. A., Henderson, T. C., McCammon, I. D.; A Survey of General-Purpose Manipulation, The International Journal of Robotics Research, 8(1): 38-62, February 1989.

A general-purpose manipulator, in conjunction with other sensory modalities, can be used to measure the three-dimensional character of the environment, support object recognition and localization procedures, and perform alternately as a delicate and powerful manipulator. This paper surveys the technologies which support general-

purpose manipulation. Some of the "bioware" supporting manipulation and haptics in humans is described. The development of hardware to support general-purpose manipulation is progressing rapidly. We focus on tactile sensing techniques and their role in perception. A variety of mechanical manipulators used in research and the methods employed to control them are presented. Finally, we discuss properties of the task, the manipulator, and the object which constrain the selection of manipulation strategies.

Maguerre, H.; BIONICS: Gripper Systems to Emulate the Feel Abilities of the Human Hand., Elektronik (West Germany), 39(1): 56-59, January 5, 1990. In German.

Describes how the human hand carries out its force sensing by means of the Organs of Golgi and shows a mechanical force and torque sensor based on strain gauges. The design of a modular gripper system with feedback is illustrated, which can be combined with visual detectors. Minimum force is applied to the workpieces handled.

Wilson, J. F. and Mahajan, U.; The mechanics and positioning of highly flexible manipulator limbs., Transactions of the ASME, Vol. 111: 232-237, 1989.

The authors have developed several versions of flexible manipulators that are modeled after natural systems such as elephant trunks and squid tentacles. This paper provides an analysis of the typical limb as a series of polymeric tube elements. One end is fixed and the payload at the other end is manipulated by varying the internal pressure in each element. An adaptive computer program is developed to improve positioning accuracy and speed.

Wilson, J.F., Li, D., Chen, Z., George, R.T., Jr.; Flexible robot manipulators and grippers: relatives of elephant trunks and squid tentacles., NATO Advanced Research Workshop on Robots and Biological Systems, Tuscany, Italy, June, 1989.

This paper briefly reviews the overall structural forms and motions of elephant trunks and squid tentacles, and discusses how the authors incorporated some of their biological characteristics in the design of a flexible arm manipulator and a two-fingered gripper. These are both designed of convoluted, orthotropic, polyurethane tubes that bend when subjected to internal pressure. Open-loop pressure control was used in simulating an elephant trunk lifting a payload, while closed-loop control was used in simulating two squid tentacles in parallel. The authors conclude that flexible arm manipulators and grippers are robust, fast-acting, and lightweight.

Wilson, J.F., Wainwright, S., et al.; A continuum model of elephant trunks., J. of Biomechanical Engineering (In Press).

This interdisciplinary article studies the detailed anatomy and materials properties of the elephant trunk with the objective of relating form to function. Other articles by Wilson describe the implementation of this work in flexible robotic manipulators.

Navigation Systems

Diercks, K. J.; Biological Sonar Systems--A Bionics Survey, Report no. ARL-TR-72-34 (Naval Ship Systems Command contract N00024-68-c-1339) September 1972.

PREVIOUS BIONICS SURVEY. The literature on biological sonar systems (bats, birds, marine mammals) was reviewed and investigators interviewed to ascertain the contributions of work in this field to high resolution sonar technology. Bibliographies and contacts are enclosed in the report.

Guastella, Martha J.; Bionic Modeling of Knowledge-Based Guidance in Automated Underwater Vehicles, Technical Memorandum No. 87-2068, Naval Underwater Systems Center, 1987.

This memorandum describes the auditory localization behavior of the barn owl as an example of how bionic systems may be modeled for application to underwater vehicles. The nocturnal barn owl (Tybo alba) is unique in its passive localization ability, having vertically displaced ears with different peak sensitivities. It has an audible range of 0.1 kHz to 12 kHz and a sensitivity of -18 dB SPL. Despite its small size, it can get bearing, azimuth, and elevation without leaving its perch. It can localize pure tones almost as well as noise. Based on currently available data on the owl's sensory and structural capacities, a model of its localization behaviors is developed to identify the decisions and information needed in localizing prey. The informational requirements at each stage of its mission are projected from environmental and behavioral data. Guidance is shown as an automatic system based on nulling mechanisms; after the identification of the prey, decision-making is a go/no-go election. Sensory information is continuously updated by the owl while in motion until the final attack phase. The use of intelligence is discussed. This model is offered as an illustration of how bionic systems may serve to identify the kinds of information required by an autonomous vehicle (AUV). It also suggests a model of sensors and decisions whereby localization occurs. Applications for AUV tasks are suggested.

Kayton, Myron; Animal Navigation: The Ultimate Neural Network, IEEE Aerospace and Electronic Systems Magazine, pt.1, 4(3):3-7, March, 1989.

This paper describes research, past and present, done on navigation by animals. The author's interest is to find out whether the animals' "technology" is applicable to long-distance navigation by man. Experiments done on birds and fish in the past are presented, and the author draws conclusions based on his literature search. The mission phases of a migrating bird are defined as take off, initial departure heading, speed and energy, altitude, en-route navigation, and destination and are described in terms of the navigational techniques and mechanisms used by the bird. Animal sensors are then described. The author concludes that the mechanism of animal navigation is a complex integration of many senses whose details are unlikely to be discovered soon. He sees no hope soon of being

able to write an algorithm to process the sensor data as the bird does and maintains that the engineer will profit once direct access is obtained to the animal's brain and its wiring diagram is understood. Finally, he states that knowledge of the structure of the bird's brain and the algorithms for data processing will be applicable far beyond the technology of navigation and that this study has barely begun.

Pye, J. David; The Bionic Bat: Evolution and Wave-Physics, Royal Institution Proceedings, (G.B.) 56: 175-203, 1984.

Pye discusses the bat's use of acoustic echolocation for guidance and finding prey. He describes a simple echo locator using pulsed ultrasound. During the discussion he explains interference in sinusoids in reference to rendering objects size indeterminant or invisible. Pye describes how to avoid this difficulty by using a frequency swept pulse (chirp), which allows a fairly high range resolution. Improvement of the basic echolocation system is made by adding a parabolic reflector, several different types of which are described, to aid in directionality. The transmitter section is improved by using a horn to narrow the emitted beam to detect small objects. The improvements made to the system results in a model which looks similar to a bat's features. Doppler radar is then discussed as an alternative method used by bats for detecting range and direction. The separation of horseshoe bat's nostrils by exactly half a wavelength to utilize interference to form a beam is discussed along with the use of wiggling ears as a method for determining direction of moving targets and the range of a stationary object. Another bionic bat is shown for illustration. A comparison is made for each bionic bat with the real bats to show how the form of a bat might correlate with the bat's function. A more mechanical model is shown as an alternate and radar applications are discussed. The paper provides an excellent summary of the technical explanations for theorized bat guidance/prey location.

Seleznev, Vasilii P., Selezneva, Natal'ia V.; Navigational bionics --- Russian book., Izdatel'stvo Mashinostroenie, 1987, 256 p.

Methods used in bionics studies are discussed with emphasis placed on the biological processes involved in the bionics of navigation. Attention is given to the navigation parameters and their measures, the organs and systems of higher organisms performing navigation-connected functions, and inertial biosensors which regulate the dynamics of live organisms. Special consideration is given to the structure of the visual navigation systems and to information processing in these systems, as well as to the aeroacoustic, hydroacoustic, thermal, and chemical systems of navigation. The special features characterizing the navigation systems of insects are examined. A model is presented describing the structural principles of a navigation biocomplex.

Varju, D., Schnitzler, H.U. (editors); Localization and Orientation in Biology and Engineering, Published by Springer-Verlag Berlin Heidelberg, 1984.

This book is a collection by a multitude of authors: engineers, biologists, and physicists. Topics include: localization, identification, and tracking of signal sources;

orientationa and path control; localization and identification of targets by active systems; navigation, bird migration and homing.

Voorhis, Kristina, V., Franklin, Robert F.; Computer Simulation of Animal Navigation, Annual Technical Report to University of Wisconsin, Period: 7/86-8/87; Contract No. 208G-762.

This report documents three tasks undertaken for the first year of an investigation to further the understanding of autonomous performance on rough terrain through the investigation of legged animal foothold selections, blazing trails through rough terrain, and renegotiating trails. The three tasks undertaken: performing experiments with Nubian goats to determine their strategies for foothold selection, development of a terrain module to simulate a complex and dynamic environment with both tactile and visual properties, and development of a graphics display module to provide views of the simulated terrain and vehicle. The three undertaken tasks are discussed, and a description of the code and documentation for the computer simulation of rough terrain traversal based on the animal studies is described.

Waterman, Talbot H.; Animal Navigation., Publ. by Scientific American Books, Inc., 1989.

This very readable text explores the mechanisms used by animal species to navigate within their environment. It includes chapters on senses for direction finding, spatial orientation and course keeping, the compass and visual direction finding, migration, and mapping a sense of space. The author does not directly address efforts to apply knowledge of animal navigation, but does allude to this possibility numerous times throughout the discussion.

Sensory Systems

Bel'kevich, V., Vende, E., Vil'-Vil'vams, I.; Bionics - The engineering art of nature., Joint Publication Research Service Report #17,500 (Translated from Tekhnika-Moledeshi, No. 9:36-38, Sept. 1962.

Biological Designs are marked by their miniaturization, their high degree of flexibility, their sensitivity, their capability to resolve problems, and their high degree of reliability. Examples of biological systems include: "bifocal" lenses of certain shallow-water fish; perioscopic vision of the periophthalmus; a new design for a gyroscope inspired by the clavate organ of double-winged hexapoda; navigation system based on the ability of hexapoda to precisely determine the sun's location using the polarity of sunlight; accelerometers based on the vestibular apparatus in man; consideration of the structural features of the seals hearing apparatus, chiefly the exterior canals and helix, in the design of hydrophones; infra-auditory range detection of fishes; ultra-auditory detection and location systems of bottlenosed dolphin, and electromagnetic field detection systems of lamprey and certain fishes. Also of inter-

est is a figure showing the sound and ultrasonic vibration which can be perceived by various animals and man.

Maguerre, Hans.; Bionics - at the crossroads of nature and technology., Energy Autom 10(5):32-33, 1988.

Bionics is an interdisciplinary field of research that tests ways in which models supplied by nature can be utilized for technological purposes. Although there are countless analogies between nature and technology, it's rare that solutions offered by nature can be directly adapted. Even when copying nature is virtually impossible, engineers can still learn a great deal if they allow themselves to be guided by the functional, structural, and organizational principles found in biology.

Westbrook, M. H.; The Human Body and Its Transducers: A Real-Time Real-life Computing and Control System, IEEE Computing and Control Proceedings 131(1):10-16, 1984.

This paper provides an excellent overview of the human body's "transducers" and their relationships with their engineering equivalents. The basic organization of the brain, how it can be represented as an enormously complex real-time parallel computing and control system, and how its operation relates to computing and control technology are presented first. The human senses are then considered as control system input transducers, and their engineering equivalents and their limitations are described--in particular their relevance to developments in intelligent or smart sensors is discussed. Finally, the paper describes the human output transducers as represented by the muscular system and its reflex controls. The author points out in the conclusion that the study of the human transducers can provide insights into new methods of transduction and control for use in robotics and computing and control systems. Table 1 is particularly interesting--it provides the frequency ranges, amplitude, and other specifications for human senses. This table is a good example illustrating that the strength of this paper lies not in a specifically mentioned application, but rather in a clear and concise description of the human senses from an engineering standpoint.

___; Review of biological mechanisms for application to instrument design., NASA CR 169746, N83-71803, 96 pages, 1983.

While this report is dated 1983, this report is the fifth in a series of summary reports from contracts performed between 1962 and 1967. This report, like the preceding four, reviews certain biological mechanisms for application to instrument design and engineering for the NASA Office of Advanced Research and Technology. The study investigates biological receptor mechanisms from an engineering viewpoint and evaluates these against a background of current and anticipated instrumentation requirements. This report includes photoreception, mechanoreception, chemoreception, and electrosensing. Potential applications include: variable focus optics, false

color imagery displays, pulse-coded transducers, electrical stimulation devices, and a microwave dosimeter.

Sensory Systems, Acoustic

Altes, R. A.; Bioacoustic Systems: Insights for Acoustical Imaging and Pattern Recognition., SPIE Vol. 768, International Symposium on Pattern Recognition and Acoustical Imaging (1987).

Standard performance measures and statistical tests must be altered for research on animal sonar. The narrowband range-Doppler ambiguity function must be redefined to analyze wideband signals. A new range, cross-range ambiguity function is needed to represent angle estimation and spatial resolution properties of the animal sonar systems. Echoes are transformed into time-frequency (spectrogram-like) representations by the peripheral auditory system. Detection, estimation, and pattern recognition capabilities of animals should be analyzed in terms of operations on spectrograms. The methods developed for bioacoustic research yield new insights into the design of man-made imaging and pattern recognition systems. The range, cross-range ambiguity function can be used to improve imaging performance. Important features for echo pattern recogntion are illustrated by time-frequency plots showing (i) principal components for spectrograms and (ii) templates for optimum discrimination between data classes.

Altes, Richard A.; Angle estimation and binaural processing in animal echolocation, J. Acoust. Soc. Am. 63 (1), Jan 1978

This paper is concerned with the problem of angle estimation, as it relates to mammalian hearing. The analysis begins with a problem formulation that is suggested by published physiological and behavioral data. Statistical communication theory is then used to derive a processor configuration to solve the problem. The processor is compared with its biological counterparts from the viewpoint of structure, function, and performance.

Au, Whitlow, W. L., Carder, Donald A., Penner, Ralph H., Scronce, Billy L.; Demonstration of adaptation in Beluga whale echolocation signals, J Acoust Soc Am 77(2):726-730, Feb 1985.

The echolocation signals of the same beluga whale (Delphinapterus leucas) were measured first in San Diego Bay, and later in Kaneohe Bay, Oahu, Hawaii. The ambient noise level in Kaneohe Bay is typically 12-17 db greater than in San Diego Bay. The whale demonstrated the adaptiveness of its biosonar by shifting to higher frequencies and intensities after it was moved to Kaneohe. In San Diego, the animal emitted echolocation signals with peak frequencies between 40 and 60 kHz, and bandwidths between 15 and 25 kHz. In Kaneohe, the whale shifted its signals approximately an octave higher in frequencies with peak frequencies between 100 and

120 kHz, and bandwidths between 20 and 40 kHz. The data collected represent the first quantitative evidence of the adaptive capability of a cetacean biosonar system.

Maguerre, H.; Bionics: Surface Wave Propagation and Use in Communication, Elektronik (West Germany), 39(1): 37-39, February 2, 1990. In German.

In this sixth and last of the series of articles the author considers the analogues from the animal world to modern surface wave components. The world of spiders and scorpions is full of vibration. These creatures have high sensitivity sensing organs for acoustic surface waves set up by ground vibration. Transmitted signals can be the means of obtaining high quality information; for example the presence of friend or foe and the location data. There is also the complete natural equivalent to the human developed signal processing techniques.

Manoli, S.H.; An Electronic Model of the Basilar Membrane, 29th Annual Conference on Engineering in Medicine And Biology, 6-10 Nov. 1976

Frequency discrimination of sound waves in the inner ear is achieved by the frequency-space transformation characteristic of the basilar membrane. A new modeling approach, using simple active butterworth filters has been successfully attempted. The paper discusses the theoretical background and describes a relatively simple circuit design. The model is currently being used in evaluation and analysis of spoken words.

Pettigrew, J. D. and Larsen, O. N.; Directional hearing in the Plains-Wanderer, Pedionomus Torquatus., Information Processing in Mammalian Auditory and Tactile Systems, pp. 179-190, Alan R. Liss, Inc., 1990.

The authors studied the directional hearing of the Plains-wanderer, whose unlikely acoustic ability includes locating species-specific sounds whose wavelengths are orders of magnitude larger than its own head. Neurophysiological studies are conducted, and the role of the interaural canal in directional hearing is discussed. From this work the authors are developing an improved hearing aid with directional capability and the ability to separate sounds from background noise.

Trott, W. James; Symposium on Bionic Models of the Animal Sonar System, Frascati, Italy, 9/26/66-10/3/66, Office of Naval Research Technical Report ONRL-C-27-66, 1966.

Report on symposium on Bionic Models of the Animal Sonar System. Summarizes paper presentations on acoustic orientation, obstacle detection and communication by bats, porpoises, and other air and marine animals. Probable means of signal processing and experimental data on the neural processing of bat sonar are reported. Natural and auxiliary sonar assistance for the blind is discussed.

Sensory Systems, Electromagnetic

Heiligenberg, W.; Electrosensory systems in fish, Synapse, 6:196-206, 1990.

A close integration of behavioral, neurophysiological, and neuroanatomical approaches has guided research on the neural basis of electrosensation and the generation of behaviors associated with this modality. Physiological and anatomical studies have analyzed a) neural networks underlying the distributed processing of sensory information, b) the role of descending recurrent pathways and efference copy mechanisms for the filtering of incoming information, c) the significance of multiple topographic representations for sensory information processing, and d) the modulation of sensory and motor structures through various transmitters and receptor subtypes. Developmental studies have explored the significance of steroid hormones for the tuning of electroreceptors to the frequency of an endogenous neuronal oscillator which drives the electric current pulses necessary for their stimulation. Embryological studies have revealed that the development of mechanoreceptors and electroreceptors in the fish's skin is induced by the innervation of primary afferent nerve fibers which are specific with regard to their central connections as well as with regard to the type of receptor induced in the periphery.

Kalmijn, Ad. J.; Functional Evolution of Lateral Line and Inner Ear Sensory Systems, In The Mechanosensory Lateral Line: Neurobiology and Evolution, Chapter 9, S. Coombs, P. Goerner, H. Muenz, Eds. Springer-Verlag, 1989.

In detecting moving objects, the fish's lateral line and inner ear support different, but closely related, hydrodynamic functions, suggesting early developments in the vertebrate sense of hearing. In an effort to elucidate the functional evolution of the two sensory systems, this chapter examines the hydrodynamic and acoustic fields in nature, the physics and physiology of the detection process, the evaluation of the sensory data, and the ensuing behavioral responses.

Kalmijn, Ad. J.; Detection of Weak Electric Fields, Sensory Biology of Aquatic Animals, Chapter 6, J. Atema, R.R. Fay, A.N. Popper, W.N. Tavolga, Eds., Springer-Verlag, 1987.

Electric fields in natural waters present a wealth of sensory information. Bioelectric fields direct electrosensitive fishes to their prey, environmental fields provide important orientational cues, and the fields induced by the animals' motion through the earth's magnetic field offer oceanic species complete compass data. Particularly sensitive to electric fields are the marine sharks, skates, and rays, but the weakly electric fishes, the common catfishes, and several of the more primitive fishes are also known for their keen electric sense.

Maguerre, H.; Bionics, D-field procedure in difficult environmental conditions., Elektronik (West Germany)38(25):63-5, 8 Dec.1989.

The D-field monitoring procedure introduced here is based on the production of an electrical alternating field and receiving characteristic variations of field intensity. The robust D-field probe masters difficult conditions. Nature and technology have found similar solutions for monitoring environments. This is demonstrated here with detailed examination of the low frequency electric magnetic field produced by fish. The principle of monitoring is shown in a diagram. It is being further developed but even now distortions and vibrations can be detected.

Matsubara, Joanne A.; Neural Correlates of a Nonjammable Electrolocation System, Science, Vol. 211: 722-725, 13 February 1981.

The detection of objects by the electrosensory system of weakly electric fish is subject to electrical interference such as that produced by the electric organ discharges emitted by neighboring electric fish. Sternopygus is unique in that it has no jamming avoidance response, yet can electrolocate even in the presence of jamming. It appears that Sternopyggus protects electrolocation not by a behavioral strategy but by first-order central processing mechanisms that can distinguish between localized changes in the amplitudes of electric organ discharges caused by objects and large-field amplitude modulations caused by jamming. This mechanism acts as a local contrast detector and is functionally similar to the one used by retinal cells to respond to local contrast in light but not to overall changes in illumination.

Pickard, William F.; A Model for the Acute Electrosensitivity of Cartilaginous Fishes, IEEE Transactions on Biomedical Engineering, Vol. 35(4):243-249, April 1988.

A theory is put forth to account for the acute sensitivity of marine elasmobranchs (cartilaginous fishes) to exogenous electric fields. First, morphological adaptations cause a significant fraction of the voltage drop in the vicinity of the fish to occur across the epithelium of a specialized receptor organ, the ampulla of Lorenzini; that is, the stimulus is focused. Second, this stimulus modulates the delicately poised repetitive discharge of the primary afferent fibers which innervate the ampulla. Third, these fibers converge centrally to integrate the outputs of many ampullae and markedly increase the signal to noise ratio of the process. Simple quantitative estimates are given for each of these steps, and it is shown that the predicted limits of electroreception are close to those actually observed.

Shaub, Y. B., Khodzevich, A. V.; Bionic Model of Active Electrolocation in Fish., Doklady Akademii Nauk SSSR, 311(4): 984-988, 1990. In Russian.

A bionic model of active electrolocation in fish was discussed. The model reflected the following principal elements of this process: generation of the primary field, processing of information obtained, determination of coordinates and some characteristics of the object. The system can be studied, using computer-assisted modeling.

It was established that a fish positions its body in the way which makes it possible to locate the object being found in front of the fish's head in the zone of optimal location. The fish is able to determine very accurately the distance between itself and the object, and at the same time to evaluate its dimensions.

Sensory Systems, Infrared

Maguerre, Hans; Natural and Artificial Thermal Detectors, Energy & Automation X, No. 1, 1989.

In technology, the passive infrared detector was developed to sense thermal radiation and react quickly to temperature changes. Similar natural phenomena include the heat radiation eye of the rattlesnake,which helps it to distinguish between prey and predator based on the size and shape of their thermal image. Not totally by coincidence, the passive infrared detector is patterned on the heat radiation eye of the rattlesnake. Both the sensory organ and the detector work on the same principle: The heat radiation eye comprises a connective tissue membrane with sensory cells, whereas the infrared detector has a pyroelectric polymer foil made of polyvinylidene fluoride (PVDF). And both the membrane and the foil are but a few micrometers thick, permitting quick and sensitive reaction to temperature changes.

Sensory Systems, Olfactory

Krull, Ulrich, J., Thompson, Michael; Lipid Membrane Technology for Chemical and Biosensor Development, Trends in Analytical Chemistry 4(4):90-96, April 1985.

The authors evaluate biological olfactory processes in an effort to better understand natural sensing as a means to provide sufficient background to attempt to create artificial membranes which make use of such processes. The natural olfactory membrane is described, followed by an artificially prepared bilayer lipid membrane (BLM)--which is described as a suitable representation of a natural membrane. A summary of BLM interactions leading to conductance increases is presented in table form. The authors state that generally the BLM sensor can be considered as a useful prototype of a selective trace organic sensor which has numerous characteristics suitable for biosensor development, including selectivity, sensitivity, reversibility, low cost, ease of use, portability, small size, and potential biocompatibility. A BLM based ammonia gas sensor has been successfully operated with detection limits comparable to the conventional ammonia gas sensor, and with substantially greater selectivity. After briefly discussing this sensor, the authors describe the substantial future work that remains to be done before practical devices based on this technology become a reality.

Nakamoto, T., Fukunishi, K., Moriizumi, T.; Identification Capability of Odor Sensor using Quartz-Resonator Array and Neural Network Pattern Rec, Sensors and Actuators, B Chem., B1(1-6) Pt1:473-476, 1990.

Although the identification of various kinds of odors in our daily life is important,, few artificial odor sensing systems have been reported. From the biomimetic point of view, the use of plural sensors to recognize the output pattern of a sensor array for such identification is very promising. An odor sensor using a quartz-resonator array and neural-network pattern recognition has been previously reported. In the present study, optimization of the sensor array components has been made and the recognition probability has been improved.

Persaud, Krishna C., Bartlett, Jon, Pelosi, Paolo; Design strategies for gas and odour sensors which mimic the olfactory system, NATO Advanced Research Workshop, "Robots and Biological Systems", June 26-30, 1989, Il Ciocco, Tuscany, Italy.

The biochemical, physiological, and psychophysical studies involved in the elucidation of the pattern recognition mechanisms of the mammalian olfactory system will be discussed in terms of the application of biological mechanisms to gas and odour sensing devices for industrial use. We have been involved in the design of gas and odour sensors based on semiconducting organic polymers. The chemical strategies involved in making sensors which may mimic the olfactory system will be described. These sensors have a broad overlapping specificity to particular classes of chemical compounds. Sensor arrays have been incorporated into a microprocessor-based device capable of discrimination between a number of volatile compounds.

Persaud, Krishna, Dodd, George; Analysis of discrimination mechanisms in the mammalian olfactory system using a model nose., Nature, Vol. 299:352-355, 23 September 1982.

Olfaction exhibits both high sensitivity for odours and high discrimination between them. We suggest that to make fine discriminations between complex odorant mixtures containing varying ratios of odorants without the necessity for highly specialized peripheral receptors, the olfactory systems make use of feature detection using broadly tuned receptor cells organized in a convergent neuron pathway. As a test of this hypothesis we have constructed an electronic nose using semiconductor transducers and incorporating design features suggested by our proposal. We report here that this device can reproducibly discriminate between a wide variety of odours, and its properties show that discrimination in an olfactory system could be achieved without the use of highly specific receptors.

Shurmer, H., Fard, A.; Development of an Electronic Nose, Phys. Technol. 18 (1987).

There is a universal long-standing need for an electronic equivalent to the human nose. In this article we consider the progress that is being made towards the design and construction of an electronic device (nose) capable of mimicking the human ol-

factory system in discriminating with high sensitivity between chemically complex odours. In modeling such a system a large array of differential sensors must be envisaged, which immediately points to the utilization of microelectronic techniques, for simplicity, reliability and cheapness. The types of sensors that are of current interest include those using doped metal oxides, chemically sensitive field effect transistors (CHEMFETS), Langmuir-Blodgett films and conducting polymers.

Tonoike, M.; Current Status and Future View of Development for Odorant Sensors, Denshi Gijutusu Sogo Kenkyujo Iho, Vol. 52 (5), 1988.

In the present paper the current status of odorant sensors is surveyed and a future view of its development is described. First, a complex of a few gas sensors is applied to sense the odorants. Next, biomaterials are tried to catch the odorants. For new sensing methods using living things, the responses of plants and human brain waves are measured by physiological techniques for stimuli of odorants. Recently, biosensors and lipid bilayers sensors with a photoplastic film have been used with the same pattern recognition techniques as biological sensings of odorants. LB film, liposome and micro-gas chromotography are fabricated by molecule handling and microelectronic techniques. A model of olfactory nerve systems is simulated with complex connections of second order non-linear differential equations. This research will not only be applied to new types of sensors of odorants, but also to a neural computing model, and "Olfactory Engineering" will be born.

Vodyanoy, Vitaly; Olfactory Sensor, IEEE Engineering in Medicine & Biology Society 10th Annual International Conference--0997, 1988.

A molecular sensor which is based upon an electrochemical model for the molecular mechanism of ion transport associated with the initial steps in olfaction is described. The olfactory sensor is obtained by functional transfer of macromolecules from homogenates of the olfactory epithelium into artificial bimolecular membranes, monolayers and multilayers. The basic idea of this work is to use the functional reconstitution of the olfactory receptor cell to produce an artificial system responsive to small (subnanomolar) concentrations of odorant for quantitative analysis of the odorant-receptor interaction, to study this interaction, and then to apply this information to the development of a chemosensitive device. This sensor could respond to a number of substances for which no other simple instrumental assay is presently available.

Sensory Systems, Optical

Angel, J. R. P.; Lobster eyes as x-ray telescopes, Astrophysical Journal, Part 1, 223: 364-373, Oct. 1, 1979.

The imaging x-ray telescope, a new optical configuration for grazing-incidence that is similar to the reflective eyes of macruran crustaceans such as lobsters, is described. The field of view can be made as large as desired, and it is practical to

achieve good efficiency for photon energies up to 10 keV. Spatial resolution of a few seconds of arc over the full field is possible, in principle, if very small reflecting cells can be fabricated.

Carson, John C.; Smart Sensors and "Dynamic Stare", Photonics Spectra, Vol. 21 (5), May 1987.

Irvine Sensors Corp. has successfully demonstrated an advanced smart sensor module called HYMOSS (Hybrid Mosaic On Stacked Silicon). A new and revolutionary sensor concept has been born out of the parallel processing capability of HYMOSS and some of the basic functions of the human eye. "Dynamic Stare" will permit recognition of objects in highly cluttered moving backgrounds on the basis of either their shape or their motion.

Moore, Duncan T.; Gradient-Index Lenses: Technology Derived From Nature, Ceramic Bulletin, Vol. 68, No. 11, 1989.

This paper advocates the uses of gradient-index lenses, in which the index of refraction varies in a continuous way as a function of spatial coordinate. The main difference in gradient-index lenses is inclusion of not only the refraction at surfaces but also of the bending of the rays of light within the materials to reduce the number of lenses required to accomplish a given image quality. Examples of gradient-index materials found in nature precede a discussion of properties (and advantages) of gradient-index lenses.

Pelli, D. G., Chamberlain, S. C.; The visibility of 350 deg C black-body radiation by the shrimp Rimicaris exoculata and man., Nature, 337 (Feb. 2, 1989): 460-461.

The eye of the "eyeless" shrimp Rimicaris exoculata is unusual in having no image forming optics and a high concentration of rhodopsin. The shrimps swarm around 350 degree C hydrothermal vents in the Midatlantic Ridge. Physical calculations indicate the shrimp can see the blackbody radiation of the vents, even though these sources are practically invisible to the human eye.

Schefter, Jim; Moth-eye Magic, Popular Science, May 1989, pp. 136-137, 163.

This is a basic description of anti-reflective optics which mimic the corneal patterns etched on a moth's eye. The design of these surfaces is described, as well as applications which are being developed. The author describes work done by PA Technology and by Plasmon Data Systems, both in England.

Schneider, Richard T., Carroll, Edward E. Jr., Lin, Shih-Chao; Improved Resolving Power for Non-imaging Optical Elements, SPIE Vol. 829 Applications of Digital Image Processing X(1987).

This paper describes the imaging possibilities of a long cylinder lined with light sensors and equipped with an input light horn that is similar to the anatomy of the rhabdom of the insect eye. The author discusses how such a device can distinguish objects at different polar angles but not at different azimuthal angles (this may be optimized, however to improve the angular resolution). The results suggest that if the object to be detected resembles a point (an infared target for example) a small number of relatively large light horns may be superior to a lens-detector array combination. The author likens this to the use of a similarly primitive system used by snakes to locate prey with infrared radiation.

van Hateren, J.H., Nilsson, D.E.; Butterfly optics exceed the theoretical limits of conventional apposition eyes., Biol. Cybern. (West Germany). vol 57, no 3, pp. 159-68, 20 refs. 1987.

Optical experiments on butterfly compound eyes show that they have angular sensitivities narrower than expected from conventional apposition eyes. This superior performance is explained by a theoretical model where the cone stalk is considered as a mode-coupling device. In this model the Airy diffraction pattern of the corneal facet excites a combination of the two waveguide modes the corneal facet excites a combination of the two waveguide modes. This mechanism produces a higher on-axis sensitivity, and a narrower angular sensitivity than conventional apposition optics. Several predictions of the model were confirmed experimentally.

Wilson, S.J., Hutley, M.C.; The optical properties of 'moth eye' antireflection surfaces, Opt. Acta (GB) vol. 29(7):993-1009, July 1982.

A 'moth eye' antireflection surface is a very fine array of protuberances which behaves as a gradation of refractive index, and which substantially reduces the reflectance. The reflection and transmission properties of such surfaces are described, and are shown to be equal to those of the best multilayer antireflection coatings.

Sensory Systems, Tactile

Dario, P., Bicchi, A., Fiorillo, A., Buttazzo, G., Francesconi, R.; A sensorized scenario for basic investigation on active touch., Proc. 1985 International Conference on Advanced Robotics, Tokyo, Sept 1985.

The development of artificial tactile capabilities for advanced robots requires substantial progress in the fields of tactile sensors, end effectors and control. The authors study simple bionic analogs of the components of the human tactile sys-

tem, such as an articulated finger equipped with proprioceptive sensors and skin-like tactile sensors, and a static platform simulating the palm. A sensor-based control strategy intended to be a basic approach to future machine tactile perception is considered in some detail for the finger. Preliminary results on the use of simple tactile exploratory primitives demonstrate the usefulness of the proposed scenario for investigation on active touch.

De Rossi, D., Domenici, C., Chiarelli, P.; Bionic approach to development of tactile sensors and nonlinear actuators for advanced robotics., Alta Freq. (Italy). 55(1-I):55-62, 1986.

Advanced robot manipulator development is reviewed. The transduction mechanism of human skin is analyzed showing skin structure, sensitivity curves, mathematical models and the basic scheme of the transducer. Pseudomuscular actuators and operational modes are elaborated. Polymer and its piezoelectric properties are reviewed showing application possibilities.

De Rossi, Danilo, Nannini, Andrea, Domenici, Claudio; Artificial Sensing Skin Mimicking Mechanoelectrical Conversion Properties of Human Dermis, IEEE Transactions on Biomedical Engineering, Vol. 35(2), February 1988.

New possibilities in the process of designing sophisticated tactile sensors are opening up as more information on human skin sensory functions becomes available. Intrinsic mechanoelectrical conversion properties of skin tissues are investigated, and their origin is suggested to originate primarily from electrokinetic phenomena operating in the dermis. A synthetic analog implementing a mechanoelectrical transduction mechanism thought to operate in dermis is realized. A biomorphic tactile sensor is devised and its dynamic transduction response is theoretically and experimentally analyzed. The streaming potential artificial skin appears to be particularly suited for applications in which ideal mechanical matching with body tissues or soft touch grasp is required.

DeRossi, Danilo.; Biomimetic approaches to the design of materials for artificial tactile perception., IN: International Workshop on Intelligent Materials, Tsukuba, Japan, March, 1989, pp. 251-258, Society of Non-Traditional Technologies.

Three fields of investigation in artificial tactile sensing hve been identified as promising: thermotactile interactions for sensory fusion, strain dilatation sensing for low-level computation, and strain-rate-to-impulse frequency information coding. Attention is also given to the possibilities of a pseudoepidermal layer capable of resolving individual stress tensor components, and a pseudodermal pad that can serve as a rheological skin analog.

Harmon, L. D.; Tactile sensing for robots., In: Robotics and Artificial Intelligence, Edited by M. Brady et al, NATO ASI Series, Vol F11, pp. 109-157, 1984.

This review article includes a presentation of the history of tactile sensing, examination of the current state-of-the-art, and discussion of future challenges and opportunities. The author considers certain aspects of the human touch sense which seem to bear usefully on problems of machine sensing. This includes relationships of touch to vision and problems of coping with variables of shape, pose, object identification, and texture. The majority of the article however deals with the technology of machine tactile sensing. 110 references.

Patterson, Robert W., Nevill, Gale E. Jr.; The induced vibration touch sensor - a new dynamic touch sensing concept, Robotica Vol. 4 (pt. 1) Jan-Mar. 1986.

This report describes a new touch sensing concept in which active, exploratory touching resembles the manner in which humans use their fingertips. The concept utilizes the vibrations produced during sliding motion of the sensor to provide information for characterizing objects and features. The sensing system consists of a textured compliant artificial 'skin', a transduction element, and means for recognizing items of interest. A relatively simple prototype was fabricated and tested for a range of potentially useful tactile tasks. Results from these experiments demonstrate the promise of the concept. The prototype sensor is shown to be effective at recognizing feature orientation, feature position, and surface texture.

Sensory Systems, Temperature

Maguerre, H.; Bionics: membranes and films sense heat., Elektronik (West Germany). 38(24):73-4, 76, 24 Nov 1989.

For pt.I see ibid., no.23 p.48-50 (1989). Heat detection characteristics of sensors including bolometer, thermoelectric, quantum, and pyroelectric types are summarized, and criteria for sensitivity and rapid response include low thermal capacity and minimal thermal conductivity. For comparison, the heat-sensitive 'eye' of the rattlesnake is described, in which body temperature of prey is sensed on a parabolic membrane, ensuring great sensitivity and fast response. Features of the independently developed Siemens sensitive infra-red radiation detector based on thermoelectric elements made from 10 mu m thick polyvinylidene fluoride film at the focus of a parabolic mirror are presented. Performance is loosely compared with that of the snake, and the sensors can be constructed in array form to give greater directional capability.

Russell, Andrew R.; Thermal sensor for object shape and material constitution, Robotica, vol. 6, pp 31-34, 1988.

This paper describes a novel tactile sensor array designed to provide information about the material constitution and shape of objects held by a robot manipulator. The sensor is modeled on the thermal touch sense which enables humans to distinguish between different materials based on how warm or cold they feel. Some results are presented and methods of analyzing the sensor data are discussed.

Sensory Systems, Velocity

Humphrey, J. and Denny, M.; Ballooning Spiders., Mechanical Engineering, November 1989, 84-87.

In spider ballooning, air drafts stimulate a response in certain species to adopt favorable orientations with respect to wind which can result in aerodynamic lift. Once levitated, the organism is entirely passive in its aerodynamic transport. Hair sensillae are used by the spider to detect favorable wind conditions. The thread hairs are typically less than 10 micrometers in diameter, and small deflections trigger action potentials that determine behavioral responses to air motion. These are not pressure sensors but deflection sensors. Experiments indicate they are deflected about 5 degrees for air speeds of 10mm/sec, and action potentials occur in response to deflection angles of less than 1 degree. Thus they are quite sensitive to very slow air speeds. Long hairs are shown to be sensitive or air speed while short hairs are sensitive to air acceleration. Improved understanding of these sensors can lead to better models of comparable engineering systems.

Sensory Systems, Vision

Bernard, G. D.; Insect compound eyes: design of photoreceptor arrays for image pre-processing., Final Report, Army Research Office, ARO-23451-3-LS, 25 pages, Feb. 1989.

Insect eyes are constructed so that much of the destruction of irrelevant data and pre-processing of vital information is accomplished by the receptor array itself, reducing substantially the computational load placed on the neural system. One of the most important mechanisms for destruction is coarse spatial sampling, and spectral properties become particularly important. This study analyzes data from op-tophysiological measurements of butterfly eyes which demonstrate great diversity in absorbance spectra of visual pigments and spectral sensitivity.

Brill, Michael H., Bergeron, Doreen W., Stoner, William W.; Retinal model with adaptive contrast sensitivity and resolution, Applied Optics, Vol. 26, No. 23, 1 December 1987.

A computer-simulated retina (called IRIS) is described which has useful features for computer vision. IRIS discriminates small differences in reflected light when these differences occur in a restricted domain of space and time, and maintains sensitivity to these differences for a wide range of lighting environments. As prevailing light levels decrease and photon noise becomes significant, IRIS reduces its spatiotemporal resolution to provide greater redundancy. Electrically, IRIS could be implemented by a 2-D lattice of photosensors attached to a passively conducting grid. In the present study, the model is implemented in FORTRAN. Similarities to the human retina are noted; the photosensor design is based on a photoreceptor model, and each conducting grid may be realized by

tight-junction coupling of receptors and by horizontal-cell interconnections (effectively forming a syncytium).

Chiang, A.M.; CCD Retina and Neural Net Processor, NATO Advance Research Workshop, "Robots and Biological Systems", June 26-30, 1989, Il Ciocco, Tuscany, Italy.

Two types of CCDs are described: CCD solid state retinas for early vision processing such as image restoration and segmentation, and CCD two-layer neural net (NN) processors for signal processing applications such as image feature extraction and pattern classification. Each of the devices to be described can perform more than one billion computations per second. It clearly demonstrates the computation power offered by the CCD Technology.

Chitale, S.A., Nilsson, A.A., Ajmera, R.C., Newcomb, R.W.; VLSI Contrast Module for Robotic Vision, Midwest Symposium on Circuits and Systems, Vol. 26, 1983.

Design of B, H, and R, neural-type circuit modules is presented using CMOS devices. These modules emulate the behaviour of biological cells associated with the human retina. The interconnection of these three modules to produce the contrast type response has been experimentally studied on lumped electronic circuits. The VLSI circuit using CMOS devices for the three modules has been designed on the CALMA Graphics Computer, and the VLSI layout for the contrast module is presented.

Coon, D.D., Perera, A.G.U.; Spectral Information Coding By Infrared Photoreceptors, International Journal of Infrared and Millimeter Waves, Vol. 7, No. 10, 1986

Spontaneous pulsing has been observed in circuits containing cryogenically cooled silicon p-i-n diodes under dc forward bias. A strong similarity is noted between these properties and the nearly universal means of coding of visual information by animal photoreceptors and neural networks. It is proposed that exploitation of this remarkable analogy could lead to radically new approaches to acquisition and processing of infrared optical information.

Cronin, T. W., Marshall, N. J.; Multiple spectral classes of photoreceptors in the retinas of gonodactyloid stomatopod crustaceans., Journal of Comparative Physiology A, 166: 261-275, 1989.

Research into the compound eyes of 2 species of gonodactyloid stomatopods revealed the following features: 1. The cornea and crystalline cones of both species were virtually transparent from 350 to 700 nm. 2. A variety of visual pigments were found in both species, each in a specific retinal region. Their maximum absorption peaked at wavelengths from 400 nm to well beyond 530 nm. 3. Spectral sensitivity functions of all retinal regions were estimated. The 4 most dorsal ommatidial rows of the central band had a pair of narrow spectral sensitivity curves, usually separated by 50-75 nm. These 4 pairs covered the spectrum

from below 400 to beyond 650 nm. The other two rows of the central band had identical, broad sensitivity functions. 4. These stomatopod species have retained the typical crustacean layered rhabdoms in the peripheral retina and the two most ventral rows in the central band, but have converted the photoreceptors of the 4 dorsal rows of the central band into as many as 8 narrowly tuned spectral classes. This design could serve a high-quality hue discrimination system.

Cronin, T. W., Marshall, N. J.; A retina with at least ten spectral types of photoreceptors in a mantis shrimp., Nature, 339(6220): 137-140, May 11, 1989.

Stomatopod crustaceans, commonly named mantis shrimps, have compound eyes of unique design. A central band composed of six parallel rows of ommatidia separates two peripheral ommatidial groups, and all three regions view the same area of visual space. In the central bands of members of the stomatopod superfamily Gonodactyloidea, four of the ommatidial rows are built of tiers of photoreceptors; in two of these rows, the photoreceptors themselves contain colored filters. Such a design could in principle produce many spectral classes of photoreceptors using only a single visual pigment. The retina contains not one, but as many as ten visual pigments, each in a distinct photoreceptor class, having maximum absorbances at wavelengths from 400 to 539 nm. Because of the unique anatomy of stomatopod eyes, ten or more spectral types of photreceptors exist in this species.

Darling, Robert B., Nabet, Bahram, Pinter, Robert B.; Implementation of analog shunting neural networks for optoelectronic detection and processing, Washington Research Foundation, project 6-89-35, 1989..

A fully parallel and completely analog implementation of a shunting neural network is described. Such a network provides an artificial version of the biological cell connection structure and function commonly found in the more peripheral layers of a sensory organ, such as in the retina of an eye. This implementation is easily integrated with photodetector arrays and can be used to achieve many of the powerful signal processing properties normally associated with biological sensory systems. By using the circuit characteristics of a field-effect transistor (FET) biased into the voltage-variable conductance range, the implementation achieves an extremely high packing density with only one transistor per unilateral interconnection path. In this paper, dynamic range compression, edge enhancement, and preferential directional sensitivity will be discussed in relation to the implementation constraints.

Harris, J.G., Koch, C., Luo, J.; A Two-Dimensional Analog VLSI Circuit for Detecting Discontinuities in Early Vision, Science, 248: 1209-1211, June 8, 1990.

A large number of computer vision algorithms for finding intensity edges, computing motion, depth, and color, and recovering the three-dimensional shape of objects, have been developed within the framework of minimizing an associated "energy" or "cost" functional. Particulary successful has been the introduction of binary variables coding for discontinuities in intensity optical flow field, depth, and other variables,

allowing image segmentation to occur in these modalities. The associated nonconvex variational functionals can be mapped onto analog, resistive networks, such that the stationary voltage distribution in the network corresponds to a minimum of the functional. The performance of an experimental analog very-large-scale integration (VLSI) circuit implementing the nonlinear resistive network for the problem of two-dimensional surface interpolation in the presence of discontinuities is demonstrated; this circuit is implemented in complementary metal oxide semiconductor technology.

Land, M.F., Marshall, N.J., Brownless, D., Cronin, T.W.; The eye-movements of the mantis shrimp Odontodactylus scyllarus (Crustacea:Stomatopoda), Journal of Comparative Physiology A, 167:155-166, 1990.

Odontodactylus scyllarus makes discrete spontaneous eye-movements at a maximum rate of 3/s. These movements are unpredictable in direction and timing, and there is no detectable co-ordination between the two eyes. Most movements are made in a direction approximately at right angles to the orientation of the specialized central band. It is shown that the slow speed of the eye-movements is compatible with scanning, that is, the uptake of visual information during the movement rather than its exclusion as in conventional saccades. Mantis shrimps also make target-acquiring and tracking eye-movements which tend to be somewhat larger and faster than other spontaneous movements. Rotating a striped drum around the animal induces a typical optokinetic nystagmus whose slow phases are smooth, unlike target tracking which is jerky. Eye-movements may therefore be conveniently grouped into 3 classes: targeting/tracking, scanning, and optokinetic.

Land, Michael F.; The optics of animal eyes., Contemp. Phys. 29(5): 435-455, 1988.

Over the last twenty years the list of optical mechanisms known to be used in different eyes has nearly doubled, in particular by the addition of several kinds of systems based on mirrors rather than lenses. This article attempts to bring together old and new work on the diversity of image forming mechanisms in animals. Mechanisms reviewed include camera eyes with corneal lenses; aquatic lens eyes; multi-element lenses; concave mirror optics; biological mirrors; compound eyes; apposition optics; and superposition optics.

Levshin, Viktor L'Vovich; Biocybernetic optoelectronic devices of automated image recognition ---Russian book, Izdatel'stvo Mashinostroenie, 1987, 176 p. In Russian.

This work examines theoretical and engineering aspects of the development of optoelectronic systems for the detection, recognition, and tracking of objects observed from flight vehicles. Systems based on concepts of bionics and cybernetics are considered. Particular emphasis is placed on the structure, operation, and simulation of the visual systems of animals and humans as well as on the theory of object recognition according to two-dimensional images. The design of automated real-time image-processing devices is considered along with the development of adaptive learning systems.

Maguerre, H.; Bionics-from color sensing to objective color measurement., Elektronik (West Germany), 39(2): 65-68, January 19, 1990. In German.

The author discusses the mechanism of color sensing by the human eye and compares color metrology on the basis of physiological theory and measurements. A microelectronic trichromatic color sensor using beamsplitters is proposed.

Mead, Carver, A., Mahowald, M.A.; A Silicon Model of Early Visual Processing, Neural Networks, Vol. 1:91-97, 1988.

An analog model of the first stages of retinal processing that has been constructed on a single silicon chip is described. The biological processes associated with the early stages of vision is discussed, along with a silicon implementation. The silicon device shares many properties of the biological eye, including logarithmic computation for the incident light intensity in each photoreceptor--which allows an increased dynamic range and an incident light intensity independent contrasting voltage difference--and an inherent parasitic capacitance similar to that which exists in the biological eye--which serves to average input signals over time. Experimental results comparing the silicon and biological counterparts are presented. The authors state that the silicon medium can serve two complementary but inseparable roles: 1) to give computational neuroscience a synthetic element allowing hypotheses concerning neural organization to be tested and 2) to develop an engineering discipline by which real-time collective systems can be designed for specific computations. The authors have constructed an actual device based on biological principles.

Mikhailenko, V. G., Vainerman, L. I., Dunkel, E. P.; Invariant recognition of images - The bionic aspect., Bionika No. 20:77-82, 1986. In Russian.

A bionic model for isolation of invariant features of visual images is presented. The analytical procedure starts with the image expansion in the Chebyshev-Hermitian orthogonal functions. Then, using the coefficients of this expansion, the image features are constructed, invariant with regard to a number of its geometric transformations. The model makes it possible to restore an image from its features with assigned precision.

Sandini, Giulio, Dario Paolo; Retina-Like CCD Sensor for Active Vision, NATO Advanced Research Workshop, "Robots and Biological Systems", June 26-30, 1989, Il Ciocco, Tuscany, Italy.

In this paper a space-variant CCD sensor whose sampling structure mimics the distribution of the photoreceptors of some biological visual systems is presented. The chip consists of 30 concentric circles and 64 sensors per circle. The sampling distance as well as the pixel size increase linearly with eccentricity. The central part of the sensor is covered with 102 pixels at constant resolution. The sampling structure implicitly performs a logarithmic mapping that makes the mapped picture rotation and shape invariant. Simulations on real images, using the actual sensor geometry,

are presented. In particular a recognition algorithm based on a sensory-motor strategy moving the fovea in sequence to different "interest points" of overlapped 2D shapes, is presented. Finally experiments performed to test the dynamic characteristics of the sampling structure will be presented applied to object tracking and optical flow computation.

Sandini, Giulio, Tagliasco, Vincenzo; NOTE An Anthropomorphic Retina-like Structure for Scene Analysis, Computer Graphics and Image Processing, 14:365-372, 1980.

The aim of this paper is to demonstrate the intrinsic economy of a human retina-like structure, in terms of an optimum compromise among large visual field, acceptable resolution, and information reduction, in the scene analysis of man-oriented environments. A model of this structure based on a discrete distribution of elements whose radii increase linearly with eccentricity in the visual field is proposed and results of simulations are presented. At present, the technology of solid-state video cameras and appropriate scanning procedures could allow the actual implementation of the proposed retina.

Schneider, Richard T.; Multiaperature Optical System Research, Office of Naval Research Final Report 110687, 1987.

Multiaperature Optics Technology is based on the idea of using the design principles of the insect eye for optical devices having specialized applications. This research program explored the underlying basic optical principles in the basic portion of the effort, generated concepts based on the basic research, and applied the research to generate three products. The basic research portion describes multiaperture optics (MAO) and six possible applications including motion detection, tracking and measuring, robotics, parts inspection, gazing sensors, and blind man's eyes. The concepts generated by the basic research include a pop-up periscope and image transportation devices. The applied research describes three products that were developed to demonstrate that MAO principles, especially the wide field of view, are better suited for certain applications than are conventional optics. The three products are the pupil tracker (smaller, less complex than currently marketed systems), the surveillance look-out (compared to roving surveillance cameras), and the perimeter (suitable for faster screening than those on the market due to the MAO projector). The author considers the most important outcome of the program to be the concept of using a fovea for image transportation devices. This concept makes it possible to obtain a wide field of view survey of the scenery and at the same time a high resolution image of a small but important part (e.g., containing the target) of the scene.

Schneider, Richard T., Lin, S.C.; A Camera Based on the Principles of the Insect Eye, IEEE Southeastern Conference Proceedings, 1987.

A study concerning possible technological application, especially robotics, of a device based on the design of the insect eye is described. The optical system of this device comprises a multitude of light horns with entrance aperture of 300

micrometers and exit aperture of 100 micrometers. The performance of the device is shown and the optical principles are verified by ray tracing. Examples are given for applications as a camera.

Schneider, Richard T., Long, James F.; Mechanical Model of the Insect Eye, SPIE Vol 359 Applications of Digital Image Processing IV(1982).

For certain applications, instruments using multiaperture optics are superior to single aperture instruments. For study of multiaperture optics, like those found in insects, and function of the insect eye a mechanical model resembling an insect eye was constructed. A discussion of multiaperture optics, insect eye types, a mechanical model of the insect eye (including its application to practical systems), model design, and algorithms are presented, followed by results and conclusions.

Shi, Zhe Shang; Optical compound eye lens., Proc. SPIE - Int. Soc. Opt. Eng. (USA). vol 1168, pp. 393-6, 3 refs. 1989.

A new type of optical imaging system-the optical compound eye lens is described. The general design formula of the optical compound eye lens is given. There is a short focus, a large field of view and a mosaic structure of optical elements and detectors in this new type of optical system. To apply the theory of uncrossed axis in optical systems in calculation formula, the imaging formula of the limit distance point and limitless distance point on the main axis of the optical system for the optical compound eye lens are introduced. It is pointed out in the result: the resolving power is equal to the angle between two near single eye lens. Finally the clear aperture of the optical compound eye lens is defined, and the concept of overlapping images is advanced.

Tilton, Homer B.; ISAAC-I: A Color Sensing Robot, SPIE Vol. 162 Visual Simulation & Image Realism (1978).

Contrary to what the trichromatic theory hypothesizes, it now seems likely that the human color-vision system operates on a brightness-hue-saturation basis instead of a red-green-blue basis. For example, there exists significant evidence that neural hue signals originate in the retina from direct rod-cone interaction. ISAAC-I is a simple opto-electronic device which models a possible neural mechanism for generating such retinal hue signals. ISAAC-I points the direction towards commercially useful hardware in any area where color is of importance, in color TV camera design for example.

Wolken, J. J.; Low vision device developed from Copilia optics., J. Penn. Academy of Science 62(2): 100-102, 1988.

The copepod Copilia quadrata posseses an unusual imaging system. The single eye of the female is a double lens with a primary biconvex and secondary pear shaped lens. Previous work analyzed the optic parameters of this system and the data was used to

build models both for a camera lens and a hand-held low vision device. Results with both models indicate the usefulness of this device for individuals with low vision. A patent has been granted and clinical tests are underway.

Structures

Cooke, J.R., De Baerdemaeker, J.G., Rand, R.H., Mang, H.A.; A Finite Element Shell Analysis of Guard Cell Deformations., Transactions of the ASAE, 19(6): 1107-1121, 1976.

In this paper the width of the stomatal aperture, as postulated by von Mohl in 1856, is shown to be a function of the hydrostatic (turgor) pressure in the guard cells, Pg, and the pressure, Ps, of the immediately surrounding epidermal cells. Aperture width is shown to be a simple multi-linear relationship of Pg and Ps. The analysis of a guard cell as an elliptical torus shows that a stomate could function without either of the two conditions classically believed to be essential. The shell model suggests that the outermost portion of the guard cell at the widest point (and not visible in an in vivo situation) actually moves away from the neighboring cell upon opening. The opposing influence of the turgor pressure in the guard cells and in the adjacent epidermal cells is shown to be an inherent part of the stomatal mechanism. Pressure influence coefficients for the guard cell are defined and related to parameter changes, e.g., material and thickness. The multilinear relationship of aperture width to the opposing turgor pressures was found and revealed that pore width does not depend solely on the pressure difference between the guard cell and the adjacent epidermal cell.

Grosse, Siestrup C., Affeld, Klaus.; Design criteria for percutaneous devices., J Biomed Mater Res 18(4):357-382, Apr 1984.

A theoretical model of a percutaneous device is described. The model is split into several components, each with its own function. Special structures such as horns, hairs, feathers, fingernails, hoofs, teeth, and antlers are taken as examples where nature has solved the problems of 'percutaneous devices'. These structures have been regarded in relation to dimensional and structural differences of epidermis, dermis, and subcutis. Theoretical guidelines are described for the design of a prosthetic percutaneous device.

Ruehle, Herrmann; Composite application of materials and spatial structures: a general future development?, Bull Int Assoc Shell Spat Struct 27(3)-28(1):13-23, Dec. 1986-Apr. 1987.

In the introduction the author refers to bionic examples of nature's composite construction, and describes analogies to spatial structures. The paper then deals with the actual state-of-the-art on the basis of complex experience with compound material and composite structures, partially designed by the author (sandwich-structures, frame work steel arches composed of precast shell-girders, textile composite

structures, etc.). The paper describes the dependence of material consumption, the quality of the structural system, the influence of construction, the relationship of function, architecture and structure, and the experiences with the long-time behaviour and the practical application. Some possible trends of the development are discussed.

Upadhyaya, S.K., Rand, R.H., Cooke, J.R.; Role of Stomatal Oscillations on Transpiration, Assimilation and Water-Use Efficiency of Plants., Ecological Modelling, 41: 27-40, 1988.

The objective of this study was to evaluate the average transpiration rate and CO2 assimilation rate and water-use efficiency during steady-state limit cycle oscillations (time-varying cyclic changes) in stomatal pore width both for hydropassive and CO2 feedback effects. The results were compared with the corresponding values for the non-time varying pore width (pore width corresponding to a theoretically predicted unstable focus). The hydropassive model predicts that the oscillations of stomata under dry ambient conditions conserve moisture. The comprehensive model which incorporates CO2 feedback loop suggests that such oscillations not only reduce transpiration rate, but also improve water-use efficiency.

Structures, Compliant

Wilson, James F.; Compliant Robotic Structures, ARPA Order No. 5092, 1986.

This is a continuation of studies on compliant robotic structures, which are tube-like, continuously flexible arms or fingers that are designed to extend, bend or twist when pressurized. Conceptual designs are tempered by a knowledge of muscle structure in selected animals. The results of the second year studies are reported in three chapters. Chapter I presents an overview of muscle structure and function in a variety of soft animal parts. Chapter II focuses on large deformations of compliant torsion elements for robotic wrist action. Chapter III deals with the analysis and conceptual design of compliant robotic arms undergoing large deformations.

Structures, Composite

Baer, E., Ahmad, I.; Biostructures as composite materials: proceedings of an ARO workshop., Final Report # ARO 26892.1-MS-CF, March 1990.

Realizing the opportunities that the studies of biosystems can offer to materials scientists and engineers, the Army Research Office organized this workshop in which active workers in field of biomechanics and biophysics as well as material scientists participated. The focus was on the hierarchical structures of biosystems. In addition to identifying the fundamental structural design-property relationships all the way from the molecular to the engineering systems scale, participants recommended a number of areas for future research necessary to develop radically new materials and systems in which the design principles used in nature can be utilized and perhaps even mimicked. Items of particular interest for potential aerospace ap-

plications include: the structure of tendons (Baer), structure of the cornea (Farrel), impact resistant systems (Curry), stiff, lightweight structures modeled after insect cuticles (Anderson), cellular structures (Gibson), metal ceramic composites modeled after abalone shells (Aksay), and three dimensional braided composites (Ko). Conclusions called for support for characterization of structure property relationships of biosystems, study of biomineralization, study of biological systems in unusual environments, design of artificial materials, and smart materials.

Baer, E., Cassidy, J.J., Hiltner, A.; Hierarchical structure of collagen composite systems - lessons from biology., Plenary Lecture, 33rd IUPAC - International Symposium on Macromolecules, Montreal, Canada, July 8-13, 1990.

Soft connective tissue, designed to serve specific functions in the body of man and animals, are among the most advanced composite materials known made of macromolecular building blocks. By utilizing the same basic macromolecular design and only varying the hierarchical structure, a wide range of tissues possessing very different properties are synthesized by the cellular organism. This article reviews recent work on the hierarchical structure of soft connective tissues from the animal kingdom in hopes that these "lessons from biology" may provide polymer and materials scientists with new ideas for the design of high performance composite polymeric materials. Only with an appreciation and understanding of the unique structure-property relationships in such biosystems can this be achieved.

Structures, Optical

Cowan, J. J.; Aztec surface-relief volume diffractive structure., J. Optical Soc. America A, 7(8): 1529-1544, 1990.

The author has developed a technique to produce volume diffractive structures using optical lithography. These structures are modeled, in part, on the surface relief volume diffrqactive structures present on the scale of certain butterfly wings. These wings are characterized by brilliant, irridescent colors that result solely from structure since there is no color pigment. SEM of the wing scles reveal ribbed vanes that resemble a linear grating but each ribbed portion appears to have terraced steps spaced one-half wavelength apart.

Ghiradella, H.; Structure and development of Iridescent butterfly scales: lattices and laminae., Journal of Morphology 202:69-88, 1989.

Iridescent butterfly scales are structurally colored, relying upon the interaction of light with detailed architecture to produce their color. Lattices produce diffraction colors while stacks of laminae produce thin-film interference colors. The most striking interference reflectors are those that fill the interior lumen of the scale. This paper investigates the hypothesis that the lattice may form from random packing of units secreted by the scale cell and that the thin film laminae may then be derived by stretching the lattice. Results show the diffraction lattice is shaped within the boun-

daries of the scale cell by means of a convoluted series of membranes. The thin film interference laminae appear to result from the condensation of a network of filaments and tubes secreted outside the boundaries of the cell. Application of this work to multicolor holograms is under pursuit by Polaroid Corp. See reference by Cowan, J.J.

Kalstrom, David, J.; Manufacturing 'platinum standard' optical disks, Optical Information Systems, Sept-Oct, 1988, pp. 216-221.

Plasmon Data Systems has developed 5.25 inch recordable, optical disks using the unique 'moth eye' technology, which results in a highly stable disk at a low cost. The moth eye corneal microstructure, whose dimensions are much less than the wavelength of light, reduces reflectivity and improves the insect camouflage. A similar artificial surface on the surface of the optical disk reduces reflection on the incident laser light, increasing efficiency of the 'write' process.

SUBJECT INDEX

Aerodynamics **Page**

See also:

Anderson, G.W. 42
Holst, Erich V., Kuchemann, D. 42
Humphrey, J. and Denny, M. 70
Kroeger, R.A., et al. 43
Todd, D.J. 38
van Dam, Cornelis P. 43
van Dam, Cornelis P. 43
Vogel, Steven. 13

Biochemical Systems

Moore, John, JR. 1
Schnur, Joel, Rudolph, Alan 1
Stover, D. 1
Tributsch, Helmut 2

Biochemical Systems, Adhesives

Waite, J. H. 2

Biochemical Systems, Biochemical Sensors

Huve, J. L. 2
Ito, Hiroyuki, et al 2
Morton, Thomas, Nachbar, Robert . . . 3
Sugawara, M., et al 3
Valleton, Jean M. 3

See also:

Persaud, Krishna C., et al. 64
Persaud, Krishna, Dodd, George 64
Shurmer, H., Fard, A. 65
Tonoike, M. 65
Vodyanoy, Vitaly 65

Biochemical Systems, Bioelectronics

Govil, Girjesh, et al. 4
Haarer, D. 4
Hong, F. T. 4
Hong, F. T. 5
Powers, L. 5
Schick, G.A., et al. 5

See also:

Conrad, Michael 17
Conrad, Michael 17
Draganescu, M. 17
Hong, F. T. and Conrad, M. 18
La Brecque, Mort 18
Schiavone, Rebecca. 49
Sleytr, Uwe, et al 52

Biochemical Systems, Bioluminescence

Anoshin, A. I. 5
McElroy, William D. 6
Rosson, Reinhardt A. 6
Sanchez, Hugo 6

Biochemical Systems, Metabolism

Floyd, T., et al. 7
Nelson, R. A. 7

Biochemical Systems, Photoconversion

DuBois, Daniel L. 7
Khan, M.M.T., Bhatt, J.P. 8
Seibert, Michael 8

Biochemical Systems, Photosynthesis

Boxer, Steven G. 8
Calvin, Melvin 9
Gust, D., Moore, T. A. 9
Norris, J.R., et al. 9
Norris, J.R., Gast, P. 9
Petke, J.D., Maggiora, G.M. 10

See also:

Cooke, J.R., et al. 77
Upadhyaya, S.K., et al. 78

Bionics, General

Antomonov, Y. G. 10
Bernard, E. E., Kare, M. R. 10
French, M. J. 10
Gamow, R. I.; Harris, J. F. 11
Gerardin, L. 11
Gibbs, K. M. 11
Grassmann, P. 11
Halacy, D. S. 12
Horgan, J. 12
Lenihan, John 12
Maguerre, H. 12
Marteka, V. 13
Smirnov, S. N. 13
Umetani, Y. 13

Vogel, Steven. 13
von Gierke, H. E. 13

Calcium Metabolism, Bears

See also:

Floyd, T., et al. 7
Nelson, R. A. 7

Communications

See also:

Richards, Douglas G. 16

Compound Eyes

See also:

Bernard, G. D. 70
Schneider, Richard, Lin, S.C. 75
Schneider, Richard, Long, James 76
Schneider, Richard T. 75
Shi, Zhe Shang 76
van Hateren, J.H., Nilsson, D.E. 67

Control Systems

Anderson, T.L., Donath, M. 14
Hogan, N. 15
Kuperstein, Michael 15
See also:
Bekey, George A. 18
Brooks, Rodney A. 39
Chiel, H. J., Beer, R. D. 19
Cruse, Holk. 40
Easton, Thomas A. 40
Jelimek, J. 23
Sochivko, V. P. 16
Spiessbach, A. J., et al. 41
Werbos, P. J. 21
Westbrook, M. H. 58
Wilson, J. F., Mahajan, U. 54

Energy Storage

See also:

Boxer, Steven G. 8
Norris, J.R., et al. 9
Norris, J.R., Gast, P. 9
Petke, J.D., Maggiora, G.M. 10
Tributsch, Helmut 2

Hydrodynamics

See also:

Bechert, D. W., et al. 43
Logvinovich, G.V., et al. 44
Raschi, William G., Musick, John A. .44

Information Processing

Kaliaev, A. V., Galuev, G. A. 15
Kato, I., et al. 16
Levashov, O. V. 16
Richards, Douglas G. 16
Sochivko, V. P. 16
Zinner, H. 16

See also:

Antomonov, Y. G. 10
Cowan, J. J. 79
Varju, D., Schnitzler, H.U. (editors) . .57
von Gierke, H. E. 14

Information Processing, Biomolecular Computing

Conrad, Michael 17
Conrad, Michael 17
Draganescu, M. 17
Hong, F. T., Conrad, M. 18
La Brecque, Mort 18

See also:

Govil, Girjesh, et al. 4
Haarer, D. 4
Hong, F. T. 4
Hong, F. T. 5
Powers, L. 5

Information Processing, Color Displays

See also:

Ghiradella, H. 79

Information Processing, Neural Networks

Arbib, Michael A. 18
Bekey, George A. 18
Braham, R., Hamblen, J. O. 19
Chiel, H. J., Beer, R. D. 19
Daunicht, W. J. 20
Dawes, R.L. 20

Roitblat, H.L., et al. 20
Taylor, J.G. 20
Werbos, P. J. 21

See also:

Baird, Bill 27
Byrne, John H. 21
Caulfield, H.J. 21
Chiang, A.M. 71
Darling, Robert B., et al. 72
Eisenberg, Joe, et al. 29
Heiligenberg, W. 61
Kanerva, Pentti 23
Kayton, Myron 55
Kuperstein, Michael 15
Maher, Mary Ann C., et al. 33
Mead, Carver 33
Nabet, Bahram, Darling, Robert B. . . .35
Nakamoto, T., et al. 64
Pellionisz, Andras J. 24
Ross, M. D. 24
Ross, M.D., et al. 24
Sochivko, V. P. 16

Information Processing, Neural Processing

Byrne, John H. 21
Caulfield, H.J. 21
Farhat, Nabil H. 22
Freeman, Walter J., et al. 22
Haun, J. E., Nachtigall, P. E. 23
Hecht-Nielsen, R. 23
Ivanov, Muromskiy K.A. 23
Jelimek, J. 23
Kanerva, Pentti 23
Pellionisz, Andras J. 24
Ross, M. D. 24
Ross, M.D., et al. 24
Schwartz, Eric 25
Sokolov, E. N., Shmelev, L. A. 25

See also:

Peiss, C. N. 26

Information Processing, Pattern Recognition

See also:

Altes, R. A. 26
Altes, Richard A. 26
Baird, Bill 27
Freeman, Walter J., et al. 22
Kanerva, Pentti 23
Matsubara, Joanne A. 62
Nakamoto, T., et al. 64
Richards, Douglas G. 16
Rose, Gary, Heiligenberg, Walter . . .36
Schwartz, Eric 2
Sochivko, V. P. 16

Information Processing, Sensory Processing

Adamson, K., et al. 25
Altes, Richard A. 26
Altes, Richard A. 26
Altes, Richard A. 26
Arbib, Michael A., et al. 27
Baird, Bill 27
Ballard, Dana H. 27
Ballard, Dana, Brown, Christopher . . .28
Brown, Christopher 28
Burton, G.J., et al. 28
Clark, James, Ferrier, Nicola 28
Clement, R.A., et al. 29
Daugman, John, Kammen, Daniel . . .29
Eeckman, Frank H., et al. 29
Eisenberg, Joe, et al. 29
Griswold, N.C., Yeh, C.P. 30
Griswold, N.C., Yeh, C.P. 30
Grossberg, S. Marshall, J. 30
Grossberg, Stephen, Rudd, Michael . .31
Hunt, B.R. 31
Hutchinson, James, et al. 31
Jacobson, Lowell, Wechsler, Harry . . .31
Jarvis, R. A. 32
Jayawant, B.V. 32
Jobson, Daniel J. 32
Johnson, J.D., Grogan, T.A. 32
Kuyk, Thomas K. 33
Maher, Mary Ann C., et al. 33
Malecki, Gerald, Hollerbach, John . . .33
Markus, M., et al. 33
Mead, Carver 34
Meyers, Richard C. 34
Minnix, Jay L., et al. 34
Miyake, Sei, Inui, Toshio 34
Nabet, Bahram, Darling, Robert B. . . .35
Narathong, C., et al. 35
Overington, Ian 35
Peiss, C. N. 36
Porat, Moshe, Zeevi,Yehoshua 36
Rose, Gary, Heiligenberg, Walter . . .36
Shemlon, Stephen, et al. 37
Tzanakou, Evangelia 37
Watson, Andrew B. 37

Yao, Yong, Freeman, Walter J. 37
Yeshurun, Yehezkel, Schwartz, Eric . .38
Young, Richard A. 38
Young, Richard A. 38

See also:

Brill, Michael H., et al. 70
Brooks, Rodney A. 39
Chitale, S.A. et al. 71
Freeman, Walter J., et al. 22
Haun, J. E., Nachtigall, P. E. 22
Maguerre, H. 60
Matsubara, Joanne A. 62
Mead, Carver, A., Mahowald, M.A. . .74
Persaud, Krishna, Dodd, George 64
Sandini, Giulio, Tagliasco, Vincenzo . .75
Shaub, Y. B., Khodzevich, A. V. 62
Sokolov, E. N., Shmelev, L. A. 25
Valleton, Jean M. 3

Locomotion

Todd, D.J. 38

Locomotion, Ambulation

Abe, Minoru, et al. 39
Alexander, R. McN. 39
Alexander, R. McN. 39
Beletshii, V. V. 39
Brooks, Rodney A. 40
Cruse, Holk. 40
Easton, Thomas A. 40
Hanamoto, B., Martin, L. 40
Parker, Claude B. 40
Raibert, Marc, Sutherland, Ivan 41
Song, Shin M., et al. 41
Spiessbach, A. J., et al. 41
Waldron, Kenneth J. 41

See also:

Chiel, H. J., Beer, R. D. 19
Kato, I., et al. 16
Piotrowski, George. 53
VanVoorhis, Kristina, et al. 57
Wilson, James F. 53

Locomotion, Flight

Anderson, G.W. 42
Borin, A. A., Kokshaiskii, N. V. 42
Bushnell, D.M., Moore, K.J. 42
Holst, Erich V., et al. 42
Kroeger, R.A., et al. 43
Sorokodum, E. D. 43
van Dam, Cornelis P. 43
van Dam, Cornelis P. 43

See also:

Hertel, Heinrich. 44
von Gierke, H. E. 14

Locomotion, Swimming

Bechert, D. W., et al. 43
Devillers, J.F., Leriche, M.A. 44
Hertel, Heinrich. 44
Logvinovich, G.V., et al. 44
Raschi, William, Musick, John 44

See also:

Bushnell, D.M., Moore, K.J. 42
Sorokodum, E. D. 43
van Dam, Cornelis P. 43

Materials

Douglas, K., Clark, N.A. 45
Gunderson, S.L., et al. 45
Rothschild, K. J. 46
Vincent, Julian. 46
Wainwright, S.A., et al. 46

See also:

Ruehle, Herrmann 77
Waite, J. H. 2
Vogel, Steven. 13

Materials, Biomineralization

Berman, A., et al. 46
Berman, A., et al. 47
Birchall, J. D. 47
Calvert, P., Mann, S. 47
Mann, S., Calvert, P. D. 47
Mann, Stephen. 48

See also:

Berman, A., et al. 46
Berman, A., et al. 47
Birchall, J. D. 47
Calvert, P., Mann, S. 47
Jelimek, J. 23
Mann, S., Calvert, P. D. 47
Pool, R. 49

Materials, Biosynthesis

Dougherty, Elizabeth 48
Kaplan, D.A., et al. 48
Lombardi, S.J., et al. 49
Oci, T. 49
Pool, R. 49
Schiavone, Rebecca. 49
Ulrich, Donald R. 50

See also:

Moore, John, JR. 1
Schnur, Joel, Rudolph, Alan 1

Materials, Composite

Chaplin, C. R., et al. 50
Currey, J. D. 51
Gunderson, S., Schiavone, R. 51
Jeronimidis, George. 51
Sarikaya, M., et al. 51

See also:

Baer, E., Ahmad, I. 78
Baer, E., Cassidy, J.J., Hiltner, A. . . .79
Calvert, P., Mann, S. 47

Materials, Crystals

Sleytr, Uwe B, et al. 52

Materials, Surface Coatings

Baier, R.E., Meyer, A.E. 52

Mechanisms

Caldwell, D.G., Taylor, P.M. 52
Piotrowski, George. 53
Shiga, T., et al. 53
Wilson, James F. 53

See also:

Hogan, N. 15
Todd, D.J. 38
Umetani, Y. 13
Wainwright, S.A., et al. 46

Mechanisms, Manipulators

Grupen, R. A., et al. 53
Maguerre, H. 54
Wilson, J. F., Mahajan, U. 54
Wilson, J.F., et al. 54
Wilson, J.F., Wainwright, S., et al. . . .54

See also:

Daunicht, W. J. 19
Malecki, Gerald, et al. 33

Mechanoreception

See also:

Humphrey, J., Denny, M. 70

Muscle

See also:

Nelson, R.A. 7
Pool, R. 49
Shiga, T., et al. 53

Navigation Systems

Diercks, K. J. 55
Guastella, Martha J. 55
Kayton, Myron 55
Pye, J. David 56
Seleznev, V. P., Selezneva, N. V. 56
Varju, D., Schnitzler, H.U. (editors) . .57
Voorhis, Kristina, Franklin, Robert . . .57
Waterman, Talbot H. 57

See also:

Altes, Richard A. 59
Arbib, Michael A., et al. 18
Bel'kevich, V., et al. 57
Marteka, V. 13
Richards, Douglas G. 16
Spiessbach, A. J., et al. 41
Trott, W. James 60

Optical Surfaces

See also:

Moore, Duncan T. 66
Schefter, Jim 66
Wilson, S.J., Hutley, M.C. 67

Optics

See also:

Land, Michael F. 73
Schneider, Richard T., ...67
Wolken, J. J. 76

Photodetection

See also:

Carson, John C. 66
Coon, D.D., Perera, A.G.U. 71

Sensory Systems

Bel'kevich, V., et al. 57
Maguerre, Hans. 58
Westbrook, M. H. 58

See also:

Kaplan, D.A., et al. 49
Gamow, R. I.; Harris, J. F. 11
Kato, I., et al. 16
Mead, Carver 34
Seleznev, Vasilii, Selezneva, Natal'ia .56
Varju, D., Schnitzler, H.U. (editors) . .57
von Gierke, H. E. 14
Waterman, Talbot H. 57

Sensory Systems, Acoustic

Altes, R. A. 59
Altes, Richard A. 59
Au, Whitlow, et al. 59
Maguerre, H. 60
Manoli, S.H. 66
Pettigrew, J. D. and Larsen, O. N. . . .60
Trott, W. James 60

See also:

Altes, Richard A. 26
Au, Whitlow, W. L., et al. 20
Meyers, Richard C. 34
Pye, J. David 56
Roitblat, H.L., et al. 20

Sensory Systems, Electromagnetic

Heiligenberg, W. 61
Kalmijn, Ad. J. 61
Kalmijn, Ad. J. 61
Maguerre, H. 62
Matsubara, Joanne A. 62
Pickard, William F. 62
Shaub, Y. B., Khodzevich, A. V. 62

See also:

Kayton, Myron 55
Rose, Gary, Heiligenberg, W. 36

Sensory Systems, Infrared

Maguerre, Hans 63

See also:

Pelli, D. G., Chamberlain, S. 66

Sensory Systems, Olfactory

Krull, Ulrich, J., Thompson, M. 63
Nakamoto, T., et al. 64
Persaud, Krishna C., et al. 64
Persaud, Krishna, Dodd, George 64
Shurmer, H., Fard, A. 65
Tonoike, M. 65
Vodyanoy, Vitaly 65

See also:

Baird, Bill 27
Eisenberg, Joe, et al. 29
Huve, J. L. 2
Ito, Hiroyuki, et al. 2
Morton, Thomas, Nachbar, Robert . . . 3
Yao, Yong, Freeman, Walter J. 37

Sensory Systems, Optical

Angel, J. R. P. 65
Carson, John C. 66
Moore, Duncan T. 66
Pelli, D. G., Chamberlain, S. C. 66
Schefter, Jim 66
Schneider, Richard T., et al. 67
van Hateren, J.H., Nilsson, D.E. 67
Wilson, S.J., Hutley, M.C. 67

See also:

Kalstrom, David J. 80

Sensory Systems, Tactile

Dario, P., et al. 67
De Rossi, D., et al. 68
De Rossi, Danilo, et al. 68
DeRossi, Danilo. 68

Harmon, L. D. 68
Patterson, Robert, Nevill, Gale 69

See also:

Grupen, R. A., et al. 53
Maguerre, H. 69
Russell, Andrew R. 69

Sensory Systems, Temperature

Maguerre, H. 69
Russell, Andrew R. 69

Sensory Systems, Velocity

Humphrey, J., Denny, M. 70

Sensory Systems, Vision

Bernard, G. D. 70
Brill, Michael H., et al. 70
Chiang, A.M. 71
Chitale, S.A., et al. 71
Coon, D.D., Perera, A.G.U. 71
Cronin, T. W., Marshall, N. J. 71
Cronin, T. W., Marshall, N. J. 72
Darling, Robert B., et al. 72
Harris, J.G., Koch, C., Luo, J. 72
Land, M.F., et al. 73
Land, Michael F. 73
Levshin, Viktor L'Vovich 73
Maguerre, H. 74
Mead, Carver, A., Mahowald, M.A. . .74
Mikhailenko, V. G., et al. 74
Sandini, Giulio, Dario Paolo 74
Sandini, Giulio, Tagliasco, Vincenzo . .75
Schneider, Richard T. 75
Schneider, Richard, Lin, S.C. 75
Schneider, Richard, Long, James 76
Shi, Zhe Shang 76
Tilton, Homer B. 76
Wolken, J. J. 76

See also:

Carson, John C. 66
Clark, James, Ferrier, Nicola 28
Johnson, J.D., Grogan, T.A. 32
Levashov, O. V. 16
Maher, Mary Ann C., et al. 33
Miyake, Sei, Inui, Toshio 34
Nabet, Bahram, Darling, Robert B. . . .35
Overington, Ian 35
Tzanakou, Evangelia 37

Structures

Cooke, J.R., et al. 77
Grosse, Siestrup C., Affeld, Klaus. . . .77
Ruehle, Herrmann 77
Upadhyaya, S.K., et al. 78

See also:

Currey, J. D. 51
Gunderson, S.L., et al. 45
Gunderson, S. and Schiavone, R. 51
Sarikaya, M., et al. 51
Schnur, Joel M., Rudolph, Alan S. . . . 1
Wainwright, S.A., et al. 46
Wilson, James F. 53

Structures, Compliant

Wilson, James F. 78

Structures, Composite

Baer, E., Ahmad, I. 78
Baer, E., Cassidy, J.J., Hiltner, A. . . .79

See also:

Dougherty, Elizabeth 48

Structures, Optical

Cowan, J. J. 79
Ghiradella, H. 79
Kalstrom, David, J. 80

See also:

Ross, M. D. 24
Ross, M.D., et al. 24

Visual Perception

See Sensory Systems, Vision
Information Processing,
Sensory Processing

AUTHOR INDEX

Page

Abe, Minoru 39
Adamson, K. 25
Addadi, L. 46
Affeld, Klaus 77
Ahmad, I. 78
Ajmera, R.C. 71
Alexander, R. McN. 39
Altes, Richard A. 26, 59
Anderson, T.L. 14
Anderson, G.W. 42
Angel, J. R. P. 65
Anoshin, A. I. 5
Antomonov, Y. G. 10
Arbib, Michael A. 18
Au, Whitlow W.L. 20, 59
Axelrod, Timothy S. 29
Baer, E. 78, 79
Baier, R.E. 52
Baird, Bill 27
Ballard, Dana H. 27, 28
Bartenwerfer, M. 43
Bartlett, Jon 64
Bechert, D. W. 43
Beer, R. D. 19
Bekey, George A. 18
Bel'kevich, V. 57
Beletshii, V. V. 39
Bergeron, Doreen W. 70
Berman, A. 46, 47
Bernard, G. D. 70
Bernard, E. E. 10
Bhatt, J.P. 8
Bicchi, A. 67
Biggs, W.D. 46
Birchall, J. D. 47
Birge, R.R. 5
Black, N.D. 25
Borin, A. A. 42
Bowman, M.K. 9
Boxer, Steven G. 8
Braham, R. 19
Brill, Michael H. 70
Brooks, Rodney A. 40
Brown, Christopher M. 28
Brownless, D. 73
Burke, Brian 22, 29
Burton, G.J. 28
Bushnell, D.M. 42
Buttazzo, G. 67
Byrne, John H. 21
Caldwell, D.G. 52
Calvert, P. D. 47
Calvin, Melvin 9
Carder, Donald A. 59
Carroll, Edward E. Jr. 67
Carson, John C. 66
Cassidy, J.J. 79
Caulfield, H.J. 21
Chamberlain, S. C. 66
Chaplin, C. R. 50
Chen, Z. 54
Chiang, A.M. 71
Chiarelli, P. 68
Chiel, H. J. 19
Chitale, S.A. 71
Clark, N.A. 45
Clark, James J. 28
Clement, R.A. 29
Colvin, Michael E. 29
Conrad, Michael 17, 18
Cooke, J.R. 77, 78
Coon, D.D. 71
Cowan, J. J. 79
Cronin, T. W. 71, 72, 73
Cruse, Holk. 40
Currey, J. D. 46, 51
Cutler, L. 24
Dario, Paolo 67, 74
Darling, Robert B. 35, 72
Daugman, John G. 29
Daunicht, W. J. 19
Dawes, R.L. 20
De Baerdemaeker, J.G. 77
De Rossi, Danilo 68
Denny, M. 70
Devillers, J.F. 44
Deweerth, Stephen P. 33
Diercks, K. J. 55
Dietmar, Pum 52
Dodd, George 64
Domenici, Claudio 68
Donath, M. 14
Doner, J.F. 35
Donnan, G. 25
Dougherty, Elizabeth 48
Douglas, K. 45
Draganescu, M. 17
DuBois, Daniel L. 7
Dunkel, E. P. 74
Dunn, Stanley M. 37
Easton, Thomas A. 40
Eeckman, Frank H. 29
Eisenberg, Joe 22, 29
Fard, A. 64

Farhat, Nabil H. 22
Ferrier, Nicola J. 28
Fiorillo, A. 67
Floyd, T. 7
Fossey, S. 49
Francesconi, R. 67
Franklin, Robert F. 57
Freeman, Walter J. 22, 29, 37
French, M. J. 10
Fukunishi, K. 64
Galuev, G. A. 15
Gamow, R. I. 11
Gast, P. 9
Gendason, P. 48
George, R.T., Jr. 54
Gerardin, L. 11
Ghiradella, H. 79
Gibbs, K. M. 11
Gordon, J.E. 50
Gosline, J.M. 46
Govil, Girjesh 4
Grassmann, P. 11
Griswold, N.C. 30
Grogan, T.A. 32
Grossberg, Stephen 30, 31
Grosse, Siestrup C. 77
Grupen, R. A. 53
Gruschka, H.D. 43
Guastella, Martha J. 55
Gunderson, S.L. 45, 51
Gust, D. 9
Haarer, D. 4
Haig, N.D. 28, 29
Halacy, D. S. 12
Hamblen, J. O. 19
Hanamoto, B. 40
Harmon, L. D. 68
Harris, J.G. 72
Harris, J. F. 11
Haun, J. E. 22
Hecht-Nielsen, R. 23
Heiligenberg, Walter 36, 61
Helvey, T.C. 43
Henderson, T. C. 53
Hertel, Heinrich. 44
Hess, B. 33
Hiltner, A. 79
Hirose, Y. 53
Hogan, N. 15
Hollerbach, John M. 33
Holst, Erich V. 42
Hong, F. T. 4, 5, 18
Hoppe, G. 43
Horgan, J. 12
Humphrey, J. 70
Hunt, B.R. 31
Hutchinson, James 31
Hutley, M.C. 67
Huve, J. L. 2
Inigo, Rafael M. 34, 35
Inui, Toshio 34
Ito, Hiroyuki 2
Ivanov, Muromskiy K.A. 23
Jacobson, Lowell 31
Jarvis, R. A. 32
Jayawant, B.V. 32
Jelimek, J. 23
Jeronimidis, George 50, 51
Jobson, Daniel J. 32
Johnson, J.D. 32
Kaliaev, A. V. 15
Kalmijn, Ad. J. 61
Kalstrom, David, J. 80
Kammen, Daniel M. 29
Kaneko, Makoto 39
Kanerva, Pentti 23
Kaplan, D.A. 48, 49
Karandeeva, O.G. 44
Kare, M. R. 10
Kataoka, M. 3
Kato, I. 16
Kayton, Myron 55
Khan, M.M.T. 8
Khodzevich, A. V. 62
Kinzel, Gary L. 41
Koch, Christof 31, 72
Kokshaiskii, N. V. 42
Kroeger, R.A. 43
Krull, Ulrich J. 63
Kuchemann, Dietrich 42
Kuperstein, Michael 15
Kurauchi, T. 53
Kuyk, Thomas K. 33
La Brecque, Mort 18
Lam, T. 24
Land, Michael F. 73
Larsen, O. N. 60
Lawrence, A.F. 5
Lawton, Daryl T. 27
Lenihan, John 12
Leriche, M.A. 44
Levashov, O. V. 16
Levshin, Viktor L'Vovich 73
Li, D. 54
Liang, Tajen 37
Lin, Shih-Chao 67, 75
Logvinovich, G.V. 44
Lombardi, S.J. 49
Long, James F. 76
Luo, Jin 31, 72
Maggiora, G.M. 10

Maguerre, Hans 12, 54, 58, 60,62, 63
. . . . . 69, 74
Mahajan, U. 54
Maher, Mary Ann C. 33
Mahowald, Misha A. 33, 74
Malecki, Gerald S. 33
Mang, H.A. 77
Mann, Stephen 47, 48
Manoli, S.H. 60
Margit, Sara 52
Markus, M. 33
Marshall, N. J. 71, 72, 73
Marshall, Johnathon A. 30
Marteka, V. 13
Martin, L. 40
Matsubara, Joanne A. 62
Matsushima, T. 16
McCammon, I. D. 53
McElroy, William D. 6
McVey, Eugene S. 34, 35
Mead, Carver, A. 31, 33, 34, 74
Meyer, G. 24
Meyer, A.E. 52
Meyers, Richard C. 34
Mikhailenko, V. G. 74
Minnix, Jay L. 34
Miyake, Sei 34
Moore, K.J. 42
Moore, P.W.B. 20
Moore, Duncan T. 66
Moore, T. A. 9
Moore, John, JR. 1
Moorhead, I.R. 28, 29
Moriizumi, T. 64
Morton, Thomas H. 2, 3
Muller, S.C. 33
Musick, John A. 44
Nabet, Bahram 35, 72
Nachbar, Robert B. 3
Nachtigall, P. E. 20, 22
Nakamoto, T. 64
Nannini, Andrea 68
Naranyan, R. 45
Narathong, C. 35
Narita, S. 16
Nelson, R. A. 7
Nevill, Gale E. Jr. 69
Newcomb, R.W. 71
Nilsson, A.A. 71
Nilsson, D.E. 67
Nishizawa, Shoichiro 39
Norris, J.R. 9
Oci, T. 49
Odashima, K. 3
Ohteru, S. 16
Okade, A. 53
Overington, Ian 35
Overton, Kenneth J. 27
Parker, Claude B. 40
Patterson, Robert W. 69
Peiss, C. N. 36
Pelli, D. G. 66
Pellionisz, Andras J. 24
Pelosi, Paolo 64
Penner, Ralph H. 20, 59
Perera, A.G.U. 71
Persaud, Krishna C. 64
Pershin, S.V. 44
Petke, J.D. 10
Pettigrew, J. D. 60
Phadke, Ratna S. 4
Pickard, William F. 62
Pinter, Robert B. 72
Piotrowski, George 53
Plesser, T. 33
Pool, R. 49
Porat, Moshe 36
Powers, L. 5
Pyatetskii, V.E. 44
Pye, J. David 56
Raibert, Marc H. 41
Rand, R.H. 77, 78
Raschi, William G. 44
Reif, W.E. 43
Richards, Douglas G. 16
Roitblat, H.L. 20
Rose, Gary 36
Ross, M.D. 24
Rosson, Reinhardt A. 6
Rothschild, K. J. 46
Rudd, Michael E. 31
Rudolph, Alan S. 1
Ruehle, Herrmann 77
Russell, Andrew R. 69
Sanchez, Hugo 6
Sandini, Giulio 74, 75
Sarikaya, M. 51
Schefter, Jim 66
Schiavone, Rebecca 45, 49, 51
Schick, G.A. 5
Schneider, Richard T. 67, 75, 76
Schnitzler, H.U. (Editor) 56
Schnur, Joel M. 1
Schwartz, Eric L. 25, 38
Scronce, Billy L. 59
Seibert, Michael 8
Seleznev, Vasilii P. 56
Selezneva, Natal'ia V. 56
Shaub, Y. B. 62
Shemlon, Stephen 37
Shi, Zhe Shang 76
Shiga, T. 53

Shirai, K. 16
Shmelev, L. A. 25
Shurmer, H. 64
Skurnick, I. 48
Sleytr, Uwe B. 52
Smirnov, S. N. 13
Sochivko, V. P. 16
Sokolov, E. N. 25
Sonawat, H.M. 4
Song, Shin M. 41
Sorokodum, E. D. 43
Spiessbach, A. J. 41
Stoner, William W. 70
Stover, D. 1
Sugano, S. 16
Sugawara, M. 3
Sutherland, Ivan E. 41
Tagliasco, Vincenzo 75
Tanie, Kazuo 39
Taylor, J.G. 20
Taylor, P.M. 52
Thompson, Michael 63
Thurnauer, M.C. 9
Tilton, Homer B. 76
Todd, D.J. 38
Tonoike, M. 65
Tributsch, Helmut 2
Trott, W. James 60
Tzanakou, Evangelia 37
Ulrich, Donald R. 50
Umetani, Y. 13
Upadhyaya, S.K. 78
Vainerman, L. I. 74
Valdes, J.J. 48
Valleton, Jean M. 3
van Dam, Cornelis P. 43
van Hateren, J.H. 67
van Voorhis, Kristina V. 57
Varju, D. (Editor) 56
Vaziri, P. 24
Vende, E. 57
Vil'-Vil'vams, I. 57
Vincent, Julian. 46
Vodyanoy, Vitaly 2, 65
Vogel, Steven. 13
von Gierke, H. E. 14
Wainwright, S.A. 46, 54
Waite, J. H. 2
Waldron, Kenneth J. 41
Wasielewski, M.R. 9
Waterman, Talbot H. 57
Watson, Andrew B. 37
Wechsler, Harry 31
Weiner, S. 46
Werbos, P. J. 21
Westbrook, M. H. 58
Wilson, James F. 53, 54, 78
Wilson, S.J. 67
Wolken, J. J. 76
Wynne, G.F. 7
Yao, Yong 37
Yeh, C.P. 30
Yeshurun, Yehezkel 38
Young, Richard A. 38
Zeevi,Yehoshua Y. 36
Zinner, H. 16

APPENDIX B

BIONICS DIRECTORY

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Project Title: Biomimetic processing of ceramic and ceramic-metal composites.
Funding Agency: AFOSR
Classifiers: Materials, composite, Seashells.

Dr. Aksay and Dr. Sarikaya are conducting research, in collaboration with James T. Staley, Microbiology, by using biological models or biological processes to produce advanced materials. Work is broken into the following areas:i) development of lubricating biopolymers using bacteria and algae for collooidal processing of composites; ii) ultrafine particle production by using bacteria and synthetic vesicles; iii) functionally graded ceramic-metal and ceramic-polymer laminated composites for light-weight/high-strength-toughness applications based on seashell minoarchitecture; iv) biomineralization and biocrystallization; v) microstructure-property correlations in biocomposites; vi) atomic resolution microscopy and spectroscopy.

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Phone: (0532) 332911
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Project Title: Mechanics of Animal Locomotion
Funding Agency:
Classifiers: Locomotion, Ambulation

Prof. Alexander has conducted leading research in the study of animal locomotion, particularly ambulation. His work is predominantly basic research, little applied. Although, his results have been used by others in developing mobile robots.

Altes, Richard A.
Chirp Corporation
8248 Sugarman Drive
La Jolla, CA 92037
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Phone: (619) 453-4406
Fax: none

Project Title: Animal Sensory Systems
Funding Agency: DARPA, ONR, NOSC

Classifiers: Sensory systems, vision, echolocation, sensory processing, information processing

Current research: 1) Wavelet transforms. Motivated by bionic models of vision. Crossing with wideband ambiguity functions. 2) Sensor Fusion. Neuronal maps, overlaying maps to perform object recognition, vision, hearing fusion. Completed several studies of biological sonar for the NAVY in the late 70s. Generalized wavelet transforms (e.g. invertible line segment transform) for vision analysis, image source coding, object recognition, radon transform-based tomography, SAR, non-destructive testing, vibration analysis and acceleration sensitive acoustic waveforms from bat sonar models. Multisensor fusion for pattern recognition on the basis of overlaid, spacially registered maps derived from different sensors. Distributed control via control maps in register with sensory maps. These maps are motivated by superior colliculus processing in animals. Multisensor fusion based on cognitive models; Bayesian interactive activation. Neural networks for signal/array processing, e.g., a Hopfield neural network that solves a nonlinear integral equation associated with optimum (maximum a posteriori) angle demodulated (patent pending).

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Project Title: Specificity of Odor Recognition...
Funding Agency: Office of Naval Research
Classifiers: Sensory Systems, Biochemical, Olfactory

This project is a study of the basic structural principles responsible for the high degree of specificity and sensitivity observed in biological receptors associated with the sense of smell. The objective is to design and construct biosensors to detect the presence of selected chemical agents.

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NASA Headquarters
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Washington, DC 20546
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Project Title: Breakthrough Technologies
Funding Agency:
Classifiers: Bionics, General

Breakthrough Thrust encompasses space research and technology activities that advance high-payoff, highly innovative technology concepts that could provide revolutionary

improvements in space capability. Areas of interest include: power and propulsion; sensing, information acquisition and utilization; materials and structures; vehicles for aerospace flight; human support for manned missions; autonomous, adaptive performance; and new fundamental technology capabilities such as high-temperature superconductivity, micro- and nano-technology, and bionics.

Arbib, Michael A.
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Fax:

Project Title: Schemas and Neural Networks for Sixth Generation Computing
Funding Agency: NIH - NINCDS
Classifiers: Information Processing, Neural Processing

Schema theory integrates perception and action by decomposing an overall behavior into the interaction of functional, neurally explicable units called schemas. Schema theory offers an approach explixitly designed to bridge between cognitive science and brain theory, as well as to contribute to distributed artificial intelligence.

Baer, Eric.
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Project Title: Biostructures as composite materials.
Funding Agency: ARO, NASA
Classifiers: Structural Systems, Materials, Structures, Composite.

Professor Baer has worked in the area of hierarchical structures of biocomposites. Using lessons from biology, it is now possible to mimic complex biological composite systems in synthetic composites. He has detailed the hierarchical structure of connective tissue (collagen fiber reinforced) structures such as tendon, intestinal wall, and intervertebral disc. He organized a workshop on hierarchical structures for the Army Research Office in 1989. Dr. Baer is also Director of the NASA Center for Commercial Development of Space at Case Western focusing on materials for space structures.

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Industry/University Cooperative Research Center for Biosurfaces
110 Parker Hall
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Project Title: Industry/University Cooperative Research Center for Biosurfaces
Funding Agency: NSF, ONR, industry
Classifiers: Materials, Biological surfaces, Bioadhesion, Biofouling.

The NSF Industry/University Cooperative Research Center for Biosurfaces is dedicated to fundamental investigation of the interactions among four principal phases - substrata, macromolecular "conditioning" films, living cells, and surrounding media - from which all material/biosystem compatibility issues arise. The focus is on understanding, prediction, and control of the major factors promoting or preventing adhesion in wet, saline, biochemically active media. Four primary research goals are description of the nature of conditioning films as related to chemical/physical properties of the substratum, determination of the surface properties of cells as they engage or resist interactions with films, determination of the reaction between cells and supporting films, cells, and adjacent cells, films, and surrounding media, and initiation of studies of the possible macrosystem implications and dynamics of these processes.

Baird, Bill.
University of California, Berkeley
Department of Biophysics
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Phone:
Fax:

Project Title: Network model of rabbit olfactory bulb
Funding Agency:
Classifiers: Information Processing, Sensory Processing, Pattern Recognition, Smell

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Project Title: Animate vision systems
Funding Agency: NSF, NIH
Classifiers: Information processing, sensory processing, visual perception

Dr. Ballard an his co-workers work from the premise that vision is more readily understood in the context of the visual behaiors that the system is engaged in and that these behaviors may not require elaborate categorical representations of the world. Recent hardware advances now allow the integration of visual computation with visual behavior in real time. The researchers have built an anthropomorphic robot with a visual front-end designed to mimic human capabilities. They believe that this type of study will extend to all kinds of computer vision systems particularly those on mobile platforms.

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Project Title: Neural Networks for Real Time Sensorimotor Control.
Funding Agency: ONR
Classifiers: Neural Networks, Control Systems

The objective of this research is to elucidate the principles by which invertebrate nervous systems control locomotion behavior and to apply this understanding to the design of more autonomous, flexible, and robust hexapod robots. A detailed computer model of the neural circuitry and periphery involved in the cockroach escape response will be developed. This simulation will provide an interactive medium for synthesizing results of experimental and theoretical tests of system operation. To demonstrate that biological control principles can be applied to robotic design, they will also construct a hexapod robot and a locomotion controller based upon a neural model under development.

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Project Title: Bio-Control by Neural Networks
Funding Agency:
Classifiers: Information Processing, Neural Networks

Dr. Bekey recently chaired an NSF-sponsored workshop on Bio-Control in Neural Networks.

Birge, Robert R.
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Project Title: Molecular Electronics Based on Bacteriorhodopsin
Funding Agency: NSF, RADC
Classifiers: Biochemical Systems, Bioelectronics

Birge and co-workers have shown considerable interest in the potential use of light transducing proteins as active components in photonic devices. One example is the use

of the light harvesting protein, bacteriorhodopsin, as the photoactive element in spatial light modulators and optical memories. These devices make use of the high quantum efficiency and photochemical stability of this protein. For a random access optical memory using this protein, nanosecond access times are possible. Current efforts seek to improve the performance of bacteriorhodopsin throuch chemical and mutagenic modifications.

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Project Title: Neural Feedback and Musculo-Skeletal Mechanics
Funding Agency: Office of Naval Research
Classifiers: Mechanisms, Manipulators, Locomotion, Ambulation, Control Systems

The objective is to produce biologically plausible computational models of human arm and had sensorimotor control for potential implementation in teleoperator and robotic devices. The approach is a conbination of neurophysiological experiments, behavioral investigations, mathematical modeling, and theoretical studies of the computational tasks performed by the brain in the control of motor behavior. Model-based experiments are conducted to quantitatively model movement planning, execution and functional manipulation.

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Project Title: New technologies: communications, image, signal processing
Funding Agency:
Classifiers: Information Processing, Neural Networks, Pattern Recognition

Development: Neural network-based demodulation and decoding of communication signals; neural net-based vector quantization and DCPM for video data compression; neural net-based optimal controller for satellite switching applications. Research: Cellular automata-based approach to telecommunications traffic flow control; "context-sensitive" image compression (biologically motivated); pattern recognition and feature extraction in environments characterized bynon-stationary (or non-ergodic) noise processes; self-organizing neural nets applied to link scheduling and control in satellite communication networks.

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Project Title: Computational Theory and the Olfactory System
Funding Agency: Office of Naval Research
Classifiers: Information Processing, Sensory Processing, Olfactory

An attempt to forge a link between components of abstract neural network processing and the detailed anatomey and physiology of an actual neural system. This proposal links theoretical neural network models studied by Hopfield to actual structural components of the olfactory system studied by Bower. This linkage will be performed using the neural network simulation facility that the researcher has been constructing at Caltech.

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Project Title: Biomimetic Solar Conversion
Funding Agency: Gas Research Institute
Classifiers: Biochemical systems, Photosynthesis, Photosensitive bacteria.

Dr. Boxer recently completed a five year project to research the energy transfer and photochemistry in biomimetic solar energy conversion systems. One objective is to synthesize artificial systems in which efficient energy and electron transfer take place in a controlled environment analagous to that of natural photosynthesis. Also, Dr. Boxer and Dr. Birge of Syracuse Univ. are partners in a new start-up company to employ photochromic proteins, such as from halobacteria halobium or bacteriorhodopsin, as optical switching elements for optoelectronic devices.

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Project Title: Retinal model with adaptive contrast sensitivity and resolution
Funding Agency: None; prev., SDIO IS&T
Classifiers: Sensory Systems, Vision

A computer-simulated retina was designed which has useful features for computer vision, as well as certain features that are similar to human retina. The simulated retina is

designed to discriminate small differences in reflected light when these differences occur in a restricted domain of space and time, and maintains sensitivity to these differences in a wide range of lighting environments. As light levels decrease and photon noise becomes significant, the retina automatically decreases its spatiotemporal resolution to perform more integration and less differentiation, hence defeating the photon noise. The present simulation is based on photosensors attached to a passively conducting grid. Future work will concentrate on implementing the design in silicon.

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Project Title: Walking machines and insect behavior
Funding Agency:
Classifiers: Locomotion, ambulation, Adaptive structures, Structural systems

Researcher has done/is doing many projects including microbots, six legged walking robots based on animate studies, how complex behaviors are accomplished and complex structures are built by "dumb" ants.

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Project Title: Computer Vision and Behaving Systems
Funding Agency: National Science Foundation
Classifiers: Information Processing, Sensory Processing, Visual Perception

With the goal of understanding the human brain, Chris Brown wants to make an actual behaving system. Computer vision processing is simplified by animate vision - visual behaviours which seek to reveal more information about a particular scene. This work is based on studies of behaviour, physiology, and psychophysics.

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Project Title:
Funding Agency:
Classifiers: Materials, composite, Biosynthesis

Dr. Burte is Chief Scientist for the Materials Laboratory which funds and pursues on-site both bionics and biosynthesis projects of relevance to AF needs. His laboratory has responsibilty for all Air Force Materials R&D including (in context of this workshop) 1) Biosynthetic techniques (including bioremediation) that would provide a large cost benefit over competing (e.g. normal chemical processes), and synthesis of unique structures not (easily) otherwise attainable; 2) The study of microstructure-property relationships in biologically evolved materials from the viewpoint of obtaining insight that might be useful in synthesized materials.

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Project Title:
Funding Agency: NASA
Classifiers: Locomotion, Flight, Swimming, Drag reduction.

The division conducts aerodynamics and fluid mechanics research for both aeronautics and aerospace applications. The division has invested some effort in utilizing natural systems for ideas for improved aerodynamics, particularly for drag reductions. Riblets, which have been shown to provide a significant reduction in drag both on aircraft and ships, are also found on shark denticles. Nature has inspired the use of more optimal fillets on surface intersections of submarines for quieter operation. Additional areas investigates include cactus geometry for bluff body drag reduction and wing/fin serrated trailing edges for separation control at lift. Division is interested in morphological or behavioral adaptations in nektons and avians which could contribute to enhanced efficiency for cruise or burst speed including flow separation control, drag due to lift reduction, skin friction drag reduction, and vortex control.

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Project Title: Artificial Photosynthesis
Funding Agency: DoE
Classifiers: Biochemical Systems, Photoconversion, Solar Energy

The project objective is to devise a synthetic system for storing energy of visible light. The approach involves basic photochemical research in areas that will improve our understanding of the relevant parts of such a storage system. The first of these parts is a photoinduced electron transfer reaction across a phase boundary, mimicking the natural photosynthetic process.

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Project Title: Optimization of Physical Principles in Biological Systems
Funding Agency:
Classifiers: Sensory Systems, Information Processing

Within the above, and related programs, ARO supports close to twenty projects directly relevant to "bionics" as defined here. There is a need to increase the depth and widen the scope of fundamental knowledge regarding biologically evolved and tested adaptations and solutions, to learn more about the types of processes and materials employed by various organisms, both plant and animal. Basic research is supported to further our understanding of the mechanisms involved in complex biological system function, the dynamic structures supporting such functions, and the biosynthetic pathways leading to those structures. Efforts here, for example, seek to clarify how higher order structure is achieved and how it serves as a deteminant of function in such a variety of forms as olfaction, biomechanics, molecular recognition and gating, biological intelligence and catalysis.

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Project Title: Nanoheterostructures
Funding Agency:
Classifiers: Biomolecular materials, Biomolecular electronics.

Dr. Clark and Dr. Douglas are developing methods for fabrication of periodic nanometer scale structures using two dimensional protein crystals as patterning elements. This technique can serve as the basis for a technology for the inexpensive parallel nanostructuring of surfaces as well as a useful tool for studying the physics of fabrication on the nanometer scale.

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Project Title: Linear Electrostatic Microactuator Dev. for Artificial Muscles
Funding Agency: None
Classifiers: Mechanisms, Manipulators, Actuators

The premise of this research is that many of the design principles represented in muscle, such as parallel and series concatenation of linear microactuators, high force-generating surface area per unit actuator volume, and incorporation of mechanical advantage at the microactuator level, may be exploited in the design of a high-performance electrostatic actuator. Analysis indicates that an electrostatic "artificial muscle" consisting of an array of planar linear micromotors formed with standard photolithographic techniques, should be able to better the power to weight ratios of state-of-the-art electromagnetic motors by nearly an order of magnitude, as well as eliminate the need for transmissions and operate more efficiently at low speeds. Such an actuator would be ideal for use in powered prostheses and orthoses, and in robotics and teleoperation. Current research focuses on linear micromotor design and implementation, as well as on basic issues of electrostatic to mechanical energy conversion. One critical issue that we are studying is mechanisms and control of charge transfer. Controlling the locations of (both free and displacement) charges is essential for generating large forces, and is no simple matter given the complex interplay of effects such as RC charging, triboelectric charging, and electrostatic discharge, especially in the presence of solid dielectrics and floating conductors. Another issue that we are studying is the stability of electrostatic systems.

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Project Title: Neuromolecular computing: mechanisms and architectures
Funding Agency:
Classifiers: Mechanisms, Molecular Computing, Information Processing, Neural Processing, Neural Networks

Dr. Conrad develops computer models of biological information processing systems with an eye toward using such knowledge to build information processing systems that act as biological systems do. These modeled networks learn through an evolutionary process to recognize certain patterns and control their output. He proposes a "tactilizing" processor that combines a high level pattern recognition processor based on neuronal models with

the intrinsic pattern recognition abilities of enzymes. Dr. Conrad also serves as an advisor to Japan's Advanced Technology Institute.

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Project Title: Teleautonomous Robotics
Funding Agency: DARPA
Classifiers: Bionics Workshop

Current interest: teleautonomous robotics, just ahead of time control . Believes to be inherently biologically based (Fitz Law, etc). Previously the Director of Strategic Computing for DARPA. Helped organize a workshop on Planning in Animate Systems that took place in June 85 after she left DARPA.

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Project Title:
Funding Agency:
Classifiers: Biochemical Systems, Transpiration

Dr. Cooke has applied finite element stress analysis to the structure of plant stomata which are the pores used by the plant to control transpiration of carbon dioxide and oxygen. The stomata are shaped like a torus and are controlled by hydrostatic pressure. When presurized, they expand out of the plane of the leaf and open allowing gas exchange. These stomata may serve as interesting models for miniature valve for closed loop life support systems or other applications.

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Project Title: Grating Diffraction and Analysis
Funding Agency: Polaroid
Classifiers: Structures, Color Display, Butterfly

Dr. Cowan started with the work by Ghiradelli and others on the mechanism of color production by scales on the wings of butterflies and is developing replicatable step-pyramid structures in photoresist to produce diffraction gratings. Their application is multicolor holograms. Gratings can be produced holographically or by optical lithography. Technology will allow a line density of a couple of micrometers.

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Project Title: Vision in the Marine Environment; Compound Eyes in Stomatopods
Funding Agency: National Science Foundation
Classifiers: Sensory Systems, Vision

Visual specialization in a group of marine animals with species in environments from intertidal to deep-sea. Multifunctional retinas - polychromatic vision, polarization vision, spatial specialization. Control of eye movements. Scanning eye movements. Optical arrays. UV vision.

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Project Title: Coordination of Leg Movement in Walking Animals
Funding Agency:
Classifiers: Locomotion, Ambulation, Walking Machines

Dr. Cruse is studying the control and coordination of leg movement in walking animals with the intent to apply such control methods to walking, autonomous robots. When compared to the walk of a robot, the walk of an animal is much more versatile, elegant and efficient. Comparison of the biological control mechanisms of different classes of animals, such as insects, crustacea, and mammals may give insight to improved control strategies for walking machines.

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Project Title: A sensorized scenario for basic investigation on active touch.
Funding Agency: Nat'l Research Council, Italy
Classifiers: Information Processing, sensory processing, tactile

The ultimate goal of the project is to understand the basic mechanisms oftouch in humans and to replicate them into artificial systems. Research is performed on in the analysis of subsystems (proprio- and exteroceptive sensors, actuators, end-effectors, control), and on their integration to achieve truly dexterous behavior. An additional research topic is the integration of active touch with active vision. and with other sensing modalities (such as hearing). Research at the ARTS lab is also aimed at investigating different componentsand systems modelled upon biological systems, such as a number of different transducers (for example, array ultrasonic transducers in air), of actuators (including network of muscle-like actuators), and even microrobots and cellular robots.

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Project Title: Optical sensory neural network
Funding Agency: National Science Foundation
Classifiers: Sensory systems, optical sensing, vision

Major program area is integrated optoelectronics: integrating optical detectors and arrays of detectors with regular electronic circuitry in a monolithic format. A subfield of this is the development of solid-state imagers which utilize known principles of vision science to provide low-level signal processing features, e.g. luminance adaptation, texture enhancement, and preferential motion selectivity.

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Project Title: Teleoperated Satellite Repair
Funding Agency:
Classifiers: Teleoperation

Investigating the use of remotely controlled robots for satellite repair. Issues: 1) Specialized tools for repair tasks; 2) Teleoperator control architectures; 3) Visual displays to present to human operator.

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Project Title: Understanding and applying visual processes to machine vision
Funding Agency: previously AFOSR
Classifiers: information processing, sensory processing, vision

Dr. Daugman's current research interests include multidimensional signal processing, neural networks, and neurophysiological and psychological studies of biological vision systems. He has studied early vision and the parsing operations that both natural and artificial signal processing mechanisms must perform to encode information in the visual image. He also serves as a consultant to Lincoln Laboratories and as Scientific Advisor to the Hecht-Nielsen Neurocomputer Corp.

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Project Title: Neural (Biological Intelligence) Science
Funding Agency:
Classifiers: Information Processing, Neural Processing

This program fosters research to elucidate the organization, structural basis, and operational algorithms characterizing information processing within neural systems. The goal is to uncover neural architectures and algorithms that can be emulated technologically to yield artificial information processing capabilities of kinds now unique to biological systems. Areas of emphasis include research into the organizational principles and operational rules of neural networks; neural plasticity (learning); neural basis for post-retinal vision; visually guided motor behavior; and neural models for classification of complex auditory phenomena.

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Project Title: Tactile Sensing
Funding Agency: None
Classifiers: Sensory Systems, Tactile

Conducts applied research into artificial skin tactile sensors for robotic applications. Also, works in design of actuators and manipulators for robots. Also performing research in artificial muscles.

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Project Title: Advanced Electrochemical Carbon-Dioxide Transport
Funding Agency: NASA Johnson Space Center
Classifiers: Biochemical Systems, Life Support Systems

Dr. DuBois led a project for NASA on a new concept for regenerative removal of carbon dioxide using electrochemically active carrier molecules to pump carbon dioxide from low pressure to high. These carrier molecules are similar to those used by corn plants and desert plants. At peak periods, corn plants can be photosynthesizing so rapidly that they locally deplete the carbon dioxide, thus requiring a binding concentration mechanism. Likewise, desert plants allow transpiration only at night to reduce water losses, thus they require different binding mechanisms since there is no active photosynthesis at night. This process of using carrier molecules could be applied to removal of other constituents in a closed environment.

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Project Title: A Retina-like Model for Motion Detection
Funding Agency:
Classifiers: Sensory Systems, Vision

Has developed a model for motion detection based on anatomy and physiology of biological retinas. The model tracks better than Kalman filtering. Its implementation in VLSI is conseptually straightforward.

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Project Title: Neurodynamics of Biological Neural Networks
Funding Agency: NIMH, AFOSR
Classifiers: Information Processing, Biochemical Sensing, Sensory Processing, Pattern Recognition, Olfactory

Dr. Freeman conducts research into the neurodynamics of biological intelligence, particularly as they relate to neural networks. He has elucidated several important characteristics of biological nerual networks that have not been adopted in artificial neural networks. His research into pattern recognition has shown that odor recognition is a process of restriction to a local segment of a global attractor, not a bifurcation to a smaller attractor. He is currently funded to produce a hardware architecture of a neural network model of the olfactory bulb.

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Project Title:
Funding Agency:
Classifiers: Mechanisms, Manipulators, Control Systems, Neural Networks

Artificial Muscle via Contractile Gels: To create an associated linear actuator mechanism, to investigate various means of activation. Heterogenous Neural Networks: To enhance the concept of neuron from an algebraic entity to a general non-linear differential function. To derive neuron function from an understanding of various naturally occuring neurons.

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Project Title: Structure and Development of Iridescent Butterfly Scales.
Funding Agency:
Classifiers: Structures, Information Display, Color Display, Butterfly.

Dr. Ghiradelli studies the mechanisms by which butterfly wing scales produce colors. Lattices produce diffraction colors while stacks of lamellae or laminae produce interference colors. She also researches the development of these color producing scales and scales providing other functions. She has not been involved in translating this work for optical displays. Other work of interest is the study of the noctoid moth ear which has only two sensory cells and the control mechanisms of luminescence in the firefly.

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Project Title: Microstructure Design in Cellular Solids
Funding Agency: Department of Energy
Classifiers: Materials

In this project we are studying ways of improving the efficiency of cellular materials such as honeycombs and foams, partly using ideas from natural cellular materials such as wood. We hope to be able to design engineering cellular materials which exploit the same means of achieving their efficiency as natural cellular materials.

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Project Title: Chemoreception in Squid and its Role in Jet-Propelled Swimming
Funding Agency: Office of Naval Research
Classifiers: Sensory Systems, Locomotion, Biochemical Sensors, Swimming, Control Systems

The project will define chemoreceptive abilities of squid to stimuli which produce specific motor responses. It will characterize the chemosensory cells and identify ion channel actions and signal transduction mechanisms. This approach will lead to a conceptual framework for design of biosensors.

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Project Title: An approach to biomolecular electronics and bioengineering
Funding Agency: Government of India
Classifiers: Biomolecular Electronics

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Project Title: A New Stereo Vision Model Based on the Binocular Fusion Concept
Funding Agency: NASA
Classifiers: Information Processing, Sensory Processing, Visual Perception

Professor Griswold is studying the human brain mechanisms of vision to improve artificial stereo vision. He has developed computationally efficient models and methods for stereo vision that allow for surface structure reconstruction from images. By encorporating human binocular type features he is enhancing computer vision techniques. Aerospace applications of his work include docking, robotics, satellite repair, and other real scene image analysis and processing.

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Project Title: Architecures for Early Vision
Funding Agency: AFOSR, ARO, NSF
Classifiers: Information Processing, Sensory Processing, Visual Perception

Dr. Grossberg is Director of the Center for Adaptive Systems. He and his colleagues have developed a number of fundamental principles, mechanisms and architectures for contemporary neural network research. These investigatins include contributions to biological vision and multidimensional image processing; cognitive information processing; adaptive pattern recognition; speech and language perception; adaptive robotics; and

biological rhythms. They focus on the design principles and mechanisms which enable behavior of individuals to adapt successfully in real time to unexpected environmental changes. Models developed by this group have been used both to analyze and predict a wide range of interdisciplinary data about the mind and brain, as well as to suggest novel architectures for technological applications.

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Project Title: Structural Analysis of Natural Composites
Funding Agency: AFOSR
Classifiers: Structures, Materials, Composite

Research is being conducted on various natural composite structures, primarily the insect exoskeleton, for unique design concepts that can be applied to man-made advanced composites for improved performance. Some promising design concepts are being incorporated into polymeric fiber-reinforced composites and the effects evaluated.

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Project Title: Silicon Association Cortex
Funding Agency: ONR
Classifiers: Neural Processing

The objective is the silicon implementation of two existing cortex-like models. Implementation of basic silicon cortex will greatly accelerate the development of neurobiological models by providing a means for much speedier and cost effective simulation.

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Project Title:
Funding Agency:
Classifiers: mechanisms, manipulation, actuators

Currently developing an antagonist muscle pair, as well as a solid-state end effector for a robotic arm. This work could be especially useful in space applications, because of the heat characteristics of the artificial muscles.

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Project Title: Bionics Workshop, 1984
Funding Agency: NOSC
Classifiers: Bionics Workshop Co Chairman, 1984

Was Co-chairman of the Artifical Intelligence and Bionics Workshop for the Naval Ocean Systems Center. Currently very interested in Bionics but not heavily involved--works in marine program with some bionics on the side. Compiled list of experts for workshop. Provided list of researchers currently working in field.

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Project Title:
Funding Agency:
Classifiers: Materials, Biosynthesis.

AFOSR is currently funding two projects on biological models for advanced materials (UDRI and Univ. Washington). objective in both is to learn from nature through identification, analysis, and mimicking of natural structures nad natural processes. Total funding in FY 90 is $250K, but intent is to enhance this program in FY92 by adding $300K for biomimetics. They are planning a small planning workshop for Spring 1991 for the purpose of guiding funding priorities for FY92.

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Project Title: Electromagnetic sensing of fish
Funding Agency: NSF, NIMH, NINCDS
Classifiers: Sensory Systems, Electromagnetic Sensing

Sensory information processing in the electric sense of fish: computational rules and their neuronal implementation. It is our general goal to learn about natural neuronal designs for information processing. We expect benefits for the compensation of modern man-made designs.

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Project Title: Engineering derivatives from nature for aerospace applications
Funding Agency: NASA Ames Research Center
Classifiers: Bionics, information processing, neural networks, cochlear implants

Bionics project seeks to identify promising areas for aerospace applications of bionics. Mr. Hering contributed to the literature survey to document contributions and current research activity in bionics, administration of bionics workshop, annotated bibliography/directory of bionics researchers, and final project report. In other projects, Mr. Hering's research areas include neural networks and processor design for cochlear implants.

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Project Title: Using Time-to-Collision to Recover 3-D Motion for Navigation...
Funding Agency: Office of Naval Research
Classifiers: Information Systems, Neural Networks, Navigation Systems

The objective of this research is to establish the computational and psychophysical bases for design of networks that have the capacity to compute quickly and accurately the

structure and relative motions of environmental objects with which an artificial system may physically interact during the course of navigation and object manipulation.

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Project Title: Dexterity in Teleoperation
Funding Agency: Natural Sciences and Engr.
Classifiers: Teleoperation, Human Operator Dynamics, Manipulation

This project seeks to improve dexterity in teleoperation by designing or obtaining high-performance master/slave arms, hands, and visual displays. Two teleoperated manipulators are proposed: (1) a force-reflecting master glove to control a multi-fingered robot hand in grasping and manipulating arbitrary objects, and (2) hydraulic master/slave manipulator arms. A low-cost visual display is being developed combining commercial elements with some in-house components. Also using non-linear stochastic system identification techniques in conjunction with a subsystem decomposition of the human operator to characterize rapidly the dynamics for an individual human operator in pursuit tracking tasks.

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Project Title: A Thin Film-Based Molecular Optoelectronic System
Funding Agency: NIH, ONR
Classifiers: Mechanisms, Molecular Electronics

The research is centered around photobiological membranes and the R&D of molecular optoelectronic devices. A comprehensive analytical methodology for the photoelectric effect in photobiological membranes was developed using a combined electrophysiological and electrochemical approach. Membrane reconstitution techniques are emphasized. Collaborative work also involves protein chemistry, flash photolysis, and genetic engineering. Recent work is focused upon retinal proteins, such as bacteriorhodopsin, halorhodopsin and rhodopsin with the aim of utilizing these molecules as building blocks for device construction and of elucidating nature's design principles via "reverse engineering."

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Project Title: Studies in Neural Networks
Funding Agency: Office of Naval Research
Classifiers: Information Processing, Sensory Processing, Olfactory

This research is aimed at constructing model neural networks which can solve some of the computational problems of olfaction, examining the connections between the model networks and the real olfactory networks, and understanding the importance of the time-dependent aspects of olfactory processing. A neural network model of the olfactory bulb has been built, mathematically analyzed and computer simulated. The model mimics very well the observed oscillatory activities observed in the neuron population of the bulb.

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Project Title: Adaptive Control of Limb Motion by Brains and Robots
Funding Agency: Office of Naval Research
Classifiers: Mechanisms, Manipulators, Control Systems

This research is intended to advance knowledge about how the cerebellum might mediate adaptive feedforward control, and to apply this information to robotics. The investigators will conduct computer simulations of motor systems, in the form of simulated neural networks, that are based on the anatomy and physiology of the cerebellum.

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Project Title: Prospects for artificial neural systems in vision computations
Funding Agency:
Classifiers: Information Processing, Sensory Processing, Visual Perception, Neural Processing, Neural Networks

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Project Title: McGill/MIT Direct Drive Robot Arm
Funding Agency: Natural Sciences and Engineeri
Classifiers: Mechanisms

A major part of this project is to explore the use of Nickel-Titanium (NiTi) shape memory alloy as a robot actuator. We have discovered a new method of activating NiTi that circumvents previous cooling limitations and improves the speed one-hundred-fold over what has previously been reported. We plan to develop an artificial muscle having fiber-like actuators arranged in parallel. We are also developing a microrobot capable of manipulating microscopic objects, such as single living muscle cells. This microrobot has a position resolution of one nanometer and may be operated with a large scale replica master as a force-reflecting teleoperator system.

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Project Title: Tactile Sensing in Robotics
Funding Agency:
Classifiers: Information Processing, Sensory Systems, Sensory Processing, Tactile Sensing, Touch

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Project Title: Biophysics Research
Funding Agency: AT&T
Classifiers: Materials, Biochemical Systems

This group conducts fundamental research aimed at discovering and elucidating known biophysical phenomenon in areas of potential impact to AT&T. Current research involves experimental programs directed at a fundamental understanding of how biological

memories are stored and how learning takes place and how various natural and synthetic molecules carry out their biological processes. Areas of interest in biomolecular materials include biological self-assembly, use of biological macromolecules as resists for photolithography, exploiting principles of biological assembly to build robust, synthetic, non-biological materials, and use of the exceptional specificity of proteins for biosensors.

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Project Title: Natural Composite Materials
Funding Agency:
Classifiers: Materials, Composite

Dr. Jeronimidas is active in research and teaching on composite materials, natural and artificial, with a particular interest in wood. He has authored a number of articles on the properties of fibrous materials and the design principles used by nature that may be adapted to artificial composite materials design. He is co-inventor on a patent for a composite structural panel with a structural reinforcing fiber with an angle of orientation based on that found in wood.

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Project Title: Sensory Systems in Fishes
Funding Agency: ONR, NSF
Classifiers: Sensory Systems, Electromagnetic Sensing

Dr. Kalmijn has undertaken a systematic study of the electric sense of lower aquatic vertebrates. His research seeks to understand the physics of the peripheral sensory apparatus, the process of sensory transduction, the coding of afferent nerve signals, and the central processing of information. He studies both the passvie and active modes of electrosensory capability used to detect prey and other objects as well as to orient the organism in the Earth's magnetic field. Dr. Kalmijn is also interested in the mechanosensory capabilities displayed by the lateral line of fishes.

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Project Title: Parallel Structures in Human and Computer Memory
Funding Agency:
Classifiers: information processing, pattern recognition

Sparse Distributed Memory. This type of computer memory allows a computer to recognize patterns and recall sequences in a manner similar to humans. The sparce distributed memory emphasizes sensitivity to similarity for recall. Prototypes have been constructed and work is ongoing.

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Project Title: Biotechnology-Derived Materials and Processes
Funding Agency: DoD, USDA
Classifiers:

The focus of this research program is the design, synthesis or use of biological macromolecules for polymer and material designs. The program includes studies on genetic approaches for control of polymer structure, self-assembling systems to orientate and control the design of complex molecular-scale systems, nanoscale composites through controlled crystallization, and intelligent system concepts based on the integration of biological macromolecules with synthetic components. The work includes direct synthesis using biological systems, the processesing attributes found in biological systems to assemble complex macromolecules and composites, or a combination of biological and synthetic materials or processes to develop these materials and systems. Specific examples include: 1) Recombinant spider silk proteins for high-strength fibers and composites. 2) Fungal and bacterial polysaccharides and polyesters for biodegradable packaging materials and food coatings. 3) Biomineralization processes: characterization of the organic matrices involved and mimicking of these processes to develop new approaches to nanoscale ceramic composite designs. 4) Biological assemblies through organized protein-pigment complexes to effect optical signal transduction for environmental blending in the visible spectrum. 5) Enzyme catalyzed polymerization reactions in novel systems for new resonant polymer systems for nonlinear optical and electrical properties.

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Project Title: Corp R&D VP; formerly DARPA--originator of 1985 Bionics Workshp
Funding Agency: SAIC
Classifiers: Bionics Workshop

Originated idea for DARPA Workshop on Planning and Problem in Animate Systems. Knows researchers involved in that project. Not currently doing bionics research personally--corporation does Neural Networks research emphasizing implementations. Has videos of legged motion bionics work.

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Project Title: Navigational Integrated Circuits
Funding Agency: Office of Naval Research
Classifiers: visual perception, vision, sensory processing, position/orientation sensing, navigation systems, information processing

The objective of this research is to develop theoretical models for computation for early visual processes toward analog VLSI chips for use in robotic vision systems. Also, developing integrated circuits for navigation in working environment. Chips motivated by visual systems of fly and mammalian visual cortex. Utilizing characteristics such as time to contact, rate of looming for range measuring, swooping. Furthermore, the lab emphasizes the design and fabrication of analog CMOS VLSI circuits with on-chip 1-D and 2-D arrays of photreceptors for edge detection, optical flow and depth computation.

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Project Title: Neural Networks for Autonomous Motor Control
Funding Agency: ONR, AFOSR
Classifiers: Neural Networks, Control Systems

Based on a theory of neural computing in biological systems, a new robotics system capable of adaptive control of multijointed arms and a new visual system capable of recognizing handwritten numbers have been developed.

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Project Title: Optics of Animal Eyes
Funding Agency:
Classifiers: Sensory Systems, Vision, Optics

Prof. Land is a leading researcher in the optics of animal eyes of all types. While he has not been directly involved in bionics applications, his work has served as inspiration to others in building optical systems.

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Project Title: Characterization of Marine Bioadhesive Proteins
Funding Agency: Office of Naval Research
Classifiers: Mechanisms, Attachment/Bonding Mechanics

From studying the amino acid sequences of adhesive proteins from several species of mussel and of other organisms, this research aims to understand how these organisms attach themselves to wet surfaces.

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Project Title: Cloning and Structure of Different Types of Spider Silk
Funding Agency: Office of Naval Research
Classifiers: Structural Systems, Materials, Compliant

The objective is to clone the DNA encoding for proteins composing various types of spider silks and determine what protein features are responsible for their unique properties. Spider sliks have a diverse range in properties including some that exhibit tensile strength greater than steel and others that are more elastic than natural wool fiber. Synthetic fibers bearing these properties are of general interest to the Navy.

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Project Title: Biologically Based Neural Net for Active Perceptual Processing
Funding Agency: Office of Naval Research
Classifiers: Information Processing, Sensory Systems, Sensory Processing, Smell

The primary objective is an investigation of neural network interactions arising from a model of the olfactory bulb. These interactions will be based on "real" biological rules including dendritic structure, neurochemical events and spatio-temporal patterns of physiological synaptic changes. The objectives include a feasibility study of the electronic implementation of these biological processes in VLSI devices. The investigators have developed a new neural network based on a model of paleocortex which provides a novel and efficient method for hierarchical clustering of data.

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Project Title: Biomimetic Solar Energy Conversion
Funding Agency: U.S. DoE
Classifiers: Biochemical systems, Photoconversion

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Project Title: Bionics: Natural and Artificial Sensors
Funding Agency:
Classifiers: Sensory Systems

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Project Title: Perceptual Sciences Program
Funding Agency:
Classifiers: Autonomic Control, Sensory systems

Research interests include theorectical and experimental studies of multi-modal perceptual integration, and expression in what appears to be automatic control behavior. The aim of this program is to understand perceptual integration and control processes at a level that permits design guidance for human-computer interfaces and supervisory systems. Dr. Malecki was co-sponsor of the International Workshop on Dextrous Manipulation and Teleoperation.

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Fax:

Project Title: Biomineralization
Funding Agency:
Classifiers: Materials, Biomineralization

Dr. Mann conducts research into the crystallographic strateies in biomineralization that controll nucleation and growth. Emphasis is place on how macromolecules, proteins and polysaccharides, interact with the surfaces of biominerals. The goal is to develop new ways to control how inorganic materials crystallize. Modelling the interactions between inorganic and organic surfaces should lead researchers to ways to design new forms of single crystals and organized composites.

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Project Title: Biopolymeric Materials
Funding Agency:
Classifiers: Materials, Biosynthesis

This program focuses on biosynthesis of novel polymeric materials made of repetitive sequences of peptides or esters. This ARI is aimed at understanding the general principles relating microscopic three dimensional structure to macroscopic physical properties such as elasticity, adhesion, piezoelectricity, nonlinear optical properties, and tensile strength of fibrous polymers. Plans for expanding the program are underway with the following new thrusts: polysaccharides, with possible emphasis on adhesives and drag reduction agents; hierarchical structures, including natural composites and structural materials with highly regular microstructures; and biofabrication, processes organisms use to prepare highly regular structures with the aim of developin techniques for emulating these in vitro.

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Project Title: 1) NPS AUV II; 2) Underwater walking robot; 3) Past: Legged Mot
Funding Agency: 1)NAVY, 2)Japan MOT, 3)DARPA
Classifiers: propulsion, locomotion, ambulation

Current programs: 1) Small autonomous submarine. Utilizes biological sonar processing, behavior in fishes, fish fins, zero speed maneuverability based on sea animals. Prototype tested in pool. Currently active program. 2) Proposal to NSF with Japanese Ministry of Transportation for underwater walking machine to measure seawall height in Japan. Machine exists--aquarobot. Past programs: Worked for over twenty years studying and implementing multilegged walking machines based on studying horses and insects. Considered a bionics pioneer.

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Project Title: Silicon Neural Systems
Funding Agency: Office of Naval Research
Classifiers: Information Processing, Neural Processes, Neural Networks

The objective is to develop a deeper understanding of the collective computational capability of neural systems and to use silicon fabrication technology to implement these neural systems on silicon. These electronic neural chips and systems will be based on organizing principles found in the nervous system of animals. Silicon chips for visual tracking, visual focusing, binocular stereopsis, VOR, inner plexiform, neural integration, central pattern recognition, and auditory classification will be built.

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Project Title: Information processing analysis of the mammalian cerebellum
Funding Agency:
Classifiers: Information Processing, Neural Processing

Approach is to use biological evidence to drive the development of an information processing model/architecture of the mammalian cerebellum. (Project assumptions: cerebellum is a motor reflex coordination element; it "computes" and stores sensory (external and internal) event patterns which are both spatial and temporal in extent.) Primary focus is on the development of a system which leads to an increased engineering understanding of 1) distributed/parallel processing, 2) spatial-temporal processing techniques, 3) sensory-fusion methods, and 4) the combing or integration of memory/processing elements.

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Project Title: Biological and Biomimetic Detection Systems
Funding Agency: ONR, Industry
Classifiers: Sensory Systems, Olfactory, Biochemical Sensors

This newly formed Institute is actively pursuing study of the chemical constituents of olfactory mucus and the chemical changes that occur as the first step in transduction. They are studying the physiology of olfactory organ slices as well as molecular modeling of the chemistry involved. They are also adapting the second messenger system as an artificial amplifier for an "artificial nose." Vitali Vodyanoy has joined them and is a leading researcher in this field. The dog is used as a primary biological model, having capability to detect 10 to the -18th power molar concentrations. Metal ion sensors are

being developed. Neural networks to handle arrays of sensors are being designed. Genetic engineering of microorganisms to function as bioluminant biosensors is being performed. Antibody design and production for incorporation within biosensor systems is an active area.

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Project Title: Dolphin Echolocation/Previously Co-chaired bionics workshop
Funding Agency: Office of Naval Research/Tech
Classifiers: Sensory Systems, Acoustic, Navigation Systems, Workshop

Currently involved in dolphin echolocation, particularly high noise and reverberation environment material classification. Studying mechanisms that dolphins use for matching objects to ones they have previously encountered. How clicks are used, decision processes, sonar. Previously co-chaired NOSC Artificial Intelligence and Bionics Workshop in 1984. Chaired workshop in Paris Conference on Simulation of Adaptive Behavior: Animals to Animats, September 1990. Chaired NATO Advanced Studies Institute on Animal Sonar (1986) and edited book, Animal Sonar: Processes and Performance (1989). Also working on dolphin vision, chemoreception, and cognitive processes.

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Project Title: Motion-vision architectures
Funding Agency: AFOSR, SDIO
Classifiers: Sensory Systems, Vision, Neural Networks

Dr. Narathong has developed a fast tracking algorithm for video tracking by implementing a highly parallel neural network to determine displacements on object surfaces between successive frames. The algorithm utilizes a spherical sensor with biological features to estimate three dimensional motion. The algorithm has been implemented based on Hopfield-Tank neural network architecture. They are seeking to implement rapid prototyping of neuroprocessors for specific applications, su as motion estimation, and are developing a chip which should be available for physical testing mid 1991.

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Project Title: Sleep Patterns, Protein and Calcium Metabolism in Denning Bears
Funding Agency:
Classifiers: Biochemical Systems, Calcium Metabolism

Dr. Nelson has studied the mechanisms by which denning bears remain recumbent for periods of months but do not lose calcium from their bones. The hormonal methods employed may be instructional in developing effective pharmacological countermeasures to bone calcium loss experienced in microgravity and also in clinical osteoporosis. During denning, bears are in a tranquil, alert state at normal body temperature. They do not eat, drink, urinate, or defecate. They remain in a non-weight bearing state. Despite fasting, they protect lean body mass, maintain normal bone remodeling and thus do not lose calcium from bones. Substances have been isolated which are only associated with these states and are now being assayed in biologic assays. Applications for NASA center around long term space flights for assistance in psychosocial adjustments, reducing dietary needs and preventing loss of muscle and bone tissue.

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Project Title: Plant Materials
Funding Agency:
Classifiers: Materials, Mechanics

Dr. Niklas is a botanist interested in studying the materials and mechanical design principles in natural plants. Among other research interests, he has studied the aerodynamics of pine cones to shown them to be efficiently designed to trap pollen grains.

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Project Title: Artificial photosynthesis
Funding Agency: Department of Energy
Classifiers: Biochemical systems, photoconversion, electron transfer, photosynthesis

The development of chemical systems that mimic accurately the process of photo-induced charge separation as it occurs in the natural process of photosynthesis.

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Project Title: The induced vibration touch sensor - a new dynamic touch concep
Funding Agency:
Classifiers: Sensory Systems, Tactile Sensing

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Project Title: Development of artificial olfactory sensors
Funding Agency:
Classifiers: Sensory systems, Olfactory

Development of gas/odor sensors based on conducting organic polymers; Integrated sensor development; Pattern recognition software; Olfactory modelling; Physiology/biochemistry of biological transduction processes in olfaction and gustation

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Project Title: Electrosensitivity of Cartilaginous Fishes
Funding Agency:
Classifiers: Sensory Systems, Electromagnetic Sensing

Dr. Pickard's research concerns the fundamental processes of mass ans charge transport in organisms and also the fashions in which these processes can be influenced by the electromagnetic field. He has studied the detailed biophysical basis for the remarkable electromagnetic sensitivity of cartilaginous fishes, and has proposed a theory to account for this acute sensitivity to exogenous electric fields.

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Project Title: Visual Integration and Recognition
Funding Agency: Office of Naval Research
Classifiers: Information Proccessing, Sensory Processing, Visual Perception

This research is aimed at specification of biologically plausible implementation models for visual integration and recognition.

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Project Title: Synthesis of novel materials based on biological models.
Funding Agency: ONR
Classifiers: Biosynthesis, Materials, Structures.

This program is part of the FY91 University Research Initiative Research Initiation Program. They are soliciting proposals, due Sept.13, 1990, on synthesis of novel materials based on biological models and chemical routes. The goal is to explore novel synthetic routes to tailor chemistries and microstructures so as to control physical and mechanical properties. The nature of interactions between levels in structural hierarchies and their relationship to macroscopic properties should be addressed. Materials of prinary interest include composites, consisting at least in part of a ceramic and/or metal and having potential for exhibiting advanced structural, acoustic, or electromagnetic properties. One approach is to use natural biostructures as models for such advanced materials and to develop synthetic routes to simulate their hierarchical structures.

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Project Title: Generalized Gabor Scheme of Image Rep. in Biol. & Mach. Vision
Funding Agency: Israel Acad. of Sci. & Humanit
Classifiers: Information Processing, Sensory Processing, Visual Perception

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Project Title: The ultimate in microelectronics: biomolecules
Funding Agency: Utah State University
Classifiers: Mechanisms, Molecular Electronics

The Center of Bio-catalysis Science and Technology (CBCST) was established in 1988 by a $670,000 grant from the State of Utah Department of Community and Economic Development. The goals of this center are 1) to explore and elucidate the basic principles of bio-catalytic processes, especially those involoving metals, to develop synthetic analogs of bio-catalysts; 2) to develop time resolved spectroscopic technology necessary for these basic studies, and 3) to apply this basic knowledge to the development of bio-catalysis technology and the new time resolved instrumentation to industrial and environmental monitoring and management. Dr. Powers is also involved in the design and construction of miniature parallel processing devices for control and sensors, and the design and construction of optical and x-ray instrumentation for monitoring.

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Project Title: Polarization Contrast Vision
Funding Agency: Office of Naval Research
Classifiers: Sensory Systems, Optical, Imaging/Vision

The technical objective of the proposed research is to prove that some vertebrates (as exemplified by the green sunfish, Lepomis cyanellus) can detect targets in their environment on the basis of a novel form of visual information -- polarization contrast -- and to establish the biophysical and neural bases of this ability. A novel video camera bsed on this hypothesis is also to be constructed and tested.

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Project Title:
Funding Agency: NASA
Classifiers: Information processing, Neural processing, Sensory systems, Accelerometers, Macula, rat.

Dr. Ross and colleagues have taken 570 serial microscope sections of the rat macula, photographed these, traced the nerve fibers, receptor cells, synapses, and digitized this into a PC. They then use computer image animation to reconstruction the three dimensional neural anatomy. Using this method, they were the first to establish that the macula is a parallel processor with feedforward and feedback loops and lateral connectivity. By uncovering the principles of organization, one can genralize to computer information networks leading to the possibility of developing biological accelerometers, for example to use in control of autonomous rovers.

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Fax:

Project Title: Retina-like CCD Sensor for Active Vision
Funding Agency:
Classifiers:

Professor Sandini is interested in the field of active vision and sensory fusion. By studying human vision and applying preprocessing techniques, he is developing methods to direct vision processing so that the pertinent data is used for processing while redundant data is removed. He has modelled a human retina-like structure to demonstrate the economy in terms of an optimum compromise of different levels of visual data for use in such areas as scene analysis and active vision control.

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Project Title: Design and processing of materials by biomimicking.
Funding Agency: AFOSR
Classifiers: Materials, composite, Seashells.

Dr. Sarikaya and Dr. Aksay are conducting research, in collaboration with James T. Staley, Microbiology, by using biological models or biological processes to produce advanced materials. Work is broken into the following areas:i) development of lubricating biopolymers using bacteria and algae for collooidal processing of composites; ii) ultrafine particle production by using bacteria and synthetic vesicles; iii) functionally graded ceramic-metal and ceramic-polymer laminated composites for light-weight/high-strength-toughness applications based on seashell minoarchitecture; iv) biomineralization and biocrystallization; v) microstructure-property correlations in biocomposites; vi) atomic resolution microscopy and spectroscopy.

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Project Title:
Funding Agency: AFOSR, Wright Patt. AFB
Classifiers: Materials, composites, Insect exoskeleton, Biosynthesis.

Ms. Schiavone in part of a team at UDRI which is supporting Wright Patterson AFB and AFOSR in taking advantage of biological models and biosynthesis methods to design and produce advanced materials, particularly composites. Of particular interest is their work with insect cuticle which is a strong, lightweight composite with good impact damage tolerance. Some of the unique characteristics of insect cuticle may have possible applications and effects on synthetic composites, especially ceramic and metal matrix composites.

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Project Title: Large Coherent Fiber Optics. Past: Multiaperature Optical Sys
Funding Agency: Current int. Past: ONR
Classifiers: insect eyes, imaging/vision, optical, sensory systems

Current project: using natural system philosophy to unscramble light in an incoherent optical fiber. Subcontract to General Imaging, Gainsville, FL. Past project: using design

principles of the insect eye for multiaperature optical devices with applications in robotics, motion detection, tracking and measuring, parts inspection, gazing sensors, and blind man's eyes.

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Project Title: Novel Applications of Self-Assembled Lipid Microstructures
Funding Agency:
Classifiers: Materials

Certain chemically modified phospholipids, when dispersed in water or in a water/alcohol system, self assemble into hollow cylindrical microstructures called tubules. These unusual lipid based microstructures can be the starting point for many novel applications including drug delivery, producing mildew resistant, anti-corrosive or anti-fouling paints, and lightweight, crack-resistant ceramics.

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Project Title: Binocular Stereo Segmentation
Funding Agency:
Classifiers: Information Processing, Sensory Processing, Visual Perception

Dr. Schwartz has developed a technique of image processing for computing the distances between objects in stereo images. This algorithm, which is very fast and suitable for parallel processing, is based on an interpretation of the neuroanatomy of the brain. The new algorithm works by matching image data from small corresponding regions of left and right eye views, and was inspired by the way thr brain represents visual images. It is now being used to help align pairs of cameras in robotic systems.

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Project Title: Photoconversion: A Future Energy Technology Option
Funding Agency: DoE
Classifiers: Biochemical Systems, Photoconversion

Research includes studies of natural photosynthesis for the purpose of harnessing or mimicking processes in order to produce fuels and chemicals. Areas of interest are primary and secondary processes of photosynthesis, including reaction center and water-splitting studies; semiconductor particles; donor/acceptor molecules; enzyme immobilization; catalysis synthesis for electrochemical CO2 pumping and reduction, photodetoxification, and other aspects of artificial photosynthesis.

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Project Title: Experimental Data Base Generation for Computational Modelling
Funding Agency: Office of Naval Research
Classifiers: Information Processing, Neural Processes, Pattern Recognition

The goals of the proposed research are to obtain physiological data from invertebrate nervous systems which can be used to support the development of new computational models of neural functioning. These can serve as the basis for pattern recognition and motor control algorithms.

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Project Title: Optoelectronics applications of photochromic bacteria.
Funding Agency: Venture Capital
Classifiers: Biochemical systems, photosensitve bacteria, photosynthesis.

Ms. Silvernail is managing this start-up company to develop and commercialize optoelectronic devices using photochromic proteins from bacteria. They use bacteria to grow protein, harvest protein, produce thin films, and make thin film devices. Proof of concept devices have been made, now in process of making prototype devices. They are using both photosynthetic center protein and bacteriorhodopsin, as present in retina. Applications will include detectors, memory devices, and spatial light modulators. Scien-

tific principals are Dr. Robert Birge, Syracuse University (315) 443-1900 (Connie Salveti, Admin.) and Dr. Steven Boxer, Stanford University (415) 723-4482.

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Project Title: Materials Science/Design Principles
Funding Agency: DARPA
Classifiers: adaptive, noise reduction, materials, structural systems, biochemical systems

Biologically derived physical properties. Using recombinatory DNA techniques to form 2D crystals with vibration energies suitable for optically detonated explosives and other interesting/unusual properties. Monolayer films for deposit on water surface to reduce surface generalted acoustic noise. Interested in any application where interesting properties of biological systems may be applied.

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Project Title: Biologically based visual systems
Funding Agency:
Classifiers: sensory systems, vision, information processing, neural networks

Dr. Tzanakou's research interests lie in the application of neural networks to the understanding of biological vision processes with the goal of building artificial vision systems that act and bahave as much as possible like the human vision system. They utilize an optimization procedure called ALOPLEX to provide a response feedback that somehow mimics the synaptic changes and are asking if such a process can influence and modulate the stimuli patterns so that they appear optimal.

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Project Title: Elastomeric Polypeptide Biomaterials
Funding Agency: Office of Naval Research
Classifiers: Materials

The aim of this research is to establish the fundamental efficiency of polypeptide elastomeric biomaterials to function in free energy transduction. This will provide an understanding of the potential application of these materials as sensors and transducers of interest to the Navy as well as provide basic design principles for protein folding and assembly. A second major objective is to achieve microbial biosynthesis of the repeating sequences relevant to elastomeric polypeptides to facilitate design modifications and for econoomical preparation of the materials.

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Project Title:
Funding Agency:
Classifiers: Locomotion, Flight, Drag Reduction

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Project Title: Natural Composites
Funding Agency:
Classifiers: Materials, Composite

Dr. Vincent is a leading researcher in the structure-property relationships of biological materials. He conducts research into natural composite materials such as the physical properties of nacre and the composite design of insect cuticle.

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Project Title: Olfactory Sensors
Funding Agency: U.S. Army, NSF
Classifiers: Sensory Systems, Biochemical Sensing, Olfactory

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Project Title: Systems Biology
Funding Agency:
Classifiers: Sensory Systems, Biochemical Sensors

Dr. Vodyanoy leads three programs of relevance to bionics. The Membrane Electrochemistry Program focuses on physical-chemical properties of membrane structures associated with transmembrane charge transport and energy transduction. The goal is to provide a fromework for sensor design based on biological principles. The Odorant Discrimination Program seeks to characterize the molecular mechanisms associated with the detection and recognition of chemicals by olfactory receptor neurons and other chemosensory receptors of vertebrates. The Vestibular Transduction Program seeks to understand fundamental biophysical and biochemical mechanisms governing the operation of vestibular system receptors.

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Project Title:
Funding Agency:
Classifiers: Bionics

Dr. von Gierke was a principal figure in the Air Force Bionics programs of the 1960s and 1970s. He is now semi-retired, working part time for the Biodynamics and Bioengineering Division, and remains a proponent of the concept of translating engineering principles from nature to artificial systems.

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Project Title: Mechanical Design in Organisms
Funding Agency: Self
Classifiers: Materials, mechanics, locomotion.

Dr. Wainwright has been studying the mechanics of postural and locomotor systems and their materials in plants and animals for over 25 years. In this pursuit, he has studied static and dynamic mechanical properties of biostructures and has studied the design of systems that make their constituent materials and systems suitable or optimal for function. He has collaborated with Dr. Wilson at Duke who designed a pneumatic robotic manipulator inspired by elephant trunks and squid tentacles. He has worked for the Navy to help understand the kinematics of dolphin swimming and his student has deduced the structure of whale blubber and its role in swimming. He is also under contract to Wright Patterson Materials Lab in their study of certain design features of biocomposites as models for lightweight, stiff aerospace materials.

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Project Title: Marine Cement: Anatomy of a Natural Composite Material
Funding Agency: Office of Naval Research
Classifiers: Mechanisms, Attachment/Bonding Mechanics

The objective is to examine in detail the molecular structure of the marine mussel adhesive with the goal of understanding why this natural fiber-filled resin is such a successful cement in marine environments. The unique chemical and physical stability of these adhesives and varnishes is imparted by quinone-tanning, an oxidative process that leads to the polymerization of DOPA-containing and other proteins. Commercial products have been developed based upon this naturally occurring protein adhesive.

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Project Title: The Adaptive Suspension Vehicle
Funding Agency: None (formerly DARPA)
Classifiers: Locomotion, Ambulation, Mechanisms, Manipulators

6-legged walking vehicle - prrof of concept for a transportation vehicle in very rough terrain. Vehicle models and responds to previously unknown terrain.

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Project Title: A Perceptual Components Architecture for Digital Video
Funding Agency: NASA RTOP
Classifiers: Sensory Systems, Vision

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Fax:

Project Title: Sea Urchin Crystalline Composite Material
Funding Agency:
Classifiers: Materials, Biomineralization

Weiner and his co-workers are seeking to uncover the clues to how the sea urchin is able to generate tough, fracture resistant, single crystals of calcite, a normally brittle materials. They has discovered the role of proteins in modification of the microstructure of the crystal. Using x-ray diffraction, they also have determined that domains within the crystals are smaller and less precisely aligned that similar synthetic crystals of calcite. The investigators hope that this research will lead to new processes to control crystal growth in synthetic materials production.

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Project Title: Neuroengineering
Funding Agency:
Classifiers: Information Processing, Neural Processing

Neuroengineering, though funded at only about $1.2 million/year at NSF, remains an area of great interest to NSF, and they have been seeking to foster collaboration with the aerospace community. The NSF emphasis is on neural control. Neurocontrol is the use of neural networks to directly output the signals which control motors or actuators, etc. NSF has jointly sponsored a workshop on aerospace applications of neurocontrol at the Univ. of Washington, Oct. 23-25, 1990. Potential applications include robot control, manufacturing and process control, real-time control of the National Aerospace Plane or autonomous vehicles, and large scale communications systems.

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Project Title: Biomolecular Materials
Funding Agency:
Classifiers: Materials

Dr. Wickman organized an NSF Panel Workshop on Biomolecular Materials, Oct. 10-12, 1990 in Washington, DC. This workshop sought to identify important scientific research opportunities at the interface between materials research and biology. Increasing attention is being paid to molecular details of materials derived from nature and to man-made materials that possess electronic, mechanical, optical structural or other properties inspired by phenomena found in nature. The Workshop will produce a report summarizing its deliberations for distribution to the scientific community.

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Project Title: Electrochemistry of [Coupling Channels] in the Eye of the Fly
Funding Agency: Office of Naval Research
Classifiers: Sensory Systems

The main objective is to understand the function and the molecular mechanisms of photoreceptors coupling. Such research will add to an understanding of cell communication and signal transduction. This will lead to a conceptual framework for design of biosensors.

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Project Title:
Funding Agency: DARPA
Classifiers: Mechanisms, Manipulators, Locomotion, Ambulation, Sensory systems, tactile.

Dr. Wilson has conducted several interdisciplinary projects in the area of fluid activated robotic manipulators and actuators that imitate the form and function of flexible animal appendages. These include models of elephant trunks and squid tentacles for pneumatically controlled manipulators, models of jumping spiders, and models of insect antennae for tactile probes.

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Project Title: Engineering derivatives from nature for aerospace applications.
Funding Agency: NASA Ames Research Center
Classifiers: Bionics

Current project seeks to identify promising areas for aerospace applications of bionics. Projects includes a literature survey of the field of bionics to document contributions and current research activity. A workshop will address the specific areas of bionics of most potential utility in aerospace applications. An annotated bibliography and a directory of researchers in the field of bionics will be produced.

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Project Title: Bioacoustics Signal Classification
Funding Agency: ONR
Classifiers: Sensory Systems, Acoustic

Dr. Yost has organized a Conference on Bioacoustic Signal Classification to conceptualize the critical research issues and methodologies appropriate for investigation under the ONR 1991 Advanced Research Initiative. Particular emphasis is given to biological solutions to the signal classification problem.

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Project Title: Signal Transduction in Electroreceptors
Funding Agency: Office of Naval Research
Classifiers: Sensory Systems, Electromagnetic

The goal of this research is to determine the mechanisms underlying electroreception in skin cells of a certain species of fish, Sternopygus. This includes measurements of the kinetics of ion concutances and voltage sensitivities of the recpetor cell membranes. This research would provide the basis for the development of minature electronic sensors of potential use to the military and civilian sector.

APPENDIX C

WORKSHOP AGENDA AND PARTICIPANTS

AEROSPACE APPLICATION OF BIONICS

November 12-14, 1990
Kiawah Island Inn

Monday, November 12

7:00pm	RECEPTION	BRIGANTINE VERANDA
8:15 - 9:30pm	OPENING SESSION	BRIGANTINE 1
	• Welcome	D. Winfield
	• Role of Bionics in NASA's Breakthrough Technology Thrust	J. Anderson
	• Contributions of Bionics to Aerodynamics	D. Bushnell
	• Biomimetics in Support of NASA Technology Development	H. Frisch
	• Workshop Objectives and Logistics	D. Winfield

Tuesday, November 13

8:00 - 9:30am	PLENARY SESSION	CLUB CONFERENCE A-B
	BIONICS OVERVIEWS	
	• Biological Materials and Structures	S. Wainwright
	• Sensors and Information Processing	E. Tzanakou
	• Mechanics and Dynamics	J. Wilson
	• Biochemical Systems	M. Seibert
9:30 - 10:00am	Break	
10:00 - 2:00pm	WORKING GROUP SESSION 1	
	I. Materials and Structures	CLUB CONFERENCE A
	II. Sensory Systems and Information Processing	CLUB CONFERENCE B
	III. Mechanics and Dynamics	CLUB CONFERENCE C
	IV. Biochemical Systems	CLUB CONFERENCE D
	Deli Lunch During Working Group.	

2:30 - 4:00pm	MID-PLENARY SESSION	CLUB CONFERENCE A-B

- Reports from two working groups.
  30 minutes plus discussion.
  To include:
  promising ideas, observations, concepts, questions to be addressed.

Each group encouraged to assemble a brief set of audio-visuals to illustrate current work or new concepts.

Wednesday, November 14

8:00 - 9:30am	MID-PLENARY SESSION (Cont'd.)	CLUB CONFERENCE A-B

Remaining two working groups report (see above).

9:30 - 10:00am	Break	
10:00 - 12:00	WORKING GROUP SESSION 2	
	I. Materials and Structures	CLUB CONFERENCE A
	II. Sensory Systems and Information Processing	CLUB CONFERENCE B
	III. Mechanics and Dynamics	CLUB CONFERENCE C
	IV. Biochemical Systems	CLUB CONFERENCE D
12:00 - 1:00pm	Lunch	
1:00 - 3:30pm	FINAL PLENARY SESSION	CLUB CONFERENCE A-B

- Reports from each working group.

  To include:
  Most promising concepts with description of the biology, anticipated NASA application, projected benefits and research required.

- Summary of conclusions and development of recommendations.

4:00 - 5:30pm	STEERING COMMITTEE MEETING	CLUB CONFERENCE C

- Synthesis of workshop results.
- Action items for follow-up.

WORKSHOP ATTENDEES

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AEROSPACE APPLICATIONS OF BIONICS
A NASA Sponsored Workshop

November 12-14, 1990

INTRODUCTION

Nature and natural systems have always been an inspiration for engineering creativity. Many of the machines we design and build share a commonality of functional purpose with systems which have evolved in nature. Yet, these natural systems are almost universally better optimized and more efficient than any artificial systems. While there have been many advances made possible through the study of nature, there are undoubtedly innumerable opportunities for further technological advances by adapting design methods employed in nature.

This approach of deriving engineering principles from nature and applying these principles to artificial systems has been called "bionics" ("biomimetics" has been used as well). Aeronautics and hydronautics have taken many design lessons from birds and fishes for efficient propulsion and drag reduction. Bionics, as a formal program, was established and actively pursued as a result of the work by the Air Force in the early 1960s. Bionics was sporadically pursued by various organizations through the 60s and 70s; while current programs are not organized formally into "bionics", there continue to be many projects with a bionics objective.

Bionics may be a fruitful area to identify opportunities for advanced development leading to breakthrough technologies of interest to NASA for future aerospace missions. The NASA **Ames Research Center** and the NASA **Office of Aeronautics, Exploration and Technology** are sponsoring a survey and workshop on the Aerospace Applications of Bionics. Organized by the **Research Triangle Institute,** this workshop will convene bionics researchers, NASA technologists and NASA program managers for two and one-half days of presentations and discussions. While aeronautics applications of bionics will be included, the workshop will focus predominantly on aerospace technologies. Primary topics will include materials and structures, sensory systems and information processing, locomotion/propulsion, fluid dynamics, mechanisms, and biochemical systems.

WORKSHOP OBJECTIVES

The objectives of this workshop are:

- Establish a dialogue between NASA participants and bionics researchers through which NASA technology needs and relevant designs from nature can be investigated.
- Identify and develop recommendations for promising areas for bionics-derived technology research of interest to NASA.
- Brainstorm ideas for relevant bionics research in light of projected NASA space capability requirements.

These objectives will be accomplished through a mix of invited presentations, both overviews and specific technologies, and ample periods of both small group and large group discussions. Breakout groups will be asked to generate ideas, concepts, and recommendations within four topic headings:

* Materials/Structures
* Sensory Systems/Information Processing
* Locomotion/Dynamics
* Biochemical Systems

Each of these is discussed in more detail below. Generic, breakthrough technologies will be emphasized; we will not focus on specific NASA missions. However, common constraints for all new technologies for NASA aerospace applications are weight, size, power consumption, and reliability. Nature optimizes systems around these same parameters; promoting fertile ground for breakthrough concepts. To give the non-NASA participants some perspective on the type of mission applications, we have compiled an overview list which is attached as Appendix A. Also, as part of this study, we have developed a draft taxonomy (Appendix B) to serve as a classification scheme for the various natural engineering systems. This will be revised and comments are welcome.

LOCATION

The workshop will be held at the Kiawah Island Inn on Kiawah Island, approximately 20 miles south of Charleston, SC. This resort has received numerous awards and citations for their preservation of the natural environment of a barrier island. The ambiance is informal, restful and unobtrusive, allowing nature itself to take credit for the island's beauty. It is truly an appropriate setting for a meeting on bionics, and we are confident this will foster the creative dialogue so important to a successful workshop.

For this meeting, we have secured a very attractive group rate of $75.00 per night single or double. Reservations should be made directly with the Inn using the enclosed Reservation Sheet or by calling (803) 768-2121. Air service is into Charleston, SC, and you may make reservations for a round-trip limo service on the Reservation Sheet as well.

While at Kiawah, you may wish to take advantage of the many recreational opportunities, whether that be golf, tennis, fishing, a safari ride, bicycling or, simply, a walk on the ten miles of natural beach. And historic Charleston is only minutes away. The enclosed brochure gives more information on Kiawah Island.

WORKSHOP CONTACTS

You may obtain more information on the scope and objectives of this workshop by contacting one of the following:

Mr. Dan Winfield Research Triangle Institute P.O. Box 12194 Research Triangle Park, NC 27709	Phone: (919) 541-6431 Fax: (919) 541-6221
Mr. John Anderson NASA Headquarters Code RS Washington, DC 20546	Phone: (202) 453-2756 Fax: (202) 426-7288
Dr. Michael McGreevy NASA Ames Research Center Mail Stop 241-1 Moffett Field, CA 94035	Phone: (415) 604-5784

WORKSHOP TOPICS

Bionics is perhaps the archetype of an interdisciplinary field of research, and research items falling under this heading do not lend themselves to classification. As a key element in a new NASA thrust, the workshop should include any bionics concepts of relevance to NASA. Thus the workshop topics are not only cross-disciplinary, but also extremely diverse, touching on all aspects of biological systems.

To provide coverage of such a broad field, the workshop will devote roughly equal time to plenary and breakout sessions. The breakout sessions will first be asked to brainstorm new concepts for general bionics-derived technology research, then to evaluate these with regard to NASA technology requirements and develop research plans for priority opportunities. Plenary

sessions will allow critique and discussion by all attendees. Brief discussion of the specific breakout topics follows.

Materials and Structures

The efficiency and performance of all engineering systems is limited, in part, by the materials of which they are produced. Nature has developed means to produce structures of widely varying physical properties (using essentially the same starting materials) by controlling the hierarchical structure to very fine levels. Structural designs in nature are optimized for specific functions within their environments. The study of laminated and fiber reinforced, natural composites, cellular solids, biomineralization, and structural frames offer opportunities for advanced development of strong, lightweight materials and efficient structures for the space environment.

Researchers at the University of Washington have already achieved a 40% increase in fracture toughness of boron carbide-aluminum cermets by modeling them after the microstructure of abalone shells. The beetle exoskeleton seems to offer an excellent model to achieve high stiffness in thin cross sections of lightweight material. How do cellular organisms use organic membranes to control the crystallization of inorganic materials? The answers may provide us tremendous potential to make single crystals and organized composites or, alternatively, to use organisms to fabricate specialty materials. As the architecture and function of more complex biological systems, particularly membranes, becomes better known, novel concepts should influence the design and fabrication of molecular machines and electronic devices. Optical materials and structures may be another fruitful area. Polaroid Corp. is developing optical diffraction gratings based on the microstructure of butterfly scales for application to multicolor holograms. The surface texture of the moth eye has been shown to be anti-reflective (a defense against predator detection), and this texture has been used on optical disks.

Biosynthetic or bioderived materials offer a new frontier for investigation of unique thermoplastics, fibers, adhesives, elastomers, etc. For example, researchers at Natick have cloned the spider silk gene and are selectively modifying composition to effect structural changes in the silk fiber. Fiber spinning of this recombinant silk protein will involve mimicking the natural process used by the spider.

Can biosurfaces, such as those of marine animals, be used to prevent biofouling in closed loop life support systems? Will some of the spatial structures in nature give insight to new structural designs for efficiency in microgravity? The questions to be considered are quite boundless, and the potential payoff of advanced research is promising indeed.

Sensory Systems and Information Processing

Nature presents some of the most adaptive, precise, and reliable sensors known. Already, engineers have adopted strategies from nature in designing better sensors, as well as the information processing strategies which accompany them. Mead's group at Caltech has implemented an artificial retina on silicon, for improved speed and efficiency in machine vision processing, and also an electronic cochlea useful for auditory perception. Engineers at Pisa, MIT, Utah, Florida and elsewhere have developed tactile sensors for robots based on human skin. Accurate biochemical sensors, which model the tongue and nose, are being designed by Persaud at the University of Manchester. Other, less familiar animal sensors may well lead to innovative sensing techniques in other regimes as well. The pit viper has a precise sense based solely on the infrared spectrum, as do moths. The "eyeless" shrimp senses blackbody radiation at 350°C around deep thermal vents. While some of these sensors may not outperform current technology, they are very efficient in terms of size and power requirements. Very sensitive electromagnetic field detectors are used for navigation and prey localization by many birds and cartilaginous fishes. Dolphins and bats employ sophisticated sonar to similar ends. Nature also provides insight into the design of neural networks, which are useful for understanding parallel computer architectures, pattern recognition, data compression, and stable control systems.

The aerospace implications of bionics may be far-reaching. For example, Brooks, at MIT, is integrating sensors and distributed control (another bionics application) into autonomous micro-robots which can scramble over rough terrain. These robots are inexpensive (expendable), robust, and can perform all sorts of tasks in hazardous conditions. For example, they can explore, collect data, and perform sample analysis using a variety of biochemical, electromagnetic, visual, acoustic, and tactile sensors. The same principles can be applied to make larger spacecraft more efficient and reliable: biochemical sensors can automatically check for contaminants or fuel leaks, speech perception can be used to simplify tasks for human operators, and neural networks gathering information from different sensors can provide real-time decision making, guidance and control. The design of bionic transducers may find

application in areas other than sensor design as well. Unraveling and applying the principles of natural processing stands to greatly enhance current techniques.

Mechanics and Dynamics

Mechanics and dynamics will also receive important consideration during the workshop and in the final report to NASA. These engineering fields are being interpreted to include mechanical design, mechanisms, actuators, hydrodynamics, aerodynamics, propulsion and locomotion, balance, and manipulation. NASA is interested in learning more from other experts about how natural biological systems have adapted and evolved to produce high-energy-density, dexterous, fast and strong manipulators, mechanisms for walking, efficient designs for flying and swimming, and specialized biological machines for unique tasks. Surfaces, actuators/servos and seals should be evaluated along with the other mechanisms and machine elements.

Some potential applications of improved NASA mechnical and aerodynamics engineering designs which could be based on natural systems include:

- walking or handhold maneuvering in space
- transport across planetary and lunar surfaces
- space robots, manipulators and maneuvering vehicles
  -- bearings, joints, links, actuation, mobility
- surface drilling and mining
- reentry aerodynamics, planetary atmospheric flight
- low mass propulsion systems
- manipulation in confined space vehicles or habitats
- grasping objects in microgravity
- mechanics of multi-arm coordination
- reactionless application of forces
  -- anti-rotation or anti-translation designs for tool use
- mechanisms for safety and failure prevention
- pumping, compressing, and fluid transport systems
  -- e.g. air convection, fuel delivery plumbing
- fastening and attachment -- e.g. spacecraft coupling
- lubricating valves
- damping and shock absorbing mechanisms
  -- e.g. for lunar lander
- tethers

Biochemical Systems

The term "biochemical system" is used loosely in this context to include any systems approaches which involve biochemistry or physiology. There may be limited overlap to some of the above areas (appropriately addressed from a different direction), but will also include energy conversion and storage, oxygen generation, thermal management, bioluminescence, control of membrane permeability, biosensors and biosurfaces.

WORKING GROUP SESSION ONE

PRODUCT

1. Key contributions of bionics. Confirmed examples of technology developed based upon the study of nature.

2. Existing bionics R&D with potential aerospace applications.

3. New concepts where further research into biological systems offer promise for technical advancement.

For items 2 and 3, provide:

- Brief description of research or new concept.
- Potential applications and benefits.
- Current knowledge to support the promise of the concept.

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WORKING GROUP SESSION ONE

GUIDELINES

Session One is to be a brainstorming session. However, ideas should be considered in relation to the following guidelines:

- **Must have a basis in nature.**
- **Priority on potential for breakthrough technology (as opposed to incremental).**
- **Anticipate relevance to NASA, but do not eliminate because the NASA need is not apparent.**
- **Sufficient knowledge to expect progress in reasonable timeframe.**
- **Cost not a factor at this time.**

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Specific attention will be given to applications for closed loop life support systems including methods for air revitalization, water reclamation, waste processing, and environmental sensing. Biological wastewater treatment is used widely, and plants have been used to purify both water and air. Can we learn the exact purification mechanisms and apply this knowledge to design of improved artificial systems? Can we develop biochemical sensors for use as environmental sensors to control regenerative life support systems? Biosurfaces of marine animals may help prevent biofouling in these systems. Are there unique methods which animals employ for thermal management that may aid design of thermal control systems for portable life support systems used during extravehicular activity?

Plants and animals have developed specialized, highly optimized means of energy conversion, storage and utilization. Biomimetic photosynthesis for solar energy conversion systems is being researched. Muscles fiber energetics may be a promising area for design of internally powered actuators. Can we employ the enzymes used for bioluminescence for low energy lighting systems?

Within this area we will also seek to address some of the health care concerns involved in long duration spaceflight. Mars missions will take two years, future missions even longer. Is hibernation a possibility? Black bears maintain bone calcium and density during denning, while recumbent humans and humans in microgravity lose bone mass. Can we develop a countermeasure to prevent loss of bone mass during spaceflight? We will also look for similar bionics connections that may help address other physiological effects of microgravity, e.g. red blood cell loss, cardiovascular deconditioning, muscle atrophy, space motion sickness, and immunological changes. In this area, as in the other three topics, there is much that we can learn from nature about engineering principles and design which, once harnessed, can advance current man-made systems.

NASA MISSION APPLICATIONS

SURFACE EXPLORATION

Rovers

- Mobility
- Guidance, hazard avoidance, terrain sensing
- Power systems
- On-board autonomy, failure recovery

Sample acquisition, analysis and preservation

- Multispectral imaging and ranging to identify sample location
- Autonomous acquisition (pick, drill, etc.)
- Multipurpose end-effector
- Elemental, chemical and physical property analysis
- Containment concepts

Autonomous lander

- Guidance, navigation and control
- Hazard detection and avoidance
- Mechanization/mechanical systems

Surface Power

- Power generation, regenerative fuel cells, photovaoltaic, solar dynamic systems
- Energy storage, electrical/thermal/chemical
- Electric power management

Photonics

- Optical processing
- Fault tolerant networks
- Autonomous planetary systems
- Spatial Light modulators

IN-SPACE OPERATIONS

Autonomous Rendezvous and Docking

- Guidance, navigation and control
- Sensors for short and long range, laser, millimeter wave radar, video image recognition system
- Mechanisms, high reliability and autonomy, mass and power restrictions

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Assembly and construction

- Construction concepts, high load carrying mechanisms
- Large area welding/bonding
- Strong, lightweight permanent joints
- Telerobotic manipulation, large scale
- Space crane concept

Resource processing pilot plant

- Materials handling and processing, telerobotics
- Separation processes, mechanical/electrochemical
- Materials analysis
- Oxygen production
- Metals production

Optical communications

- Diffraction-limited laser transmitters
- Precision pointing systems

Cryogenic fluid depot

- Long term storage of cryogens
- Transfer of cryogenic fuels
- Robotic manipulation

Space nuclear power

- Refractory metal reactor
- Thermoelectric magnetic pump
- Thermal to electric energy conversion
- Heat rejection systems

MATERIALS AND STRUCTURES

Space durable, dimensionally stable materials
Light alloys and intermetallics
Advanced metal matrix composites
Ceramic matrix composites
Polymer matrix composites
Processing and joining
Seals and lubricants
Coatings
Polymer films
Insulation
Thermal protection concepts
Space structural concepts
Dynamics and control of large space structures
Leading edges/nose caps
Actively cooled concepts
Cryogenic tank structure
Seals

PRECISION SEGMENTED REFLECTORS

Lightweight, thermally stable precision surfaces
Truss structure
Advanced magnetic suspension actuators
Deformable surfaces
Control systems, sensors and actuators

HUMANS IN SPACE

EVA and on-surface suits

- Materials
- Joint designs
- Coatings
- Waste management
- Portable life support system
- Mobility aids
- Gloves and end effectors
- Thermal control

Regenerative life support

- Air revitalization
- Water reclamation
- Waste management
- Environmental sensors
- Closed ecological life support system

Medical Care

- Radiation protection
- Countermeasures, bone and muscle maintenance, cardiovascular conditioning
- Environmental health system
- Sensors

Space human factors

- Man-machine interfaces
- Display technologies
- Telerobotic control

AERONAUTICS

- Drag reduction
- Low or high density atmospheric flight

ADVANCED MISSIONS

Microspacecraft
Microrovers
Tether systems
Aerobraking

WORKING GROUP REPORT FORMAT

Working Group Co-Moderators are responsible for report, but anyone or a mix of people may give the report.

Report should give past contributions first as a quick overview.

Current R&D and new concepts should be organized according to sub-topics.

Reporters are encouraged to use illustrations (slides, viewgraphs, drawings), however, accompanying presentations should be brief and to the point.

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WORKING GROUP SESSION TWO

GUIDELINES

The NASA personnel will play a larger role to examine the concepts in view of projected technology needs.

However, include true breakthrough opportunities, even if the NASA connection is tenuous.

Relative prioritization should be made so that the group narrows to 4 to 6 concepts. Factors to consider include:

- **Likelihood of success**
- **Breadth of technical impact (i.e., many applications)**
- **Potential benefit to NASA**
- **Resource/time requirements.**

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WORKING GROUP SESSION TWO

PRODUCT

Final list of most promising bionics opportunities of relevance to NASA.

For each opportunity provide:

- **Brief description**
  - * **Basis in nature**
  - * **Applications R&D**
  - * **Projected NASA benefits**
- **Brief outline of research plan**
  - * **What needs to be done?**
  - * **How long?**
  - * **Resources?**

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13. ABSTRACT *(Maximum 200 words)*

Research Triangle Institute has conducted a study of past contributions and current research in the field of bionics or biomimetics, defined as the derivation of engineering principles from natural systems and the application of these principles to improved technological systems. This report includes a history of bionics, focusing on research programs and engineering contributions from the past three decades. Relevant literature has been compiled into an Annotated Bibliography, and a Directory of bionics researchers is included. A workshop was conducted of leading bionics researchers and NASA technologists to identify opportunities for accelerated bionics research topics applicable to aerospace systems. Promising research opportunities are discussed in the areas of materials, structures, sensors, information processing, robotics, autonomous systems, life support systems, and aeronautics. Evolutionary forces have resulted in biological systems which are small and lightweight and which demonstrate robust performance while minimizing energy requirements. For these reasons we can expect that adaptation of biological design principles will offer advantages for future space technology. Specific technologies expected to benefit from this research approach include composite materials, adaptive (smart) materials, neural networks, miniature sensors (optical, tactile, acoustic, etc.), biochemical sensors, signal processing, artificial photosynthesis, biomolecular electronics, and robotic actuators, end-effectors and control systems.

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