SYSTEMS AUTONOMY

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TECHNOLOGY FOR FUTURE NASA MISSIONS

AN AIAA/OAST CONFERENCE
ON CSTI AND PATHFINDER

12-13 SEPTEMBER, 1988

WASHINGTON D.C.
SYSTEMS AUTONOMY PROGRAM

ENABLING TECHNOLOGIES FOR THE NATIONAL SPACE CHALLENGES

THE EVOLUTION OF MACHINES THAT THINK

- LOWERS MISSION OPERATIONS COSTS
- INCREASES PRODUCTIVITY
- RENDERS HIGHER QUALITY DECISIONS
- MAINTAINS TECHNOLOGICAL LEADERSHIP
END-TO-END SYSTEMS INTEGRATION OF HUMANS, INTELLIGENT SYSTEMS, AND FACILITIES
SYSTEMS AUTONOMY PROGRAM
WHY INTELLIGENT AUTONOMOUS SYSTEMS

REDUCE MISSION OPERATIONS COSTS

• AUTOMATE LABOR INTENSIVE OPERATIONS

INCREASE MISSION PRODUCTIVITY

• AUTOMATE ROUTINE ONBOARD HOUSEKEEPING FUNCTIONS

INCREASE MISSION SUCCESS PROBABILITY

• AUTOMATE REAL-TIME CONTINGENCY REPLANNING
DESCRIPTION OF INTELLIGENT AUTONOMOUS SYSTEMS

CHARACTERISTICS

KNOWLEDGE-BASED SYSTEMS
• DYNAMIC WORLD KNOWLEDGE ACQUISITION, UNDERSTANDING, AND EXECUTION OF COMMAND FUNCTIONS
• RELIABLE DECISIONS IN UNCERTAIN ENVIRONMENTS
• LEARNING ABILITY
• ALLOWS "GRACEFUL" RETURN TO HUMAN CONTROL

CAPABILITIES

GOAL-DRIVEN BEHAVIOR
• COMMUNICATE AT HIGH LEVELS WITH HUMANS AND OTHER MACHINES

"COLLABORATIVE" HUMAN-MACHINE INTERACTIONS
• RECOGNIZE AND RESOLVE COMMAND ERRORS

SELF-MAINTENANCE
• OPERATE AUTONOMOUSLY FOR EXTENDED PERIODS OF TIME
SYSTEMS AUTONOMY PROGRAM
HOW DO WE GET THERE - PROGRAM ELEMENTS

ONGOING CORE TECHNOLOGY
- PLANNING AND REASONING
- OPERATOR INTERFACE
- SYSTEMS ARCHITECTURE

RESEARCH PRODUCTS

TECHNOLOGY FOCUS

PERIODIC DEMONSTRATIONS
- LONG TERM EVOLVING TESTBED
- SHORT TERM SPECIFIC DOMAIN DEMOS

IN SPACE CONSTRUCTION

SPACE STATION

SHUTTLE LAUNCH DIAGNOSTICS

SHUTTLE MISSION CONTROL
SYSTEMS AUTONOMY PROGRAM

TECHNICAL CHALLENGES

• **REAL-TIME** KNOWLEDGE-BASED SYSTEMS

• **DYNAMIC** KNOWLEDGE ACQUISITION AND UNDERSTANDING

• **ROBUST** PLANNING AND REASONING

• **COOPERATING** KNOWLEDGE-BASED SYSTEMS

• **VALIDATION** METHODOLOGIES
SYSTEMS AUTONOMY PROGRAM - TECHNOLOGICAL CHALLENGES

A. WHERE WE ARE TODAY

REAL-TIME KNOWLEDGE-BASED SYSTEMS
- NO PARALLEL SYMBOLIC-NUMERIC PROCESSORS
- SLOW SPECIAL-PURPOSE HARDWARE (1 GBYTE MEM, 5 MIPS)
- PROTOTYPING S/W SHELLS (ART, KEE, KNOWLEDGECRAFT)
- DIAGNOSIS AND PLANNING DECISIONS IN 1-10 MINUTES

DYNAMIC KNOWLEDGE-ACQUISITION & UNDERSTANDING
- NO AUTOMATED EXPANSION OF K-B
- SMALL STATIC PRE-PROGRAMMED K-B
- DEC "XCON" LARGEST (5000 RULES, 2000 COMPONENTS)

ROBUST PLANNING AND REASONING
- HEURISTIC RULES ONLY, NO CAUSAL MODELS
- PRE-MISSION PLANNING (NO REAL-TIME REPLANNING)
- DIAGNOSIS OF ONLY ANTICIPATED SINGLE FAULTS
- "FRAGILE" NARROW DOMAINS (RAPID BREAKDOWN AT K-B LIMITS)

COOPERATING KNOWLEDGE-BASED SYSTEMS
- SINGLE STANDALONE DOMAIN SPECIFIC SYSTEMS
- HUMAN INTERACTION ONLY, NO INTELLIGENT SYSTEMS INTERACTION

VALIDATION METHODOLOGIES
- CONVENTIONAL TECHNIQUES FOR ALGORITHMIC SYSTEMS
OPERATOR INTERFACE

DISPLAYS

CONTROLS

OPERATORS AND EXECUTION STATUS

SIMULATOR

MONITOR

KNOWLEDGE BASE

TASK PLANNING & REASONING

DIAGNOSER

INTERROGATIONS

PLANNER

EXECUTOR

SENSING & PERCEPTION

INTERNAL OBSERVABLES

CONTROL EXECUTION

EXTERNAL OBSERVABLES

STATE CHANGES

EXECUTION COMMANDS

SYSTEM ARCHITECTURE & INTEGRATION
SYSTEMS AUTONOMY PROGRAM DEMONSTRATION
SYSTEMS AUTONOMY DEMONSTRATION PROJECT (SADP)

OBJECTIVES
DEMONSTRATE TECHNOLOGY FEASIBILITY OF INTELLIGENT AUTONOMOUS SYSTEMS FOR SPACE STATION THROUGH TESTBED DEMONSTRATIONS

- 1988: SINGLE SUBSYSTEM (THERMAL)
- 1990: TWO COOPERATING SUBSYSTEMS (THERMAL/POWER)
- 1993: HIERARCHICAL CONTROL OF SEVERAL SUBSYSTEMS
- 1996: DISTRIBUTED CONTROL OF MULTIPLE SUBSYSTEMS

PARTICIPANTS AND FACILITIES

PARTICIPANTS
- AMES RESEARCH CENTER
- JOHNSON SPACE CENTER
- LEWIS RESEARCH CENTER
- MARSHALL SPACE FLIGHT CENTER
- INDUSTRY

FACILITIES
- ARC INTELLIGENT SYSTEMS LABORATORY
- JSC INTELLIGENT SYSTEMS LABORATORY
- JSC THERMAL TEST BED
- LeRC POWER TEST BED

SCHEDULE

<table>
<thead>
<tr>
<th>Year</th>
<th>TCS</th>
<th>TCS/Power</th>
<th>Hierarchical Multiple Sys.</th>
<th>Distributed Multiple Sys.</th>
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<tbody>
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1988 DEMONSTRATION SYSTEMS AUTONOMY DEMONSTRATION PROJECT
SPACE STATION THERMAL CONTROL SYSTEM (TEXSYS)

OBJECTIVES
IMPLEMENTATION OF AI TECHNOLOGY INTO THE REAL-TIME DYNAMIC ENVIRONMENT OF A COMPLEX ELECTRICAL-MECHANICAL SPACE STATION SYSTEM - THE THERMAL CONTROL SYSTEM.

- REAL-TIME CONTROL
- FAULT DIAGNOSIS AND CORRECTION
- TREND ANALYSIS FOR INCIPIENT FAILURE PREVENTION
- INTELLIGENT HUMAN INTERFACE
- CAUSAL MODELLING
- VALIDATION TECHNIQUES

PARTICIPANTS AND FACILITIES

PARTICIPANTS
- AMES RESEARCH CENTER
- JOHNSON SPACE CENTER
- INDUSTRY: LEMSCO, ROCKWELL INTERNATIONAL, GEOCONTROL SYSTEMS, STERLING SOFTWARE

FACILITIES
- ARC INTELLIGENT SYSTEMS LABORATORY
- JSC INTELLIGENT SYSTEMS LABORATORY
- JSC THERMAL TEST BED

SCHEDULE

<table>
<thead>
<tr>
<th>Development</th>
<th>Requirements Definition</th>
<th>Design Definition</th>
<th>Integration V &amp; V</th>
<th>TCS Demonstration</th>
<th>Power System Interfaces</th>
<th>TCS/Power Demonstration</th>
<th>Analysis, Reporting</th>
</tr>
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# System Autonomy Demonstration Project

## TCS Functional Capabilities

### Prototype Objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>DEMO 1/87</th>
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<tbody>
<tr>
<td>Causal Models/Simulation</td>
<td>●</td>
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<tr>
<td>Limited Fault Diagnosis</td>
<td>●</td>
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### Demonstration Objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>1 6/87</th>
<th>2 9/87</th>
<th>3 12/87</th>
<th>4 2/88</th>
<th>5 5/88</th>
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<tbody>
<tr>
<td>Nominal Real-Time Control</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<tr>
<td>Fault Diagnosis and Correction</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<tr>
<td>Trend Analysis</td>
<td></td>
<td>●</td>
<td>●</td>
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<td>●</td>
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<tr>
<td>Intelligent Interface</td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
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<tr>
<td>Design Assistance</td>
<td></td>
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<td>●</td>
<td>●</td>
<td>●</td>
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<tr>
<td>Training Assistance</td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

**Knowledge Base Expansion**

- **1 6/87**: ●
- **2 9/87**: ●
- **3 12/87**: ●
- **4 2/88**: ●
- **5 5/88**: ●
SYSTEMS AUTONOMY PROGRAM - TECHNOLOGICAL CHALLENGES

B. WHERE WE NEED TO GO

REAL-TIME KNOWLEDGE-BASED SYSTEMS
• PARALLEL SYMBOLIC-NUMERIC PROCESSORS (100 GBYTES, 500 MIPS)
• NEURAL NETWORKS (BRAIN CELL EMULATION)
• LAYERED TRANSPARENT SW
• DIAGNOSIS AND PLANNING IN MILLISECONDS

DYNAMIC KNOWLEDGE ACQUISITION & UNDERSTANDING
• AUTOMATED K-B EXPANSION IN REAL-TIME (LEARNING)
• LARGE DYNAMIC DISTRIBUTED K-B

ROBUST PLANNING AND REASONING
• COMBINED HEURISTIC RULES AND CAUSAL MODELS
• REAL-TIME CONTINGENCY REPLANNING
• DIAGNOSIS OF UNANTICIPATED FAULTS
• SPECIFIC DOMAINS ON BROAD GENERIC K-B (GRACEFUL DEGRADATION)

COOPERATING KNOWLEDGE-BASED SYSTEMS
• HIERARCHICAL AND DISTRIBUTED SYSTEMS
• HUMAN AND INTELLIGENT SYSTEMS INTERACTION

VALIDATION METHODOLOGIES
• METHODOLOGY FOR EVALUATING DECISION QUALITY
• FORMAL THEORETICAL FOUNDATION
Architecture of an Autonomous Intelligent System

Operator Interface

Operator

Display

Controls

Execution Status

Simulator

Exections

Actualities

Nominal World

Direct World

State Changes

State Updates

Monitor

KNOWLEDGE BASE

- Dynamic World Model
- CAD/CAM Data Base
- System Configuration
- Heuristic Rules

Perceptor

Vernier Control

Internal Observables

Effecter

Commands

State Changes

Sensing & Perception

External Observables

System Architecture & Integration

Task Planning & Execution

World State

Nominal Plan

Planer

Replan Order

Nominal Plan

Executor

Anomalies

Inferred World State Updates

Diagnoser

State Observables
### SYSTEMS AUTONOMY
#### DEMONSTRATION PROJECT

**Technology Demonstration - Evolutionary Sequence**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1988</td>
<td>Automated Control Of Single Subsystem (&quot;Intelligent Aide&quot;)</td>
</tr>
<tr>
<td></td>
<td>Thermal Control System</td>
</tr>
<tr>
<td></td>
<td>* Monitor/real-time control of a single subsystem</td>
</tr>
<tr>
<td></td>
<td>* Goal and causal explanation displays</td>
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<tr>
<td></td>
<td>* Rule-based simulation</td>
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<tr>
<td></td>
<td>* Fault recognition/warning/limited diagnosis</td>
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<tr>
<td></td>
<td>* Resource management</td>
</tr>
<tr>
<td></td>
<td>* Reasoning assuming standard procedures</td>
</tr>
<tr>
<td>1990</td>
<td>Automated Control of Multiple Subsystems (&quot;Intelligent Apprentice&quot;)</td>
</tr>
<tr>
<td></td>
<td>Thermal Control System and Power System</td>
</tr>
<tr>
<td></td>
<td>* Coordinated control of multiple subsystems</td>
</tr>
<tr>
<td></td>
<td>* Operator aids for unanticipated failures</td>
</tr>
<tr>
<td></td>
<td>* Model-based simulation</td>
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<tr>
<td></td>
<td>* Fault diagnosis for anticipated failures</td>
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<tr>
<td></td>
<td>* Real-time planning/replanning</td>
</tr>
<tr>
<td></td>
<td>* Reasoning about nonstandard procedures</td>
</tr>
<tr>
<td>1993</td>
<td>Hierarchical Control of Multiple Subsystems (&quot;Intelligent Assistant&quot;)</td>
</tr>
<tr>
<td></td>
<td>* Multiple subsystem control: ground and space</td>
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<tr>
<td></td>
<td>* Task-oriented dialogue &amp; human error tolerance</td>
</tr>
<tr>
<td></td>
<td>* Fault recovery from unanticipated failures</td>
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<tr>
<td></td>
<td>* Planning under uncertainty</td>
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<tr>
<td></td>
<td>* Reasoning about emergency procedures</td>
</tr>
<tr>
<td>1996</td>
<td>Distributed Control Of Multiple Subsystems (&quot;Intelligent Associate&quot;)</td>
</tr>
<tr>
<td></td>
<td>* Autonomous cooperative controllers</td>
</tr>
<tr>
<td></td>
<td>* Goal-driven natural language interface</td>
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<tr>
<td></td>
<td>* Fault prediction and trend analysis</td>
</tr>
<tr>
<td></td>
<td>* Automated real-time planning/replanning</td>
</tr>
<tr>
<td></td>
<td>* Reasoning/learning, supervision of on-board systems</td>
</tr>
</tbody>
</table>
AUTONOMOUS SYSTEMS FOR ADVANCED LAUNCH SYSTEMS (ALS)
UNMANNED LAUNCH VEHICLES

NASA Ames Research Center
OAST/AF-Sponsored Research
AI Research Issues

- MACHINE LEARNING

- COOPERATING KNOWLEDGE-BASED SYSTEMS

- REAL-TIME ADVANCED PLANNING AND SCHEDULING METHODOLOGIES

- MANAGEMENT OF UNCERTAINTY

- AUTOMATED DESIGN KNOWLEDGE CAPTURE

- VALIDATION OF KNOWLEDGE-BASED SYSTEMS
MACHINE LEARNING

PREDICTIONS:

BAD

BETTER

GOOD

REMEMBER SEARCH MISTAKES

MODEL REFINEMENT

BEFORE

AFTER

SCHEDULING HEURISTICS

Technicians are in great demand

Histogram Pane
COOPERATIVE INTELLIGENT SYSTEMS
DESIGN KNOWLEDGE LOST WHEN DESIGNER LEAVES:

BUT WHY IS THIS APERTURE 2.7 mm?

CONSERVATION OF DESIGN KNOWLEDGE

WHY DID THEY CHOOSE SILVER INSTEAD OF STEEL?

ELECTRONIC NOTEBOOK

HUMAN USE:

PROCESS CONTROL
DIAGNOSIS
REPAIR
DESIGN

"(DRIVEN-BY $OBJECT MOTOR-3977)"

AUTOMATED USE:

DESIGN KNOWLEDGE
FROM 'LIFECYCLE'

DOMAIN
KNOWLEDGE

PHYSICAL
LAWS
Knowledge Intensive

- Strong prior theory
- One (or few) examples
- Verification by proof
- Learned concept must be useful

Knowledge Weak

- Weak prior model
- Many examples required
- Cannot prove theory
- Learned concept reflects intrinsic structure

EBG

Discovery Learning

Markov Models

Classification Models

Model Discovery

Supervised

Unsupervised

Series Prediction
The spectra show two closely related IRAS classes with peaks at 9.7 and 10.0 microns. This discrimination was achieved by considering all channels of each spectrum. AutoClass currently has no model of spectral continuity. The same results would be found if the channels were randomly reordered. The galactic location data, not used in the classification, tends to confirm that the classification represents real differences in the sources.
Evolution of Advanced Architectures for Real-time, On-board Teraflop Systems

Photonic Processors → Coarse-Grained Parallel Systems → Fine-Grained Architectures

Function:
- RT Image Processing
- Knowledge Understanding & Control
- Deep Reasoning

Technology Status:
- Applied R&D
- Development
- Basic Research

Technology Forecast:
- Late 1990s
- Current
- Early 2000s

Examples:
- KBS-controlled Photonic Processor
- SVMS (6-Processor System)
- Neural Networks Fuzzy Logic Computers & Controllers
Computer Architecture Research Issues
(Numeric/Symbolic Multiprocessor Systems)

- OPERATING SYSTEMS FOR REAL-TIME MULTIPROCESSING SYSTEMS IN A HETEROGENEOUS ENVIRONMENT
- VALIDATED COMPILERS AND TRANSLATORS FOR AN ADA-BASED MULTIPROCESSING ENVIRONMENT
- DATABASE MANAGEMENT FOR LARGE DISTRIBUTED DATABASES GREATER THAN 10GB
- AUTOMATED LOAD SCHEDULING FOR MULTIPROCESSORS
- REAL-TIME FAULT TOLERANCE AND RECONFIGURATION
- RADIATION HARDNESS WITH MINIMUM PERFORMANCE COMPROMISES
  - PROCESS TECHNOLOGY
  - VLSI/VHSIC TRADEOFFS
  - EFFICIENT COMPILERS AND INSTRUCTION SET ARCHITECTURES
SPACEBORNE VHSIC MULTIPROCESSOR SYSTEM (SVMS)
NASA/AF/DARPA COLLABORATION

SYSTEM CHARACTERISTICS
• PARALLEL ARCHITECTURE
  - 40-BIT SYMBOLIC PROCESSORS
  - 32-BIT NUMERIC PROCESSORS
• FAULT-TOLERANCE/AUTOMATED RECONFIGURATION
• OPTICAL INTERCONNECTS
• 25 MIPS SUSTAINED UNIPROCESSOR PERFORMANCE (40 MIPS TARGET)
  - MINIMUM OF 100 MIPS OVERALL SYSTEM PERFORMANCE
• DBMS FOR 16G BYTE MEMORY MANAGEMENT

PROCESS
VHSIC TECHNOLOGY
0.5μ TARGET
1.25μ BACKUP
RAD-HARD CMOS
10^5 RADS RADIATION RESISTANCE
NO SINGLE EVENT UPSETS

POTENTIAL SPACE
& AERONAUTICS APPLICATIONS
PHOTONIC PROCESSOR FOR REAL-TIME IMAGE UNDERSTANDING

OBJECTIVES

- REAL-TIME PHOTONIC PROCESSORS & TECHNIQUES for Terrain Analysis Tasks
- SYSTEM CONTROL & INTEGRATION OF EMBEDDED PHOTONIC PROCESSORS with integrated Numeric/Symbolic Multiprocessor Systems
- TECHNOLOGY FEASIBILITY DEMONSTRATIONS Focused on Planetary Rovers & Space Vehicles

BENEFITS

- Real-time, High Performance Parallel Processing for Image Processing & Understanding
- Fault Tolerance
- Low Power, Weight, and Size

POTENTIAL APPLICATIONS

Autonomous Landing
Sample Acquisition and Analysis
Sample Return

NASA AMES RESEARCH CENTER
OAST-SPONSORED RESEARCH
Knowledge-Based Systems

The tasks involved with an image-understanding-system can be divided into three layers as shown. The problem is to find a synergistic balance between all layers so that as knowledge of the image accrues, the reliability of the interpretation, recognition, and enhancement increases, while the amount of required computation decreases. Methodologies of organizing a knowledge-base of object and using a rule-based system to effectively search the knowledge-base and directing the computations of photonic processors are being developed. The majority of the domain specific knowledge for a task will reside in the interpretative level making the photonic processor a general purpose computing tool.
Backward-Error Propagation

Hopfield

J.J. Hopfield demonstrated the formal analogy between a net of neuron-like elements with symmetric connections, called a "Hopfield Net," and a material called a spin glass, which consists of a random mixture of both ferromagnetically and anti-ferromagnetically interacting spins, exhibiting both excite and inhibit its neighbors.

Adaptive Resonance Theory

RUMMELHART

There are many models in the real world that cannot be represented in a two-layer system such as the Hopfield model. For example, there exist no values that can be assigned to connection strengths to yield to appropriate outputs for the exclusive-OR (XOR) function. The solution is to introduce a third layer, called the hidden layer, between the input and output layer. This hidden layer creates the ability to incorporate an internal representation that facilitates difficult mappings between the two external layers.

Self-Organizing Maps

KOHONEN

One important organizing principle of sensory pathways in the brain is the placement of neurons in orderly, and often reflects some physical characteristics of the external stimulus being sensed. For example, at each level of the auditory pathway, nerve cells and fibers are arranged according to the frequency which elicits the greatest response in each neuron. Kohonen presents one such algorithm which produces self-organizing feature maps similar to those that occur in the brain.

Neocogniton

GROSSEBERG

Carpenter and Grossberg, in the development of their Adaptive Resonance Theory, have designed a net which learns new features when it is trained without supervision. The net is able to learn the first input as the exemplar in the first layer of the network. The second input is compared to the first input exemplar. If it "believes" the second input is within the first, it is discarded and the first input exemplar is used as the exemplar for the next input. Otherwise, the second input is used as the exemplar for the next input. This process is repeated for all remaining inputs and all neurons in the network.

Neural Networks

Bidirectional Associative Memory

KOSKO

A bidirectional associative memory (BAM) is a two-layer nonlinear feedback network that behaves as a heteroassociative content addressable memory. The stimulus-response associations (A, B) are stored by a BAM by summing bipolar correlation matrices. They are recalled as fixed points of the BAM dynamical system.

Counter Propagation

HECHT-NIELSEN

The counterpropagation network (CPN) will self-organize a nearest-optimal lookup table approximating the mapping used to generate its data. The method works equally well for binary and continuous vector mappings. It is shown that for sufficiently large network the mapping approximation can be made essentially as accurate as desired.

The counterpropagation network architecture is a combination of a portion of the self-organizing map of Kohonen and the outer structure of Grossberg.
America's Future in Space