A RAND NOTE

POTENTIAL APPLICATIONS OF EXPERT SYSTEMS AND OPERATIONS RESEARCH TO SPACE STATION LOGISTICS FUNCTIONS

Thomas F. Lippiatt, Donald Waterman

June 1985

N-2315-NASA

Prepared for

The National Aeronautics and Space Administration

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PREFACE

This Note documents a Rand briefing summarizing the results of a brief study of potential applications of operations research, artificial intelligence, and expert systems to space station logistics functions. It presents a brief needs assessment and suggests a specific course of action in each area.

This study was conducted under the sponsorship of the Kennedy Space Center, National Aeronautics and Space Administration (NASA) Contract No. NAS10-10438. The study results should be of interest to those NASA and contractor personnel who are concerned with logistics support for the space station during all phases of its life cycle: design, development, and operations. Readers should have some familiarity with the space station program and its initial operational and support concept.

SUMMARY

The space station presents new and unique challenges for logistics management. There is a basic difference between the space station and the kinds of systems logistics research has typically dealt with in the past. Much of the past research for both the military and the airlines has focused on airplanes where the airplane is typically treated as a single system supported by a relatively large ground-based logistics system. The space station, on the other hand, encompasses or must support multiple systems, most of which will have their own operational objectives and will potentially compete for the available logistics support. Another major difference is that the space station will have to support itself using only on-board resources for extended periods of time. Moreover, the multiplicity of systems will also require a wide variety of expertise to support the diagnosis of on-board problems and maintenance activities.

This is the final report of an assessment study to determine the applicability of operations research, artificial intelligence, and expert systems to logistics problems for the space station. The goal of the study is to identify promising application areas for space station logistics.

OPERATIONS RESEARCH APPLICATIONS

Space station logistics functions will require models and/or management systems that will assist in determining resource requirements, in making tradeoff analyses, and in assessing the value of contract incentives. The study focused on resource requirement systems that would aid in the determination of requirements for on-orbit maintenance manhours, on-orbit spare parts, and the transportation of spares to and from orbit. Models will also be required to assist tradeoffs between resources, level of repair analyses, and determining the "optimal" spare parts mix aboard logistics module (LM) resupply missions. Finally, models will be required to assess the value (or necessity) of contracting for reliability enhancements and use of common parts in the various systems that will make up the space station.

Developing logistics models for the space station presents a unique problem. The operational objectives of the space station are not analogous to those of military aviation or even the STS. Because of the multiplicity of systems that will make up the basic station and the missions it must support, it is not possible to identify a single performance measure that would reflect all the operational objectives of these various systems. Consequently, logistics modeling for the space station must take into account not only the manpower, spare parts, and transportation needed to meet the objectives of each system; it must also be capable of factoring in the relative importance of systems, given constraints on logistics support. Although the desired operational goal may be to have all systems up all the time, it may not be possible in the face of logistics resource constraints, and tradeoffs may have to be made based on relative system "essentiality" or downtime costs. As a result, it appears that individual system availability (e.g., percentage of time in operation) is the best operational measure to be used in logistics models.

In addition to these operational considerations, logistics modeling and management systems for the space station must also factor in potential constraints. Obviously, competition for logistics support will be a major consideration. The potential constraints include on-orbit space for logistics resources, on-orbit maintenance manhours, and LM resupply frequency and volume.

Given the unique nature of the space station's operational objectives and constraints, and the wide range of systems that will require logistics support, it is recommended that the Space Station Program develop an *integrated* logistics decision support system to be used by all management levels during the design, development, and operational phases. This system should provide insights into likely results of logistics support decisions as well as aiding in making the decisions themselves. The system should be integrated in the sense that all systems requiring logistics support should be represented and that the competition for all logistic resources be considered in computing individual system availabilities.

Personnel at the Kennedy Space Center have been working on a matrix or "spreadsheet" approach for determining the total requirement for "constrained" logistics resources. The rows of this matrix represent on-orbit systems to be supported and the columns represent logistics resource requirements with totals at the bottom. We believe this approach is a good one and, with some modifications and modeling support, could become the heart of an integrated logistics decision support system.

Three major logistics modeling capabilities should be developed to support a decision support system. The first and most important of these would provide on-orbit availability for each individual system. The projected availability should reflect the hardware reliability and redundancy and all aspects of the logistics support systems performance. The model should also reflect the competition for support resources with other systems, in particular spares and maintenance manhours.

The second recommended modeling capability would compute the mix of on-orbit spares for each system that minimizes the storage space required but still meets the availability target. This capability will help to minimize the LM resupply requirements as well.

The third capability would compute an "optimum" spares mix for each LM resupply mission and be able to reevaluate projected system availabilities. Such a capability could also support some of the tradeoff analyses conducted during design and development.

Based on these modeling requirements a review was undertaken of readily available models. Because of the unique nature of the space station problem, however, none of them was appropriate. The appropriate models are probably within the current state-of-the-art of operations research and it is recommended that these models be developed in conjunction with an integrated logistics decision support system to be used at all levels of the space station program.

ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS

Applying an AI/expert systems approach to systems building provides the programmer with a set of guidelines and organizing principles for programming and debugging. This promotes the development of programs that are relatively easy to update and maintain. A number of expert system projects applied to the space program are now under way at Kennedy Space Center, Johnson Space Center, and other places. The most promising area for expert systems in the space program is the area of fault detection and diagnosis. We recommend two applications within this area: troubleshooting RMS, the remote manipulator system for the shuttle, and developing an intelligent system for ground system communication equipment in a way that will encourage a fault-tolerant design.

POTENTIAL APPLICATIONS OF EXPERT SYSTEMS AND OPERATIONS RESEARCH TO SPACE STATION LOGISTICS FUNCTIONS

Chart 1

This briefing summarizes a brief study of potential operations research and artificial intelligence and expert system applications to space station logistics functions.

The Problem

- **Space station presents new and difficult challenges for logistics management and support**
- **Requires consideration before operational phase, during design and development**
- **What logistics functions might benefit from operations research and expert systems applications?**

Chart 2

The space station presents new and unique challenges for logistics management. There is a basic difference between the space station and the kinds of systems logistics that research has typically dealt with in the past. Much of the past research for both the military and the airlines has focused on airplanes where the airplane is typically treated as a single system supported by a relatively large ground-based logistics system. The space station, on the other hand, encompasses or must support multiple systems, most of which will have their own operational objectives and will potentially compete for the available logistics support. Another major difference is that the space station will have to support itself using only on-board resources for extended periods of time. Moreover, the multiplicity of systems will also require a wide variety of expertise, in orbit and on the ground, to support the diagnosis of on-board problems and maintenance activities. Because of the complex nature of the space station support problem, most of the critical tradeoffs and decisions concerning logistics will have to be made during the design and development phase. The purpose of our study was to identify applications of operations research and expert systems that could assist in assuring effective space station logistics support.

Organization of Briefing

- **Operations research applications**
- **Artificial intelligence and expert systems applications**

Chart 3

This briefing has two parts: In the first, we discuss applications of operations research, and, in the second, expert systems. In the operations research area the focus is on the identification and assessment of modeling tools that could be effectively applied to logistics management and the design of space station support. The second part focuses on the application of expert systems technology to logistics support problems that require specialized, potentially scarce expertise. Each part is independent of the other with its own recommendations and conclusions.

Study Outline

- **Identify logistics modeling requirements**
- **Assess space station operational objectives and constraints**
- **Identify a modeling approach and assess applicability of readily available models**
- **Suggest additional NASA research with assessment of technical feasibility**

Chart 4

To establish possible applications of operations research, we began by reviewing the available documentation on the space station and discussing the issues with NASA personnel. This allowed us to identify potential logistics decisions and management functions that might benefit from modeling support. Next, we reviewed the operational objectives of the station and the probable constraints on logistics support. (A primary goal of logistics models should be to tie decisions as closely as possible to a system's primary operational objectives, while fully considering relevant operational constraints to providing logistics support.)

After these reviews, we then identified a modeling approach and assessed models readily available elsewhere, in terms of their applicability to the space station environment. Finally, we developed a suggested research agenda and an assessment of technical feasibility.

This study approach description also provides an outline for the remainder of the briefing on operations research applications.

Space Station Logistics Modeling Requirements

- **On-orbit resource requirements**
  - **Maintenance**
    - **Manpower - skills**
    - **Test equipment**
  - **Spares**
  - **Transportation**
- **Logistics tradeoff analyses**
  - **Among resources**
  - **Level of repair**
  - **"Optimal" cargo mix for logistics module**
- **Design tradeoff analyses**
  - **Redundancy**
  - **Improved reliability**
  - **Parts commonality**

Chart 5

Logistics activities cover a wide range of support decisions and management functions. Most of these functions are interrelated and decisions made in each area can potentially affect the viability of logistics support throughout the space station life cycle. After discussions with NASA personnel, we narrowed the scope of our study to those areas considered most pressing. As you can see, we have focused on areas that will have the most impact on space station design--on-orbit space parts and maintenance, and resupply.

During the design and development of space station, models and/or management systems will be required that can assist in determining resource requirements and in making tradeoff analyses. For the purpose of this study, determination of resource requirements will focus on on-orbit spare parts, and the transportation of spares to and from orbit. Determination of required maintenance manhours will be particularly important because of the limited manpower available on-orbit for maintenance activities and the diversity of skills that is likely to be required.

Models will also be required to assist in tradeoff analyses. During the design and development of the space station and the development of space station logistics policy, logistics managers will need to examine the tradeoffs among resources. For example, one might want to look at the tradeoff between on-orbit spare storage requirements and the frequency of Logistics Module (LM) resupply missions.

Level-of-repair analyses will examine whether the repair of broken parts should take place on-orbit or back on earth. If repair were to take place on-orbit then more on-orbit manhours would be consumed for maintenance, and space would have to be made available for making the repairs. Increased skill levels would also be required. However, less space might be required for storing spares because only the small spare subcomponents needed for repair would have to be stored. If, on the other hand, no repair were to occur within the space station, then fewer maintenance manhours and less maintenance space would be required. But more space would probably be needed for spare parts.

Another logistics tradeoff analysis would determine the "optimal mix" of spare parts to be placed on board the LM for each resupply mission--if there is inadequate space for all the spares that might be wanted.

Moreover, there are important design decisions that will affect logistic support resource requirements and operations, and models will be required to assist in assessing the impact of these decisions. These models would show the value, in terms of required on-orbit logistics resources and system performance, of contracting for additional redundancy, improved reliability, or parts commonality across systems.

Space Station Operational Objectives Are Unique

- **Space station will comprise many systems, several of which are independent**
  - **Basic station**
  - **Commercial missions**
  - **SAA and TD missions**
- **Have individual objectives**
- **Vary in essentiality or down time costs**

Chart 6

Before considering the kinds of models that could be used to support the activities shown on the previous chart, we looked first at the space station's operational objectives and constraints, because potential modeling techniques should reflect these objectives and constraints as closely as possible.

The current trend in logistics modeling is to tie logistics resource requirements and management systems closer to measures that reflect ultimate operational objectives, rather than to intermediate measures that reflect supply or manpower objectives. For example, the military has moved away from the more traditional intermediate measures such as backorders or fill rates for supply system performance because it has been repeatedly shown that logistics models that explicitly use the more operationally oriented measures as objectives provide better operational performance for the same investment level. This improved performance has been demonstrated by mathematical analysis and operational tests. These models also tend to consider a wider range of logistics resources and, as a result, facilitate a more integrated approach to logistics management.

Operational measures also proved more appropriate and effective in our study of the STS. Models that explicitly reflected operational measures such as expected launch delay performed much better than those using traditional supply system measures like fill rate.

However, developing logistics models for the space station presents a unique problem. The operational objectives of the space station are not analogous to those of military aviation or even the STS. Here, it is not possible to identify a single performance measure that would reflect all the operational objectives of the system being modeled.

The basic space station itself will comprise many individual systems and be designed to support the many others that will make up the various mission packages. Many of these systems will be essentially independent of one another and will have their own objectives. Moreover, the vast majority of basic space station and mission systems will require logistics support and will share logistics resources. Consequently, logistics modeling for the space station must take into account not only the manpower, spare parts, and transportation needed to meet the objectives of each system; it must also be capable of factoring in the relative importance of systems, given constraints on logistics support.

Although the desired operational goal may be to have all systems up all the time, it may not be possible in the face of logistics resource constraints, and tradeoffs may have to be made based on relative system "essentiality" or downtime costs. For example, some systems, like the on-board life support systems, will be essential to the viability of the space station itself and all its missions. Others, like some small experimental package orbiting nearby on a platform but supported by the space station, will not. Another consideration in the "competition" for logistics support will be the relative financial costs of having a system down. Although downtime for many of the research oriented missions may result in negligible real dollar costs, the downtime costs for some commercial programs could be prohibitive for their sponsors.

Potential Space Station "Constraints"

- **Logistics support for each system will compete for:**
  - **Space**
  - **Manhours**
  - **Resupply**

  with all other systems

- **On-orbit space for logistics resources**
  - **Spares**
  - **Maintenance facilities**

- **On-orbit maintenance manhours and skills**
  - **Unscheduled - failure driven**
  - **Scheduled**
    - **Inspections**
    - **Preventative**
    - **Refurbishing**
  - **Affects manhour availability for missions**

- **Logistics module resupply**
  - **Cargo space and weight**
  - **Frequency**

Chart 7

In addition to these operational considerations, logistics modeling and management systems for the space station must also include potential constraints. Obviously, competition for logistics support will be a major consideration. Although the logistics support resources shown here are constraints in a mathematical or modeling sense, from a designers point of view they may, in fact, represent design or operational goals. As the chart shows, these include on-orbit space for logistics resources, maintenance manhours, and LM resupply.

Modeling Implications of Objectives and Constraints

- **No single operational measure will capture the relative importance of each system**
- **When constraints are faced, relative system importance is likely to be negotiated during system integration**
- **Individual system availability seems to be the best measure for supporting logistics and design decisions**
  - **Basic station systems**
  - **Missions**

Chart 8

Given the preceding description of space station objectives and constraints, no single operational performance measure for the space station as a whole will capture the relative importance of each system, nor is it likely that the relative performance of the various systems could be specified in advance. Although some systems are obviously very critical, specifying the relative importance of the remainder could be quite difficult. When constraints on logistics resource availability are faced, relative system importance is likely to be negotiated during system integration.

As a result, it appears that individual system availability (e.g., percentage of time operational) is the best operational measure to be used in logistics models. Such a measure will allow the flexibility to "negotiate" (specify) relative system importance throughout the entire space station life cycle, and in doing so, facilitate the design and implementation of an integrated logistics support system.

Need Integrated Logistics Decision Support System

- **Provide individual system availability as a function of on-orbit logistics support resources and resupply performance**
- **Determine the total requirement for "constrained" resources**
  - **Space**
  - **Manpower - skills**
  - **Resupply**
- **Logistic support tradeoff analyses**
  - **Among resources**
  - **Level of repair**
  - **LM resupply mix**
- **Design tradeoff analyses**
  - **Improved reliability**
  - **Parts commonality**
  - **Relative system availability**
  - **Redundancy**

Chart 9

Given the unique nature of the space station's operational objectives and constraints and the wide range of systems that will require logistics support, the Space Station Program needs an *integrated* logistics decision support system to be used by all management levels during the design, development, and operational phases. This system should provide insights into likely results of logistics support decisions as well as aiding in making the decisions themselves. The system should be integrated in the sense that all systems requiring logistics support should be represented and that the competition for all logistic resources be considered in computing system availabilities. The intent here is not to describe such a system in detail, but to describe enough of its desired characteristics to identify potential modeling requirements.

The decision support system should compute individual system availability, aid in determining logistics resources, and support tradeoff analyses, including assessments of relative changes in system availability targets. In addition, such a decision support system should provide value assessments (in terms of logistics resource requirements and system availability) of redundancy, improved system reliability, and parts commonality.

KSC
MATRIX APPROACH

Systems	Maintenance man hours/week		On-orbit space			System avail.
			Spares			
	Sched.	Unsched.	LM	Other	Maint.	
Basic station						
Power						
Environ.						
Comm.						
⋮						
Missions						
Commercial						
⋮						
SAA						
⋮						
TDM						
⋮						
Subtotal						
Totals						

Chart 10

Personnel at the Kennedy Space Center have been working on a matrix or "spreadsheet" approach for determining the total requirement for "constrained" logistics resources. We believe this approach is a good one that, with some modifications and modeling support, could become the heart of an integrated logistics decision support system.

The rows of the matrix represent on-orbit systems for which logistics support must be provided. The definition of a system, at present, is not important but, for modeling purposes, it should ultimately represent a collection of components for which the explication of system availability is important. For example, a system may represent all the components of a particular mission or the mission components may be divided into two or more systems where the availability of one may be more important than another.

The columns represent that system's contribution to the requirement for shared, constrained logistics resources and the projected or target system availability. As the chart shows, two columns represent the expected requirement for scheduled and unscheduled maintenance man-hours. Three of the columns are for on-orbit space requirements. Space for spares can be on the LM or elsewhere on the space station. The space on the LM also represents part of the resupply constraint. Space for off-line, off-equipment maintenance of components is represented in the third on-orbit space column. This space may be shared by many systems and its allocation to individual systems may be somewhat arbitrary. This allocation is important, however, when conducting levels of repair tradeoffs, especially under conditions where additional maintenance space may be required. The last column contains the projection of system availability.

Such a matrix approach would, with appropriate modeling support, provide the total requirement for "constrained" logistics resources, and provide the visibility and support required for the various tradeoff analyses.

Decision Support System
Operations Research Modeling Requirements

- **System availability as a function of:**
  - **Time between maintenance actions**
    - **Time between failures**
    - **Time between scheduled maintenance**
  - **Time to accomplish maintenance**
    - **Elapsed maintenance time**
    - **Time awaiting maintenance**
  - **Time awaiting spares considering:**
    - **On-board spares - commonality**
    - **On-board spare part repair**
    - **LM resupply**
  - **System redundancy**

Chart 11

This chart and the one that follows describe the three major logistics modeling capabilities that would be needed to support an integrated logistics decision support system. The most important of these modeling capabilities is the one that would provide on-orbit system availability. As the chart shows, the projected availability should reflect the hardware reliability and redundancy, and all aspects of the logistics support system performance. The model should also reflect the competition for support resources with other systems, in particular spares and maintenance manhours.

The ability to compute system availability in conjunction with a matrix-oriented decision support system should provide insights into the various logistics tradeoffs that are likely to be faced in the design of the space station and the logistics system that will support it.

Decision Support System
Operations Research Modeling Requirements

- **On-orbit spares requirements**
  - **Minimize spares space requirements given target system availability, on-orbit maintenance, and LM resupply**
  - **Take into account spares common across systems**
- **Logistics module spares mix**
  - **Compute "optimum" spares mix for LM resupply missions given current state of systems, on-orbit spares, on-orbit maintenance, target system availabilities, and LM space constraints**

Chart 12

As the integration of the space station design proceeds and target system availabilities are established, it would be useful to have the capability to compute the mix of on-orbit spares for each system that minimizes the storage space required but still meets the availability target. This capability will help to minimize the LM resupply requirement as well.

During the operational phase there may be situations where space on the LM is constrained and there is insufficient room to resupply all of the spare parts required. Under these conditions it would be useful to be able to compute an "optimum" spares mix for that mission and to be able to reevaluate projected system availabilities. Such a capability could also support some of the tradeoff analyses conducted during design and development.

At present we judge these three modeling capabilities as most important for a decision support system. As the design of such a system unfolds, other modeling needs are likely to be identified.

In addition to providing modeling support the decision support system should be designed for ease of use by all levels while maintaining its integrated nature. It should also be implemented in a way that easily supports the various tradeoff analyses that will be undertaken.

Technical Feasibility

- **Readily available logistics models do not reflect unique nature of the space station problem**
- **Most of the modeling requirements are within the state of the art**
- **Two difficult problems which are probably solvable**
  - **Spares commonality across systems**
  - **Maintenance queuing**

Chart 13

Given these modeling requirements, we undertook a review of models readily available. This review included models used extensively in the military and the airlines and those proposed for STS operations. Because of the unique nature of the space station problem, none was appropriate. The appropriate models are probably within the current state-of-the-art of operations research. However, two important modeling problems will perhaps prove especially difficult to solve: analytic models that reflect the queuing that might occur for available maintenance manhours and the commonality of spare parts across systems. Although these models will be more difficult to develop than others, the inherent problems are probably solvable.

Recommendations

- **Develop an integrated logistics decision support system for use by**
  - **Level B**
  - **Level C**
  - **Contractors**

  in all phases of design, development, and operations

- **Develop a standard set of models for inclusion in the decision support system to be used by all**

- **Develop a standard set of procedures for using the system to evaluate**
  - **Alternative target system availabilities**
  - **Level of repair alternatives**
  - **Common part proposals**
  - **Reliability enhancements**
  - **Manpower alternatives**
  - **LM resupply alternatives**

Chart 14

The integration of the basic space station elements and all the missions it will potentially support will be a complex and difficult task. Assuring adequate logistics support will be an important part of this integration process. With most of the basic station and mission systems competing for the same scarce support resources, decision support tools will have to be developed to aid in this integration process.

We recommend that NASA develop an integrated logistics decision support system similar to the one described here. Such a system should be standardized and hierarchical so that it can be used by all NASA levels, as well as contractors, during the space station design, development, and operational phases.

In addition, a standard set of operations research models should be developed and incorporated in the system. Finally, a standard set of procedures should be developed that describes how the system is to be used and what assumptions should be made in evaluating logistics support alternatives.

AI/EXPERT SYSTEM APPLICATIONS FOR THE SPACE STATION

==> • **BACKGROUND**

• **CURRENT APPLICATIONS**

• **APPLICATION AREAS**

• **RECOMMENDED APPLICATIONS**

Chart 15

This part of the briefing is organized as follows: First we present some background on AI and expert systems, including a discussion of what AI has to offer the system builder, the programming and organizational methods AI provides, and the advantages of using these methods in a large-scale development effort. Second, we describe some current applications of AI and expert systems to the space program. Third, we discuss some interesting and important application areas for AI/expert systems development. Finally, we present our recommendations for work in AI and expert systems.

BACKGROUND

How Are AI Systems Related?

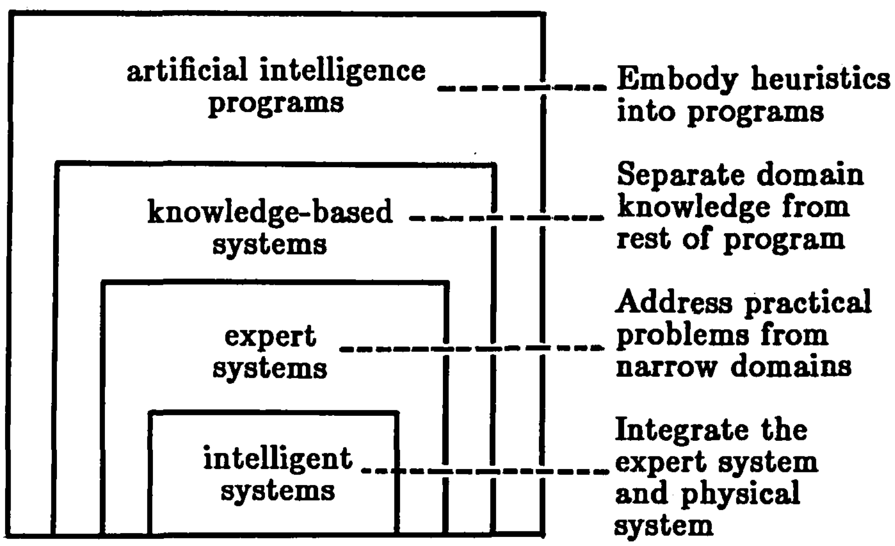

Chart 16

This figure depicts how certain types of AI systems are related [Waterman, 1985]. The most general type, an "AI program," exhibits intelligent behavior through the skillful application of heuristics or "rules of thumb" that are embedded in the program. One useful type of AI program is the knowledge-based system, where the domain knowledge is separated from the system's general problem-solving knowledge. The advantage of this representation scheme is that the domain knowledge is explicit and accessible. This facilitates program debugging, updating, and the implementation of a facility for explaining how and why the system reached particular conclusions. The most interesting type of knowledge-based system is the expert system [Hayes-Roth, Waterman, and Lenat, 1983]. This is a knowledge-based system that applies expert knowledge to difficult "real world" problems. Expert systems address practical problems with a limited scope in domains that have acknowledged human experts. One type of expert system is the intelligent system, an expert system that is embedded in some physical system such as a piece of electronic equipment. This expert system will be embedded in a microprocessor chip located in the equipment itself, and will directly interpret signals from the equipment in order to monitor, diagnose and control the equipment. We will discuss the intelligent system in more detail later.

BACKGROUND

Evolution of AI Technology

1960's		1970's		1980's		1990's
Heuristic Programming	=>	Knowledge-based Systems	=>	Expert Systems	=>	Intelligent Systems

Chart 17

AI technology is constantly evolving. In the 1960's the emphasis was on heuristic programming, in the 1970's on knowledge-based systems, today, in the 1980's, it's on expert systems. My prediction is that in the 1990's the emphasis will shift to intelligent systems, a very interesting and useful type of expert system.

BACKGROUND

What Can AI/Expert Systems Offer the System Developer?

- **Faster development**
  - **High-powered displays and workstations**
  - **High-level, flexible languages**
- **Solutions to difficult problems**
  - **Powerful programming and organizational constructs**
- **Systems designed for the users**
  - **Easily extended**
  - **Explains reasoning**

Chart 18

The use of displays with high-resolution bit-map graphics, like the Symbolics 3600 and Xerox 1100 series workstations, can significantly speed language design because of their flexibility and sophisticated support environment. Although the Symbolics and Xerox workstations are currently the most popular, many companies are now producing workstations of this sort (e.g., LMI, SUN, Tektronix, Carnegie Group, and others).

The use of LISP as an initial development tool will speed development because of its general purpose nature and the ease with which code can be treated as data. It is particularly useful for experimenting with new system designs. Prolog, a logic-based programming language, is now beginning to rival LISP as an AI development tool, primarily because of its built-in control scheme that relieves the programmer of some responsibility for organizing the search through the database. Other even higher-level languages, such as ROSIE [Fain, Hayes-Roth, Sowizral, and Waterman, 1982] can speed the development of expert systems because of the English-like nature of the code. This greatly speeds the mapping of expertise expressed in English into an executable computer program.

The AI/expert systems approach to program development provides a methodology that permits solutions to very difficult problems, problems that cannot be solved by standard numerical or algorithmic techniques. The key here is the use of symbol manipulation combined with a heuristic problem-solving approach. A bit later we will discuss some of the programming and organizational constructs used in AI.

The system that results from an AI/expert system development effort is more responsive to the needs of the users than are typical conventional software systems. This is because the expert system with its explicit domain knowledge can be easily extended, i.e., it can grow incrementally over time to meet the changing demands of its users. Furthermore, it can explain its reasoning processes and thus justify the conclusions it reaches. This increases user acceptability of the system, since users generally dislike the idea of blindly following the orders or recommendations of a computer, especially when a mistake in judgment could be costly.

BACKGROUND

What Programming and Organizational Methods Does AI/Expert Systems Provide?

- **Rule-based**
- **Frame-based**
- **Procedure-oriented**
- **Object-oriented**
- **Data-oriented**

Chart 19

AI and in particular, expert systems, provides a number of ways to organize and represent knowledge in complex problem areas. Some of the most widely used are presented here. The most popular is the rule-based method of representation.

BACKGROUND

RULE

A formal way of representing a recommendation, directive or strategy, usually expressed as an IF-THEN statement.

Chart 20

A rule is typically an IF-THEN statment of the form "If A Then B," meaning that in some situation A, either take some action B or reach some conclusion B.

BACKGROUND

A RULE FROM SACON

If:

1) The material composing the sub- structure is one of: the metals, and

2) The analysis error (percent) that is tolerable is between 5 and 30, and

3) The non-dimensional stress of the sub-structure is greater than .9, and

Then:

4) The number of cycles the loading is to be applied is between 1000 and 10000,

It is definite (1.0) that fatigue is one of the stress behavior phenomena in the sub-structure.

Chart 21

Here is an example of a rule from SACON, a consultation system that helps a structural engineer analyze the mechanical behavior of objects [Bennett, Creary, Engelmore, and Melosh, 1978]. This is an English translation of the rule, which was written in EMYCIN [Bennett and Engelmore, 1984].

Rules let us easily describe processes driven by a rapidly changing, complex environment. They can specify how the program should react to incoming data, even without advance knowledge about the type and sequencing of the data. Rules let the program examine the data at each step and react appropriately. They also simplify the process of explaining how the program reached a particular conclusion.

Frames use a network of nodes that represent concepts. They are connected by relations and organized into a hierarchy such that nodes low in the hierarchy automatically inherit properties of higher-level nodes. This provides a natural, efficient way to organize and represent a taxonomy.

Procedure-oriented methods involve the use of subroutines to increase efficiency by removing duplicate code. Furthermore, the programmer can define a special-purpose "language" composed of high-level procedures or subroutines. This language can then be used to succinctly describe the activity desired of the program. When rules and procedures are combined, as in the ROSIE language, the programmer can define procedures called rulesets, each containing rules that may call other rulesets. Thus a ROSIE programmer can organize the program in much the same way as it would be done in LISP, i.e., as a set of nested subroutines.

Object-oriented methods use constructs called objects that represent entities capable of exhibiting behavior. All the objects communicate with one another by sending and receiving messages. Each object has a database and set of rules associated with it. When an object receives a message, it consults its database and rules to decide what action to take, which normally involves sending new messages to other objects in the system. These methods provide a way to specify concurrent, asynchronous operations; it's possible to simulate many unrelated processes occurring at the same time.

Data-oriented methods use procedures that are invoked when data are changed or read. These procedures monitor the values of variables in a program. When the values change, the procedures trigger computations that may drive graphical displays or gauges showing the values of the variables.

BACKGROUND

What Are The Advantages of Using These AI/Expert System Methods?

- **Methodology**
- **Modularity**
- **Readability**
- **Efficiency**

Chart 22

The AI/expert systems approach to system building provides the programmer with a methodology: a set of guidelines and organizing principles for programming and debugging. This promotes the development of programs that are relatively easy to update and maintain.

Through the use of rules and rulesets, programs can be organized in a modular fashion. This makes them easy to extend and refine, and makes the incremental approach to system development both attractive and feasible.

Modularity also increases the readability of the program. When this is combined with an English-like syntax in the development language (as provided by ROSIE) it greatly increases the ease of understanding the code. This helps the programmer determine what the code is supposed to do and what the effects of a change would be.

The language structure and the programs written in that language are tied together--some languages encourage poorly written, inefficient computation, whereas others provide a tool in which concise efficient programs can be easily written.

AI/EXPERT SYSTEM APPLICATIONS FOR THE SPACE STATION

- BACKGROUND
- ==> CURRENT APPLICATIONS
- APPLICATION AREAS
- RECOMMENDED APPLICATIONS

Chart 23

To assure that only new, potentially high payoff applications were picked for more in-depth study, we first reviewed some of the applications of AI and expert systems currently under way within the space program.

CURRENT APPLICATIONS

Kennedy Space Center

- **LES: Liquid Oxygen Expert System**
  - **monitors the loading of liquid oxygen onto the shuttle**
- **EMPRESS: Expert Mission Planning and REplanning Scheduling System**
  - **monitors and schedules experiment-related cargo**
- **Cargo Processing System**
  - **assists with 14-day scheduling for cargo**

Chart 24

LES: Liquid Oxygen Expert System. LES models several valves that control the loading of liquid oxygen onto the shuttle (flow rate, etc.) and helps the user troubleshoot the LOX (liquid oxygen) system when problems occur. Much of the knowledge built into LES came from a human expert at KSC, skilled at troubleshooting the LOX system. LES is frame-based, modeled after the KNOBS work at Mitre. This one-year project started in November 1983 and has produced a small demonstration prototype system than runs in ZETALISP on the Symbolics 3600. The actual LOX system being modeled has 50 valves and 300 measurements. The LES group estimates it will take 2000 frames to handle the entire LOX system.

EMPRESS: Expert Mission Planning and Replanning Scheduling System. The goal of this project is to develop an expert system to monitor and schedule experiment-related cargo that has to be tested before launch. This cargo has to be positioned in testing areas for connection to the proper test equipment in a way that minimizes cargo repositioning and maximizes the use of the test equipment. The development technique involves building the knowledge from a human expert into the expert system. The human expert is skilled at scheduling the placement and testing of experiment-related cargo for the shuttle.

Cargo Processing System. Kennedy Space Center is working with Georgia Tech on this effort to do 14-day scheduling for shuttle cargo. This project is just starting at KSC.

CURRENT APPLICATIONS

Ford Aerospace
AI Laboratory
Houston, Texas

- **RPMS: Resource Planning and Management System**
  - **general-purpose planning and scheduling system**
- **RICS: Real-time Inferential Control System**
  - **helps monitor on-board navigation data during a shuttle flight**
- **RBMS: Rule-based Modeling System**
  - **schedules the use of flight control rooms**

Chart 25

RPMS: Resource Planning and Management System. RPMS is a general-purpose planning and scheduling system that assists the user in defining a schedule and minimizing resources such as time, manpower, and materials [King, 1983]. The schedule is represented graphically as a network containing tasks with bars indicating their durations and arrows pointing to successor and predecessor tasks. The user can define formal constraints between tasks, such as task A must occur before task B by moving tasks (nodes) in the network. When a task is moved the nodes and links stretch to conform to the new position. If the movement violates informal constraints (rules defining somewhat more abstract relationships between tasks), warnings to the user appear on the screen.

The user may then reconfigure the nodes or modify or augment the rule to resolve the conflict. The system also contains rules that allow it to reconfigure the network itself, attempting to level out the use of resources. RPMS is being applied to the space shuttle reconfiguration process for the Johnson Space Center. RPMS was developed at Ford Aerospace in 1984, and is funded by internal R&D money.

RICS: Real-time Inferential Control System. The goal of the RICS project is to aid human operators in the monitoring of navigation data during a shuttle flight. The system will monitor the on-board navigation data (telling where the shuttle is and where it's going), give a warning when the data from the measuring device seem to be doing more harm than good, and suggest when to restart and use data from ground observations instead. RICS decides (1) when to discount certain measurements, and (2) when to update with ground data. RICS will in fact predict in advance that a threshold will be exceeded by certain measuring devices and will give a warning to watch that data even before it is discounted. Development of a RICS prototype is just beginning. The system is being written in OPS5 and LISP and runs on the Symbolics 3600. It is funded by Internal R&D money at Ford Aerospace.

Rule-Based Modeling System. RBMS uses a flight manifest to schedule the use of FCR's (flight control rooms) over a period of months. The system replaces the STAP Computer Program (written in SLAM), a statistical approach to the problem. The input to RBMS is the flight manifest containing flight numbers, launch dates, type of flight, duration, whether or not it is a space laboratory mission, and other data. RBMS produces as output a schedule indicating the daily FCR usage (activities scheduled, number of hours required) and the average hours/day used by each FCR per month. The RBMS project was funded by NASA and is currently being used to schedule FCR's at JSC. The system is written in LISP and OPS5 (about 20 OPS5 rules) and runs on the VAX computer.

CURRENT APPLICATIONS

Johnson Space Center
Applied Technology Section

- **NAVEX: Navigation Expert**
  - **monitors radar station data for the shuttle**
- **Graphics Interface Expert System**
  - **an intelligent interface to a graphics package**
- **Logistics Planning and Scheduling System**
  - **integrate PLANS and RPMS**

Chart 26

NAVEX: NAVigation EXpert. NAVEX monitors radar station data that estimate the velocity and position of the space shuttle, looking for errors, and warning the mission control center console operators when errors are detected or predicted [Marsh, 1984a,b]. It is important to know when the data are reliable, since they are used by the guidance and trajectory systems in the control center to monitor shuttle launch and landing. NAVEX recommends possible actions to take, such as excluding data from a particular radar station, and restarting the analysis of the current data. It uses a voice synthesizer to describe the actions it has taken and a graphics screen to display the recommended actions. There is a front-end processor to NAVEX that maps the input data into GOOD/BAD categories. The goal of this project is to produce a production version of the system that will replace two of the three console operators currently doing the monitoring. It will then be used for actual missions. NAVEX is rule-based and frame-oriented, consisting of a little over 100 ART rules. The system runs in real time, making recommendations based on actual radar data. The system has reached the stage of demonstration prototype, and was developed by Inference Corporation working with NASA at the Johnson Space Center.

Graphics Interface Expert System. The goal of this planned project is to build an intelligent interface to an existing graphics package at JSC to make the package usable by untrained personnel.

Logistics Planning and Scheduling System. The goal of this project is to use a scheduling language called PLANS (they also have a statistical program and library of subroutines called PLUS) together with the RPMS system to produce a logistics planning and scheduling system.

CURRENT APPLICATIONS

Johnson Space Center
AI and Information Systems

- **Electro-chemical CO2 Removal Expert System**
  - **equipment fault diagnosis**

Chart 27

Electro-chemical CO2 Removal Expert System. The goal of this project is to build an expert system for fault diagnosis of the ECCM (electro-chemical CO2 removal) system, an electronic/mechanical device that takes CO2 out of shuttle cabin air and produces power. This work is just getting under way, including system design and selection of the development language.

CURRENT APPLICATIONS

McDonnel Douglas
Houston, Texas

- **LWP: Launch Window Processor**
  - **selects launch window for the shuttle**

- **KRT: Knowledge Representation Tool**
  - **stores and integrates knowledge about different pieces of complex systems**

Chart 28

LWP: Launch Window Processor. The LWP system takes a given payload requirement for the shuttle and selects the launch window. The input to the system includes payload constraints, the earliest and latest possible launch dates, and other data. The system calculates deployable payload injection opportunities based on longitude constraints, determines deployment sequences based on scheduling rules, calculates a launch window on the day of the launch for every acceptable deployment sequence, and allows permanent storage and retrieval of the mission definition, payload description, and payload constraint data. LWP uses a graphical display to show the launch window and deployment opportunities. The system is not mission specific but deals only with geosynchronous payloads. The user sets payload, mission and orbital parameters in a pop-up window on a graphics-oriented workstation. The system is programmed in ZETALISP and FLAVORS on the Symbolics 3600.

KRT: Knowledge Representation Tool. The goal of this project is to produce a software tool that will help members of a large engineering development effort record, communicate, and integrate their designs with other members of the team. With the KRT system, team members can describe what a particular engineering system (e.g., guidance analysis, navigation) does, how it functions, how it is organized and how its parts are related. This includes a data flow diagram to provide a system overview, process specifications to show how input data are transformed into output data, and a data dictionary that provides a hierarchical description of data. The KRT system is written in ZETALISP and FLAVORS on the Symbolics 3600.

CURRENT APPLICATIONS

Advanced Information
& Decision Systems
Mountain View, CA

- **EC/LSS Expert System**
  - **performs fault diagnosis and system management for an environmental control, life support system for the space station**
- **EPS Expert System**
  - **performs fault diagnosis and system management for the electrical power subsystem of the space station**

Chart 29

EC/LSS Expert System. The goal of this project is to design an expert system that will manage the environmental control, life support system for the space station, including troubleshooting the system when faults occur. The expert system will control the EC/LSS to assure a proper mix of gasses, detect and diagnose failures in the EC/LSS, and take corrective action during a failure to maintain atmospheric quality.

EPS Expert System. The goal of the project is to design an expert system to control the electrical power generation subsystem of the space station and perform fault analysis when the system malfunctions. AI&DS is now constructing a prototype demonstration system for EPS fault management that will be tested on an EPS simulation testbed developed by Boeing Aerospace.

AI/EXPERT SYSTEM
APPLICATIONS FOR
THE SPACE STATION

- **BACKGROUND**
- **CURRENT APPLICATIONS**
- ==> **APPLICATION AREAS**
- **RECOMMENDED APPLICATIONS**

Chart 30

We now present three application areas for AI and expert systems in the space program, which we feel have high potential payoff for the Kennedy Space Center.

APPLICATION AREAS

What Areas Are Appropriate For The Space Station?

- **Fault Detection and Diagnosis**
- **Planning and Scheduling Systems**
- **Language Design and Development**

Chart 31

Possibly the most appropriate application area for the space station is fault detection and diagnosis, where an expert system monitors the operation of mechanical or electrical equipment, detects problems, and assists with troubleshooting and repair [Dickey and Toussaint, 1984].

Artificial intelligence could also be applied to the problem of planning and scheduling. This area seems quite appropriate for logistics problems, such as planning and scheduling transportation, inventory levels and manpower. For example, an expert system that could handle the logistics of supplying parts to build and maintain the space station (loads that are on the shuttle) would be quite useful. The system could schedule consumables, replacement parts and people.

Finally artificial intelligence could be applied to the space station language design and development effort. This goal of this effort is to provide a high-order language by which a user can control his environment. This includes the ability to test systems, verify that they are operational, and command them to perform the desired tasks. AI technology could speed the design and development of a high-order language through the use of workstations with high-resolution bit-map graphics, and powerful programming languages such as LISP. AI methods, such as rule-based or frame-based knowledge representation techniques could also be used to improve the language, that is, make it more powerful and flexible than conventional languages. Without AI constructs embedded in the language it would be difficult, if not impossible to meet the design goals of being readable, writable, learnable, and reviewable by nonprogramming-oriented users. Rule-based language tends to be more readable, procedure-oriented ones more writable, simple ones more learnable. Also, clever interaction and feedback with the user can make the language more learnable and reviewable.

There are other areas that could also be considered appropriate for the space station, such as {distributed computing} to enhance reliability and provide redundancy, *tutoring* to train nonspecialists in the use of specialized and complex equipment and systems, and *intelligent manuals* to help users retrieve information, fill out forms and construct documents, just to name a few. However, these areas are not as well understood by AI researchers as those mentioned earlier, and thus could require longer and more expensive development efforts. Thus they will not be explored further in this context.

Since the applications that will be recommended all fall under the fault detection and diagnosis area, this area will now be considered in more detail.

AI/EXPERT SYSTEM
APPLICATIONS FOR
THE SPACE STATION

- **BACKGROUND**
- **CURRENT APPLICATIONS**
- **APPLICATION AREAS**

==> • **RECOMMENDED APPLICATIONS**

Chart 32

We now turn to recommended applications of AI and expert systems for the space station. We will discuss two applications that seem both appropriate and important.

RECOMMENDED APPLICATIONS

- **Troubleshooting**
  - **RMS: Remote Manipulator System**
- **Intelligent System**
  - **Ground System Communication Equipment**

Chart 33

As mentioned earlier, both applications fall under the category of fault detection and diagnosis. The first is a troubleshooting application: an expert system for diagnosing faults in RMS, the remote manipulator system used by the shuttle. This system is a 50 foot long arm used for deploying and retrieving payloads from the orbit cargo bay. A mission specialist operates the arm using a combination of closed circuit television and direct viewing.

The second application involves the design and implementation of an intelligent system. The equipment targeted as the repository for the integrated expert system is any of several types of ground system communication equipment.

RECOMMENDED APPLICATIONS

RMS: Remote Manipulator System

Why RMS?

- **Responsibility shifting from JSC to KSC**
- **Highly visible**
- **Critical component**
- **Few experts**
- **Applicable to shuttle and space station**

Chart 34

Let's consider the RMS application. There are a number of reasons this is a good application area for KSC. First, responsibility for RMS is shifting from JSC to KSC, so KSC will have to become more involved with its use and maintenance. Second, the arm is a highly visible part of the shuttle program, something the general public can understand and follow. When something goes wrong with the arm, particularly in orbit, it gains much national attention. Third, the RMS system is a critical component of the shuttle program, since it is used for deploying and retrieving payloads. Fourth, only a few people are genuine experts at troubleshooting the RMS system and they are beginning to seek other jobs. Finally, an expert system for troubleshooting the RMS would be valuable for both the shuttle and space station, since both will make use of remote manipulators.

RECOMMENDED APPLICATIONS

RMS: Remote Manipulator System

What Will the RMS Trouble-Shooting System Provide?

- **Permanent storage of fault diagnosis expertise**
- **Monitoring, fault detection, and diagnosis in orbit**
- **Extended debugging and testing on the ground**

Chart 35

An RMS troubleshooting expert system will provide a number of valuable services. First, it will act as a permanent repository for knowledge about RMS operation, maintenance, and fault diagnosis. Second, it will provide a means for monitoring the RMS, detecting faults, and diagnosing them while the system is in orbit. Finally, it will act as a high-level consultant to ground personnel engaged in extended debugging and testing of the RMS on the ground.

RECOMMENDED APPLICATIONS

RMS: Remote Manipulator System

What Resources Are Needed for Expert System Development?

Personnel: Development Team

- **knowledge engineers**
- **support programmers**
- **KE/support programmers**
- **domain expert**
- **local project coordinator**

Tools: High-level knowledge engineering language

- **ROSIE**
- **ART**
- **KEE**

Time: 1-2 years

Chart 36

A project to design and build an RMS expert system would require substantial resources. This includes a team of one to two knowledge engineers, support programmers, domain experts, and a project coordinator. A high-level knowledge engineering language, such as ROSIE, ART, or KEE, is recommended as the development tool, since it will speed the development time. The system could be developed directly in LISP but would require more time and skilled personnel that it would if done in a knowledge engineering language. The time frame for the project would be one to two years or longer. At the end of one year we could expect a prototype system able to perform some simple diagnosis tasks. Additional time would be required to extend and refine such a system to the stage of a field prototype.

RECOMMENDED APPLICATIONS

Ground System Communications Equipment

Why GSC Equipment?

- **Equipment exists but needs redesign to improve fault tolerance**
- **Troubleshooting experts and design experts exist and are available**
- **High payoff if successful – implications for fault-tolerant design of equipment in general**
- **Applicable to shuttle and space station**

Chart 37

Now let's consider the GSC equipment application. There are many reasons for considering this as an application area. First, GSC equipment exists but is perceived as needing better design to improve its fault tolerance capabilities. Second, the required troubleshooting experts and design experts are available and interested in starting such a project. Third, the project will have a high payoff if successful. It will provide a new way to approach the design of fault tolerant equipment. Finally, the resulting expert system would be useful for both shuttle and space station applications.

RECOMMENDED APPLICATIONS

Ground System Communications Equipment

What Will the GSC Intelligent System Provide?

- **A methodology for fault-tolerant design**
- **Reduced time and effort spent in fault diagnosis**
- **A troubleshooting system for detecting, diagnosing and repairing faults**

Chart 38

A GSC intelligent system will be useful in a number of ways. First, it will provide a methodology for exploring and enhancing fault-tolerant design. The idea is to use a knowledge engineer, troubleshooting expert, and design expert working together to simultaneously design (or redesign) the equipment, construct an expert system to diagnosis it, and physically connect that expert system to the equipment. This extends the traditional idea of knowledge engineering. The result would be a cleaner piece of equipment that is better able to provide the data needed by the equipment troubleshooter. Second, the intelligent system would result in less time and effort spent in fault diagnosis, since the system could interpret data coming directly from the equipment and present its interpretation to the human troubleshooter, rather than requiring the human to analyze all the data himself. Finally, the intelligent system would be a useful tool for helping technicians detect, diagnose, and repair faults in the equipment.

RECOMMENDED APPLICATIONS

Ground System Communications Equipment

What Types of Equipment Might be Considered?

- **Baseband switching & routing system**
- **16 kilobit modem**
- **Local area network**

Chart 39

A number of different components of the ground system communications equipment could prove appropriate for an intelligent system development effort. For example, possibilities include the baseband switching and routing system, the 16 kilobit modem, and the local area network for distributed processing that connects various processors via a fiber-optic bus. Other equipment would also be equally appropriate, a prime concern being that the equipment designer be available and willing to work with the knowledge engineering team.

RECOMMENDED APPLICATIONS

Ground System Communications Equipment

What Resources are Needed for Expert System Development?

Personnel: Development Team

- knowledge engineers
- support programmers
- KE/support programmers
- design expert
- troubleshooting expert
- local project coordinator

Tools: High-level knowledge engineering language

- ROSIE
- ART
- KEE

Time: 1-2 years

Chart 40

A project to design and build an intelligent system would require a substantial investment in time and personnel. It would take a team of one to two knowledge engineers, support programmers, domain experts, design experts, and a project coordinator. Again, a high-level knowledge engineering language, such as ROSIE, ART, or KEE, is recommended as the development tool to speed development time and allow for experimentation. The time frame for the project would be one to two years or longer. At the end of one year we could expect a prototype system able to perform simple diagnosis tasks and a first cut at a redesign of the equipment. Additional time would be required to extend and refine such a system and apply it to the redesigned equipment.

RECOMMENDED APPLICATIONS

AI/Expert Systems Approach To Application Areas

RMS:

- **Troubleshooting**
- **Expert Subsystem Specialists**

GSC:

- **Intelligent Systems**
- **Fault-tolerant Design**

Chart 41

Now let us examine the AI approach that might be taken to develop expert systems for each of these recommended applications. For RMS the approach is the standard fault-diagnosis method applied to a subsystem of the space station or shuttle. The application is of particular interest, however, because of the system's high visibility, crucial role, and the small number of experts able to provide high quality diagnostic advice. For GSC, the approach is far from standard. It's a rather innovative merging of ideas from fault tolerant design and expert system technology to produce a new kind of intelligent system. Actually, it is somewhat strange to talk about a "new" type of intelligent system, since the whole concept of integrated expert systems and intelligent systems is just in its infancy.

RECOMMENDED APPLICATIONS

Intelligent Systems

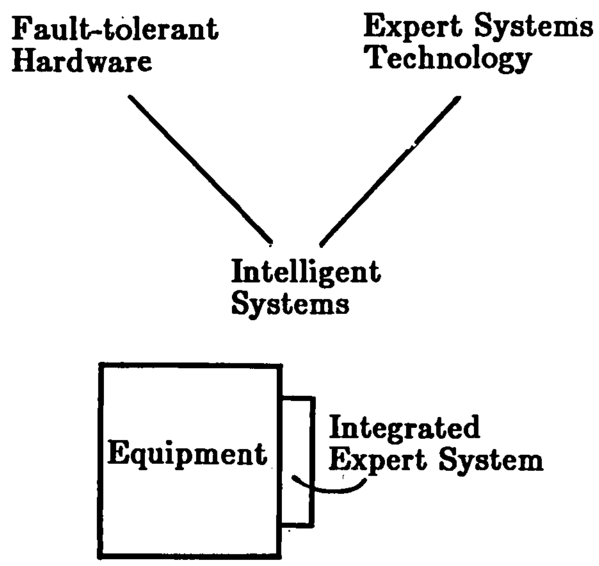

Chart 42

The intelligent system is a result of merging fault-tolerant hardware with expert systems technology. The dramatic reductions in computer hardware size and price have made it feasible for complex pieces of equipment to contain their own dedicated computers with built-in expert systems. These integrated expert systems can monitor equipment operation, diagnose faults, and suggest repairs. This produces intelligent systems that are self-diagnosing and self-correcting, with built-in workarounds.

RECOMMENDED APPLICATIONS

Intelligent Systems

Integrated Expert System:

An expert system embedded in a microprocessor chip to form an integrated hardware/software package

Example:

EEG Analysis System, an expert system in a Motorola MC6801 single-chip microprocessor

Application:

Interprets EEG's recorded from renal patients

Chart 43

Intelligent systems. Advances in computer hardware have made possible *integrated expert systems*; expert systems embedded in microprocessor chips. One example of this is the EEG Analysis System, an expert system designed to interpret electroencephalograms recorded from renal patients. Integrated expert systems can be embedded in equipment, such as complex electronic gear, to form what can be called *intelligent systems*.

RECOMMENDED APPLICATIONS

Intelligent Systems

Intelligent System:

An integrated expert system embedded in a piece of equipment, such as complex electronic gear

Example:

SPE, an expert system in a microprocessor inside CliniScan, Helena Laboratories' scanning densitometer.

Application:

Inteprets densitometer waveforms to diagnose patient diseases

Chart 44

One example of an intelligent system is SPE, an expert system embedded in CliniScan, Helena Laboratories scanning densitometer. The resulting intelligent system interprets densitometer waveforms to determine which of several diseases a patient might have. The system is now in commercial use.

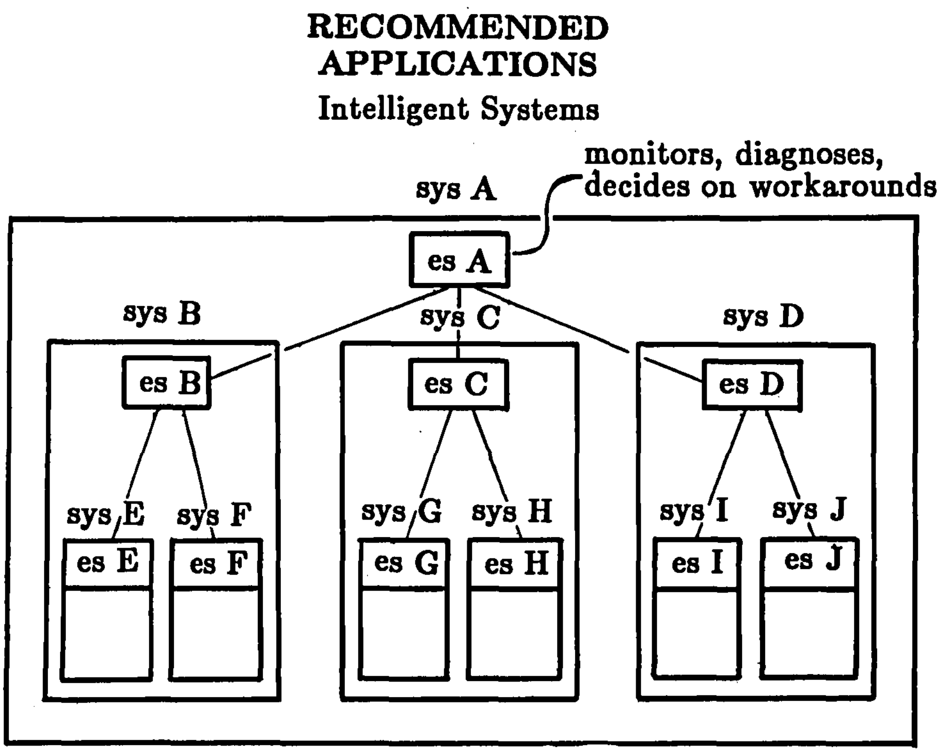

Chart 45

Intelligent systems can be arranged in a hierarchical configuration. Here the physical units are organized into a network structure. Each has an attached integrated expert system that monitors the operation of the system, its components, and suggests workarounds when lower-level system components are not operational.

RECOMMENDED APPLICATIONS

Fault-tolerant Design

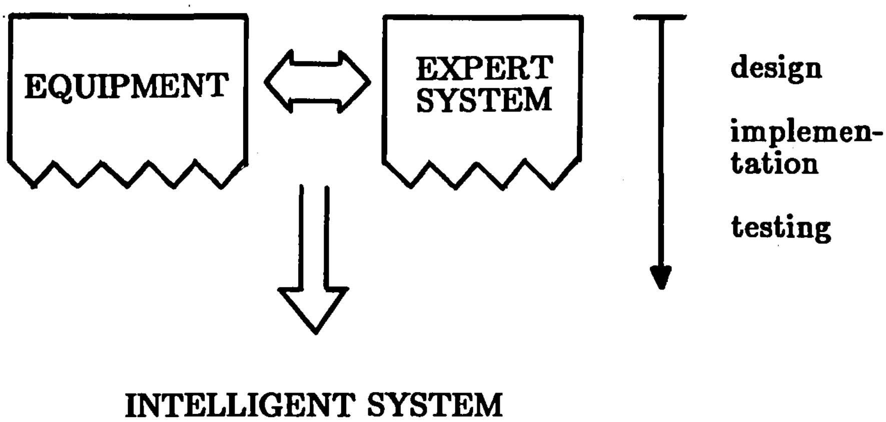

Chart 46

Fault-tolerant design. Here the idea is to have the expert system developed in conjunction with the design of the physical unit--this influences the design process and results in a fault-tolerant design and a hardware-software symbiosis. An expert system can also be developed to work with CAD systems to help the equipment designer develop a fault-tolerant design.

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