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RESEARCH IN PROGRESS

Artificial Intelligence Research and Applications at the NASA Johnson Space Center

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Abstract

Research and applications work in AI is being conducted by several groups at Johnson Space Center (JSC). These are primarily independent groups that interact with each other on an informal basis. In the Research and Engineering Directorate, these groups include (1) the Artificial Intelligence and Information Sciences Office, (2) the Simulation and Avionics Integration Division, (3) the Avionics Systems Division (ASD), and (4) the Tracking and Communications Division. In the Space Operations Directorate, these groups include (1) the Mission Planning and Analysis Division—Technology Development and Applications Branch, (2) the Spacecraft Software Division, and (3) the Systems Division—Systems Support Section. The first part of the article describes the AI work in the Research and Engineering Directorate. The second part of the article, to be published in the Conference edition of the *AI Magazine*, describes the AI work in the Space Operations Directorate.

Artificial Intelligence and Information Sciences Offices

The Artificial Intelligence and Information Sciences Office of the Research and Engineering Directorate at the Johnson Space Center (JSC) has as its basic responsibility the function of "consulting through research," that is, matching technology in universities, industry, and other NASA centers to space station applications. This requires staying abreast of the state of the art by conducting technology development and applications research in knowledge-based systems, machine vision, and robotics. A significant contribution of the AI office is the support of space station system engineering and integration (SE&I) activities.

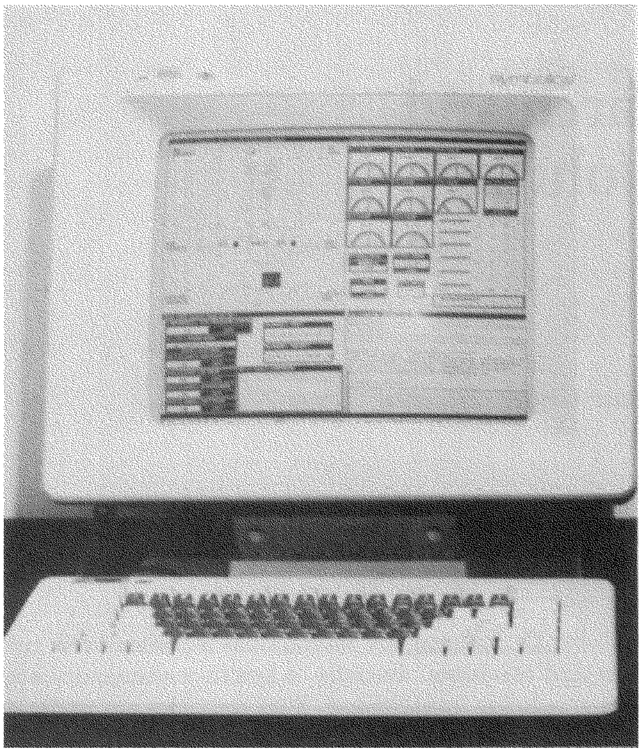
The AI office was formed in October 1984 and currently has a staff of twelve civil service personnel. Facilities include a Symbolics 3600 and a Symbolics 3670; a VAX 11/780 operating under ULTRIX (a Unix look-alike); and a robotics laboratory with a multiple-arm mobile robot, vision sensors, and mock-ups for simulating satellite servicing. Software tools for expert system development include MRS from Stanford and IntelliCorp's KEE.

Current research activities center on four areas of interest: intelligent system control; robotics and machine vision; intelligent displays and man-machine interfaces; and SE&I. The work in intelligent system control focuses on using expert system technology to develop intelligent, autonomous systems for the space station. Research in robotics and machine vision utilizes the robot laboratory facilities to develop algorithms for computer vision and robot control. The research emphasis is on the creation of intelligent software rather than mechanical systems. Work in man-machine interfaces is examining the use of expert systems to enhance the interactions between crew members and machines. Initially, a health-maintenance application is being investigated. Two activities are under way in SE&I. An automation and robotics (A&R) trade study looks at a number of criteria to evaluate space station design alternatives with regard to A&R. The other study examines methods of capturing design knowledge that is needed to support expert systems performing diagnostics or maintenance on space station systems.

Intelligent System Control

Work in this area is focused on identifying and resolving issues related to the use of artificial intelligence, especially expert systems, for developing and operating intel-

This is the first part of a two-part article describing AI work at the NASA Johnson Space Center



CS-1 Fixer Interface and Controller
Figure 1

ligent autonomous space systems. The research and development efforts have focused initially on expert systems to enhance the automated fault-management capabilities of space subsystem controllers. The work includes studies of effective approaches to knowledge engineering and knowledge acquisition during extended subsystem development, studies of the role of artificial intelligence versus conventional software in automating controller functions, and studies of the use of schematics and qualitative system models and simulators for automated verification and man-machine interface during development and operation of intelligent fault-managing software.

Two prototype expert systems have been developed, demonstrating fault-management expertise for the shuttle pressure control system (PCS) and for a space station prototype CO_2 removal module for the environmental control and life support system (ECLSS).

CS-1 FIXER: Fault Isolation and Correction. This software was developed by AI office and ECLSS engineering personnel, using the KEE 2.0 tool from IntelliCorp. The expert system is a prototype for managing faults in the CS-1, an electrochemical CO_2 removal system with a one-person capacity, which was developed and tested as a space station prototype. The FIXER software includes the expert system, a test-case generator, a simple simulator, and an operator-programmer interface. The project included a study of the effects of direct involvement of the expert in expert system software development, using a higher-order knowledge engineering environment. This approach also helped identify further knowledge engineering advances that would aid the process of developing fault-managing software systems. (See Figure 1.)

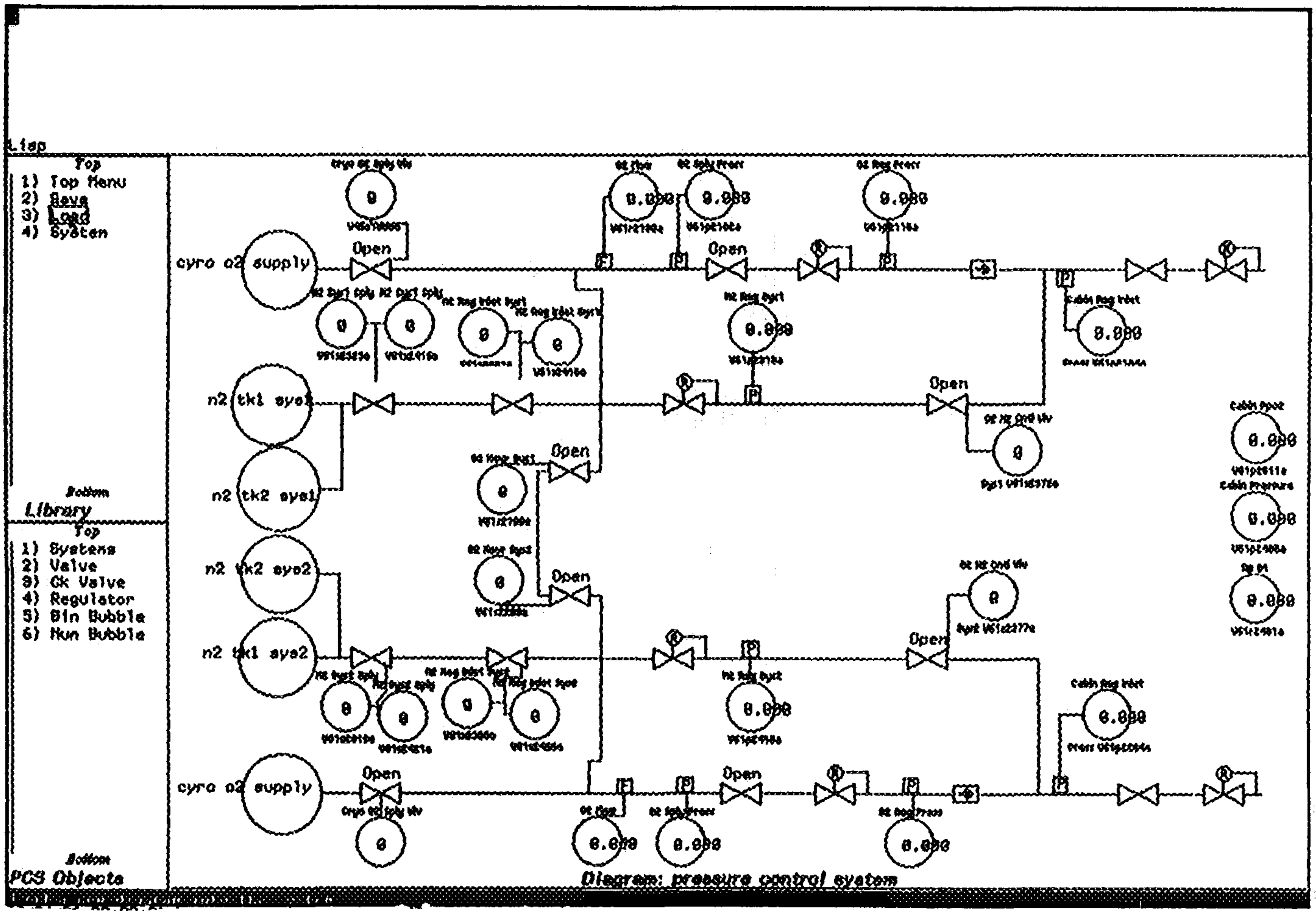
PCS: Deducing System Configuration. This software was developed by AI office personnel in conjunction with Space Operations Directorate personnel using the MRS software development system from Stanford University that was enhanced by in-house-developed software. The PCS software consists of an expert system that determines the configuration of the PCS from sparse instrumentation and a man-machine interface consisting of an active graphic schematic (see Figure 2). If it is determined that a "nominal" configuration exists, predefined malfunction procedures can be applied. Initial results have indicated the importance of qualitative system models and system simulation for development of fault-managing expert systems.

Additional issues need to be addressed in the future to provide information relevant to space station design studies. These include approaches to extracting subsystem data; embedding intelligent software in subsystem controllers; distributing intelligent control; and integrating expert system development into various stages in the process of design, development, and documentation of system hardware and software. Initial knowledge engineering studies have led to investigations in the areas of qualitative system modeling and man-machine interface. The man-machine interface work concerns the use of schematics and other graphic symbols to explain the plans and actions of intelligent systems. The qualitative system modeling work concerns the types of representations that could support cooperative man-machine problem solving (diagnosis or fault management) of complex system behavior based on structural system descriptions. A current project under way with engineering personnel working on the space station communications and tracking (C&T) subsystem provides an additional application for studying issues in the development of intelligent autonomous system controllers.

Participants: Jane Malin (contact), Tom Pendleton, Ken Baker, Brian Basham, and Nick Lance.
References: Lance & Malin (1985); Malin & Lance (1985a, 1985b).

Robotics and Machine Vision

The Artificial Intelligence and Information Sciences Office has designed and developed a low-budget test bed for investigating the capabilities and limitations of computer vision and autonomous robotic technology for proximity servicing of space station elements. During the past year, available hardware and software have been acquired



Active Schematic Diagram of the Space Shuttle Pressure Control System

Figure 2

and used in developing robot-servicing simulations to learn about the state of the art and some of the practical problems encountered.

A mock-up of a satellite has been built with six tasks in mind: replacing an electronic module, refueling, repairing a solar array, replacing a battery, rendezvousing and station keeping. A mobile robot base has been developed to perform the tasks. It has a two-wheel reversible drive system for mobility, two Microbot Teachmover five degree-of-freedom programmable robot arms for manipulation, a Polaroid ultrasonic sensor for ranging, two touch sensors for docking, a flood lamp for lighting, and two black-and-white video cameras for vision (see Figure 3).

The mobile robot base and the robot arms are controlled through an IBM PC-XT, using software developed in C. A PCVISION frame grabber board, installed in an IBM PC, provides the vision processor. Vision software has been implemented using Turbo Pascal. The IBM PC and the IBM PC-XT have been networked together to allow the vision-processing software to command the robot base and arms. Currently, the vision system is used only for docking the robot base with the satellite mock-up by way of simple pattern-recognition techniques.

Modular routines have been developed, based on the robot coordinate system, for removal and insertion of modules on the satellite mock-up. These routines are automatically initiated by the vision software once docking has been accomplished. Currently, there is no vision or force feedback for arm or gripper control. Future plans include using vision for robot arm and manipulator control.

Development of a robot task planner has recently been started. A primitive version for two-dimensional trajectory planning in a known environment (known in the sense that all objects in, say, a room are in a fixed position stored in the knowledge base) has been implemented on a Symbolics machine using Lisp. Future plans include networking the Symbolics machine to the IBM PC-XT and the IBM PC to provide the "intelligence" for the robot.

Plans also include implementing voice I/O on the robot system. A speaker-dependent, connected-speech recognition board for the IBM PC, including voice output, has been ordered.

Participants: R. Goode (contact), B. Basham, J. Gilbert, M. Heidt, R. Heydorn, and G. Houston.

Intelligent Displays and Man-Machine Interfaces

Work in this area is focused on identifying and resolving issues related to the use of AI technology, including expert systems, to optimize the interactive cooperation between man and machine in solving problems and managing tasks on the space station. This research and development effort is focused initially on a health-maintenance facility (HMF) expert system.

HMF Exercise System Physiological and Motivational Displays/Protocol Manager and Validation Expert System. This expert system monitors and manages the space station crew members' exercise sessions and assists in the assessment of cardiovascular and muscle-strength conditioning during long-term exposure to the "zero-g" environment. The expert system must also perform in-flight validation of exercise protocols based on comparative analysis of preflight, inflight, and postflight exercise performance trends. Distributed problem solving, inferential and inductive reasoning, and relational databasing will be implemented in this exercise protocol manager for in-flight validation of exercise protocols (see Figure 4).

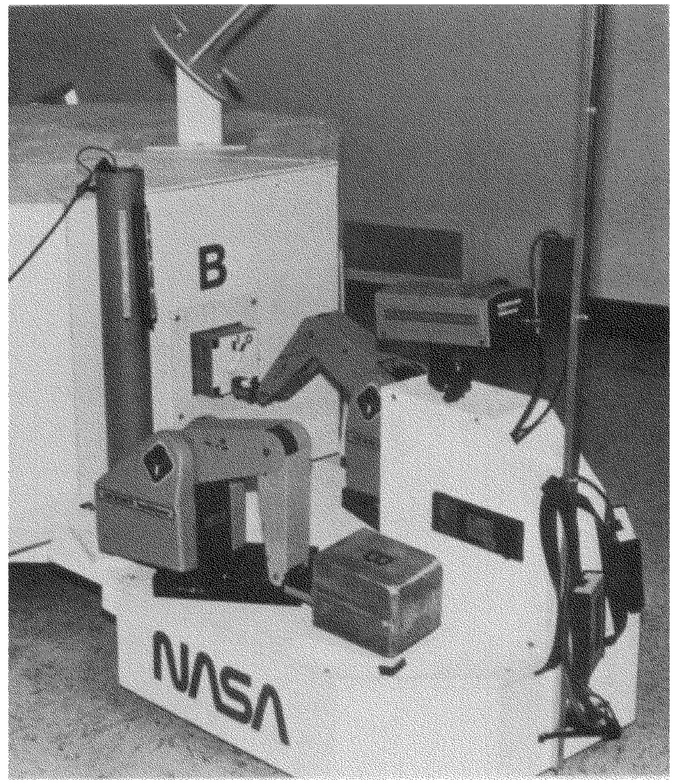
Development of this expert system will also include intelligent displays and will explore the issue of man-machine interactive cooperative problem solving and task management.

Participants: Laurie Webster (contact), Dave Wolf.
Reference: Webster (1985).

System Engineering and Integration

The AI office is involved in SE&I activities in support of the Space Station program. Current work in this area includes A&R trade studies and design knowledge bases.

Design Knowledge Bases. The goal of the design knowledge base effort is to identify the types of knowledge to capture during design of the space station and its subsystems and the hardware-software system to use in capturing the knowledge. The knowledge being sought is that which would aid an expert system or intelligent robot in some essential function, such as maintenance or repair, on a space station subsystem. It is essential that such knowledge be captured during design while it is still available and that the knowledge capture be accomplished in a way which does not unduly impact the designer. The format for the knowledge will ultimately be important because it must be integrated with the technical and management information system (TMIS) of NASA and it must be easily accessible by AI programs.



Satellite Module Replacement Simulation

Figure 3

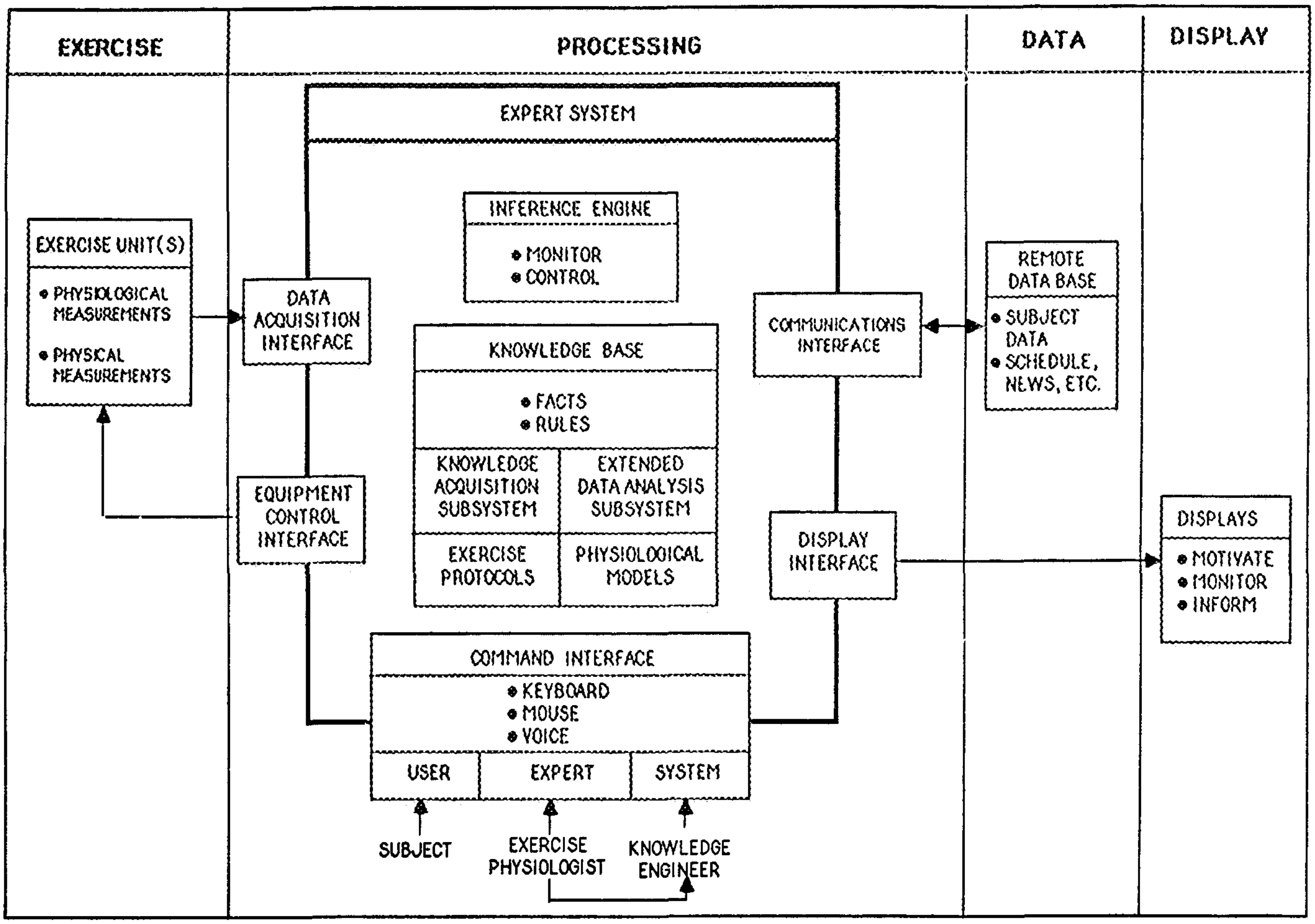
A preliminary version of a document specifying design knowledge to capture and the system to capture it with has been produced. Input for the document was provided by a workshop held at JSC in September 1985.

Future work includes further definition of the types of knowledge to be captured as well as investigation of possible systems to capture the knowledge, leading to a formal space station specification. Innovative AI-based environments for engineering design will be examined, and issues associated with the format of the knowledge in a knowledge base and integration with TMIS will be studied.

Participant: Ken Crouse (contact).

A&R Trade Studies. The purpose of the A&R trade studies is to analyze potential benefits of introducing robotic teleoperator and artificial intelligence concepts into the design of the space station. Given a number of possible design options, this study will attempt to compare these options relative to a number of competing criteria. The criteria will include life-cycle cost, productivity, maintainability, and safety. Since A&R can aid and sometimes replace space station crew members, beneficial trades of this kind are the prime focus of the study.

Uses of A&R that can reduce the life-cycle cost of the



HMF Exercise Monitoring and Control System Prototype

Figure 4

space station and increase its productivity are being studied using economic network models. These models view the space station as a collection of service elements, each of which produce a product; supply services; and, in return, demand services from other elements. By introducing A&R into these service elements, the impact on cost and productivity can be examined. Other models that lead to a prioritization of alternative A&R applications by simultaneously considering several attributes (in addition to cost and productivity) are being developed

Once the space station is in place, it is expected that evolutionary versions will emerge in which artificial intelligence and robotics take over major portions of the station operation. In fact, space station designs that are being developed today are expected to be properly "scarred" to allow for growth. Although "conventional" management tools are being developed to decide today's issues on the proper placement of artificial intelligence and robotics in the space station, artificial intelligence will also play a central role in these management tools of the future. Automatic-planning and automatic-scheduling expert systems that make use of multiattribute decision-making models and economic networks are envisioned for management tools capable of guiding the evolutionary development of the space station.

Participant: Dick Heydorn (contact).

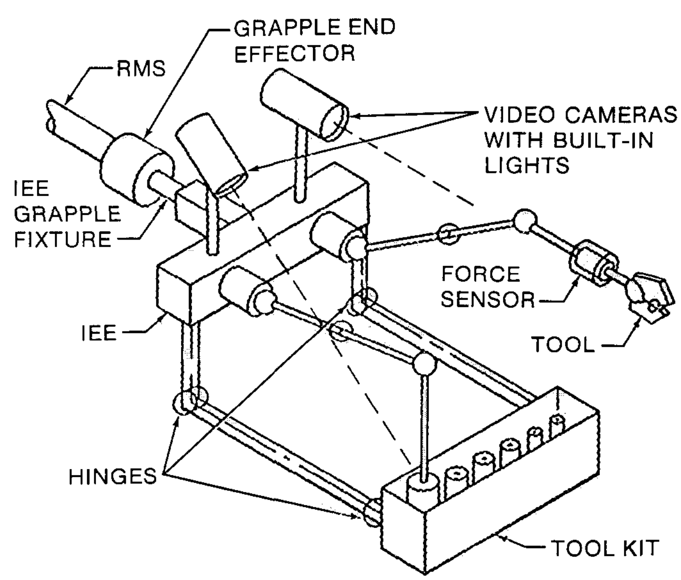
Simulation and Avionics Integration Division

The Simulation and Avionics Integration Division is responsible for the development and operation of the systems engineering simulator (SES), the primary JSC facility for real-time man-in-the-loop and hardware-in-the-loop engineering simulation. A major capability of the SES is a multibody, on-orbit, real-time simulation with orbiter, space station, manned maneuvering unit (MMU), payloads or rendezvous targets, remote manipulator system (RMS) and mobile RMS (MRMS) simulations. Integrated with the on-orbit simulation are an orbiter aft flight deck, a crew control mockup (CCM) and an MMU fixed-base crew station, all with displays, controls, and visuals. This simulation is used for engineering evaluations and on-orbit procedures development.

An LMI 2X2 Plus AI computer and an LMI Lambda AI computer were installed in the SES in January 1985 and September 1985, respectively. High-speed interface boards (LMI 2X2–SEL 32/87) and Ethernet interface boards (Lambda–SEL 32/75) are being installed to integrate these AI computers with the SES simulation computers.

The goals of the SES AI group are to demonstrate the applicability of AI techniques to orbiter and space station applications and to provide a facility where expert systems can be developed and integrated with real-time simulations and man-in-the-loop and hardware-in-the-loop operations. Integrated expert system studies in the SES will be especially valuable for early engineering evaluation of on-board hardware and software requirements with respect to expert systems and for the evaluation of expert system interface requirements with respect to man-in-the-loop operations.

Initially, several expert system prototypes were chosen for development for the purposes of providing early demonstrations to the JSC community and of developing AI skills. (Most of these prototypes are designed to operate in a stand-alone mode; that is, they are not integrated with the SES real-time simulations.)



Artist's Conception of Dual Arm IEE

Figure 5

Intelligent End Effector (IEE) Expert System

The intelligent end-effector (IEE) expert system is a collection of expert systems for scheduling and controlling a simulated end effector online. The IEE expert systems are written in Prolog and ZetaLisp and are implemented on a Lisp processor in the LMI 2X2 Plus computer. The IEE simulation is written in C and implemented on the Unix processor of the same LMI. The expert systems interface with the IEE simulation using shared memory and interface with the user by way of an LMI workstation.

The simulated end effector has two articulated arms. (See Figure 5.) It is assumed to be a loadable device at the space shuttle's RMS end effector and is to be used as a self-controlled device to perform tasks such as repair operations on stationary satellites and space station truss assembly. The end effector is equipped with a tool kit and a vision system, the latter of which is simulated in the LMI's Unix processor. A graphics simulation of the IEE and its environment is displayed on a high-resolution color monitor during execution of IEE tasks.

Each arm has four degrees of freedom, (one shoulder, one elbow, two wrist joints), and is simulated with rigid arm-link dynamics. Various end-effector specifications and faults are selectable by the user through an LMI workstation. For each joint, the user specifies the type—translational or rotational—and the actively driven axis. The user also selects active or passive freeplay in the off-driven axes and specifies the mass and geometric properties of each arm link. The simulation features a microgravity digital feedback control system with variable configuration joint servo controllers, selectable by the IEE expert systems. The simulated faults selectable by the user include movable trajectory obstacles, vision system faults, and various IEE malfunctions, such as joint run, tachometer fault, shaft encoder fault, end-effector overload, motor temperature and current out-of-tolerance conditions, tool time-outs, reach limits, and adaptation and feedback control faults.

The expert systems include an automatic task interpreter (ATI), a trajectory planner, a load adapter module, and a health monitor system. The ATI, given a desired end-effector state (position, velocity, acceleration, and so on) input by the user and a known current state, determines the feasibility of the desired transition based on inputs requested from the simulated vision system, the health monitor system, and the load adapter module. The ATI attempts to partition the desired transition into feasible segments, if necessary. (It might be that the desired transition is not feasible, at which point the user is informed of the problem.) Once the desired transition is determined to be feasible, the trajectory planner selects primitives from its trajectory primitives database to effect the transition. These primitives are used to generate minimal time, minimal energy, or polynomial interpolation trajectories. The execution of the desired transition is effected through trajectory planner commands sent on a 20-ms frame time to the IEE's variable configuration controller. The controller uses deterministic algorithms from its algorithm pool to generate joint servo commands and freeplay commands necessary for compliance.

The ATI monitors inputs from the simulated vision system, the load adapter module, the health monitor system, and the user on a 20-ms frame time. Should malfunctions occur during the execution of the desired transition, such as an obstacle entering the planned trajectory path, tool time-outs, shaft encoder faults, and so on, the ATI attempts to adapt to the malfunction (for example, resegment trajectory in case of obstacles). If adaptation is not possible, the ATI aborts the execution of the desired transition and notifies the user.

Participants: W. Kohn, D. Lai, D. Widjaja, R. Campbell/LEMSCO, and K. J. Healey/JSC (contact).
References: Campbell & Kohn (1985); Jurica, Kohn & Lai (1985); Kohn & Healey (1986); Kohn & Valkenburg (1985a, 1985b); and Widjaja (1985).

Automatic Procedures Generator for Orbital Rendezvous Maneuver

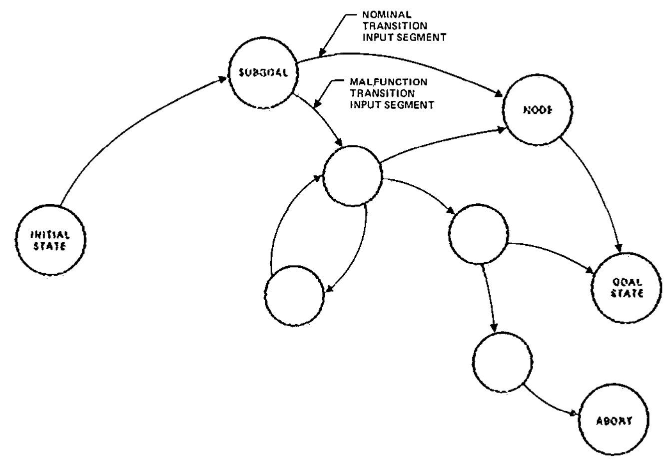
Rendezvous between the orbiter and other vehicles or payloads (for example, satellites and, later, the space station) currently involves the development of procedures detailing the phases, required maneuvers, and conditions that must prevail for rendezvous completion. Once developed, these procedures are published in documents that the astronauts must study and take on board for reference during flights. This process is repeated for each mission and for each rendezvous within that mission. Additionally, should unforeseen anomalies occur during a flight, new procedures must be developed and tested in real time in ground simulators and relayed to the crew.

The expert system automates the generation of the procedures and documents those procedures in the form of directed graphs, in which the nodes represent the state of the vehicles at each stage or procedural event, and the edges represent transitions (for example, jet firings) between these events. Three special nodes on the graph are the initial event, the goal event, and the abort event. The initial and goal events are inputs to the expert system. The abort event represents inability or failure to achieve the goal event (see Figure 6).

The knowledge database is composed of three sets of rules or heuristics:

Navigation Laws. These are rules that are dynamically driven by an on-orbit simulation of the vehicles and their currently active control laws. The simulation, which provides the vehicle states as measured by the on board sensors, is written in C and executes on a SEL 32/87 computer. The LMI and SEL computers are connected by way of high-speed interface boards.

Sensor Rules. These are rules and associated heuristics that represent the operation of those sensors considered in this study, a radar, and a crew optical alignment sight (COAS), installed in one of the vehicles involved in the rendezvous maneuver. It is assumed that other sensors are operated correctly and perform perfectly.



Conceptual Directed
Graph Representing Procedure

Figure 6

Man-Machine Interactions. These are heuristics that represent all crew-initiated actions, including erroneous actions or omissions.

The expert system constructs a directed graph with the minimum number of events that satisfy these rules.

During execution of the desired maneuver, a subset of the directed graph is displayed to the crew on a monitor. This subset consists of nodes representing the previous event, the current event, and the next event. The nodes are connected by lines that represent the associated transitions. The crew can obtain detailed information about each event or transition (for example, crew actions required to effect the transition from the current event to the next event) by "mousing" the appropriate node or connecting line. The directed graph subset is dynamically updated to reflect nominal and off-nominal (due to sensor failures, and so on), transitions to new events.

An expert system such as this one is essentially a crew assistant. However, it has the potential of evolving to an autonomous rendezvous expert system that is merely supervised by on-board crew members. Additionally, the techniques developed for this prototype are widely applicable to space procedures other than those of rendezvous.

Participants: C. Dunn (contact), J. Van Valkenburg, R. Norsworthy, K. Hopping, and W. Kohn/LEMSCO.
References: Hopping (1986); Kohn (1985a, 1985d); Kohn, Van Valkenburg & Dunn (1985).

Simulation Aided Design Tool for Distributed Control of the Space Station

Given a set of system performance requirements, a set of available sensor and actuator dynamics, and a plant dynamics definition, this expert system constructs a distributed digital controller that satisfies requirements, is robust (adaptable) for a given range of uncertainty and a given set of malfunctions, minimizes intercontroller data flow, and minimizes expected control-moment gyros (CMG) saturation. Sensor, actuator, and plant dynamics are input in the form of symbolic Z-transfer functions.

The expert system is evaluated using a simulation of the space station initial operating configuration (IOC), with CMGs and reaction control system (RCS) actuators, inertial measurement units (IMUs), attitude gyros, and a laser radar as sensors. A flow-state processor network is used as the implementation bed for the controller. Linear (dead-beat, algebraic synthesis, linear quadratic) and extended bang-bang quantized control-law techniques are used.

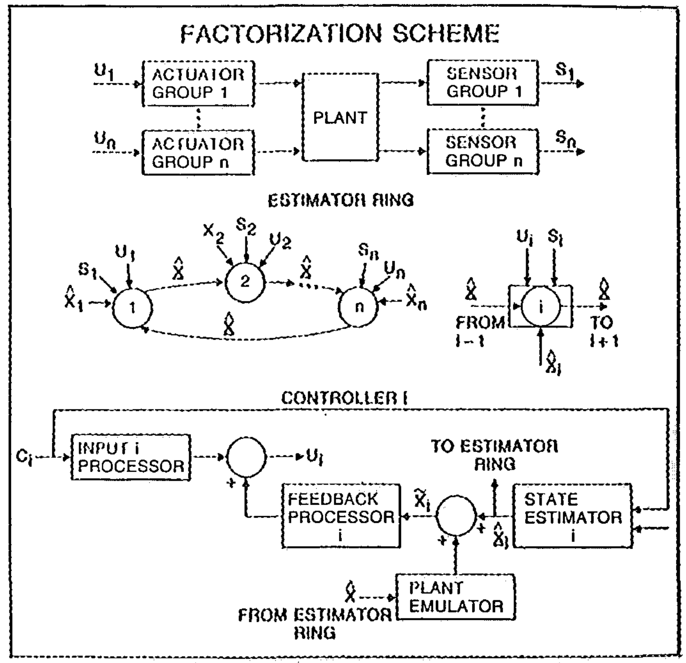
The expert system first generates a centralized controller transfer function from the requirements, a symbolic multivariable transfer function mathematics knowledge base, and a control techniques knowledge base. A simulation program for the symbolic centralized design with parameter-evaluation design capabilities or parameter estimators is generated in C. Closed-loop simulations of the candidate centralized design and the space station are run and evaluated. This procedure is repeated iteratively until a design meeting all requirements is generated (if possible).

Given a satisfactory centralized controller transfer function, the expert system generates a symbolic distributed controller adapted to the flow-state processor network, which minimizes degradation with respect to the centralized controller. Knowledge bases for the distribution include transfer function factorization, separation, and hierarchical decomposition. As in the design and testing of the centralized controller, a simulation program is generated, and the distributed controller is evaluated through closed-loop simulations (see Figure 7).

This expert system and simulation are implemented on the LMI 2X2 Plus, the expert system in Prolog and ZetaLisp, and the simulation in C. The expert system executes in a Lisp processor, and the simulation executes in the Unix processor. This expert system allows symbolic adaptive design of large-space structure control systems; accommodates changes in requirements after the initial design; and facilitates parametric studies for sensor and actuator designs, locations, and groupings. The flow-state processor network distribution scheme tolerates processor failure with minimum system performance degradation.

Several enhancements of this expert system are being considered. In most real-world situations, the models of plant, sensor, actuator, and flex dynamics are presented to the designer as a set of ordinary nonlinear differential equations. It is proposed to incorporate modules to linearize and discretize these differential equations.

The linearization module would accept from the user a model of an item as a set of coupled ordinary differential equations and a set of linearization requirements



Distribution of the Centralized Controller

Figure 7

and then generate a linear set of differential equations representing the item dynamics. Three user-selectable linearization techniques would be incorporated: (1) linearization around an equilibrium point (user selectable), (2) linearization around a trajectory (either user specified or propagated by the system), and (3) piece-wise linearization (propagated by the system). The discretization module would take the output of the linearization module and generate the corresponding Z-transfer function matrix.

An additional enhancement under consideration is that of an expert system for the optimal allocation of sensors and actuators. The user specifies the optimization criterion, and the system uses it and a rule base to generate a finite set of allocation alternatives. The enhanced distributed control expert system would then be called to generate a controller design for each alternative. Each design would be evaluated using the user-supplied criterion.

The optimal-allocation expert system would then generate a new set of potentially better allocation alternatives by perturbing (singular perturbation) the best of the previously evaluated alternatives. For each new alternative, the cycle above is repeated until some termination law (to be determined) is satisfied.

Participants: W. Kohn (contact), R. Norsworthy, and J. Arellano/LEMSCO.
References: Arellano & Kohn (1985); Kohn (1985a, 1985b, 1985c, 1986); Kohn & Norsworthy (1985); Norsworthy, Kohn & Arellano (1985).

Expert System Requirements Analyzer (ESRA)

Current SES software simulation requirements "push" the available memory and duty-cycle limits of the simulation computer hardware. The integration of new software simulation requirements requires a high level of human expertise and is labor intensive. Designing configurations for new simulations is equally difficult. Because the SES is frequently tasked to upgrade or modify its simulations in a timely manner, an expert system, ESRA, is under development to automate these functions. ESRA is implemented in Prolog and ZetaLisp on the LMI 2X2 Plus. ESRA is a breadth-first search expert system that solves the following class of computer software configuration problems: Given (1) a finite set of routines that completely satisfy a simulation's requirements, (2) a set of identical multitask processors, each with cache memory, (3) a central shared memory area (data pool) that is shared by all processors, and (4) an initial feasible configuration, find an allocation of routines to tasks and tasks to processors that satisfies routine frequency requirements, satisfies the data dependencies between routines, and minimizes the duty cycle of the implementation. Minimizing the implementation duty cycle is defined as maximizing task concurrency, subject to data dependencies among routines, task size constraints, cache size and probability law constraints, and context-switching heuristic constraints.

Each routine is represented by its name, size, execution-time function, frequency, and input and output variables. The expert system generates a causality tree, representing the data dependencies among routines, from the input and output variable information. Then, using concatenations of defined configuration generators (task create, task combine, processor allocate, and so on), ESRA produces an improved software configuration. This process is continued iteratively to generate other configurations. Each configuration is evaluated according to evaluation heuristics to determine whether it meets all requirements. After a predetermined number of iterations, the best configuration generated is selected.

Initially, concatenations of configuration generators are selected at random. However, ESRA maintains and updates a statistics knowledge base during its execution that is used to weight the concatenations according to their success under various configurations. The final state of this knowledge base is used as the initial state of the knowledge base for the next execution of ESRA.

Participants: V. Yuen (contact), K. Hopping, P. Kane, and W. Kohn/LEMSCO.
References: Kane, Yuen, Hopping, & Kohn (1985).

The CCM Expert System

The CCM is a mock-up that provides a means to explore, develop, and demonstrate new display and control devices and techniques for possible use on-board the space station. It consists of a command and control center, a proximity operations center, and a control and display development center. It is integrated with the SES real-time on-orbit space station simulation, including real-time functional simulations of various space station subsystems. The CCM expert system is designed to plan the reconfiguration of space station subsystems, based on the operational configuration, at notification of an unplanned event. The event is one that demands the reconfiguration be accomplished on short notice; therefore, the reconfiguration planning and implementation must be accomplished on board. Inputs to the expert system are read in a "single snapshot" from the space station subsystem simulations and the SES on-orbit simulation. Subsystems modeled include propulsion; guidance, navigation, and control; C&T; electric power distribution and control; environmental control and life support system; orbital maneuvering vehicle (OMV); and the MRMS. The expert system determines if the operation is feasible, produces a sequence of procedures and an associated time line, indicates potential problems, and displays the results to an on-board user. The on-board user then manually reconfigures the subsystems as specified by the expert system. Typical reconfiguration procedures are OMV safing, MRMS safing, powering up fuel cells, stowing solar panels, reorienting and holding space station altitute and so on (see Figures 8 and 9).

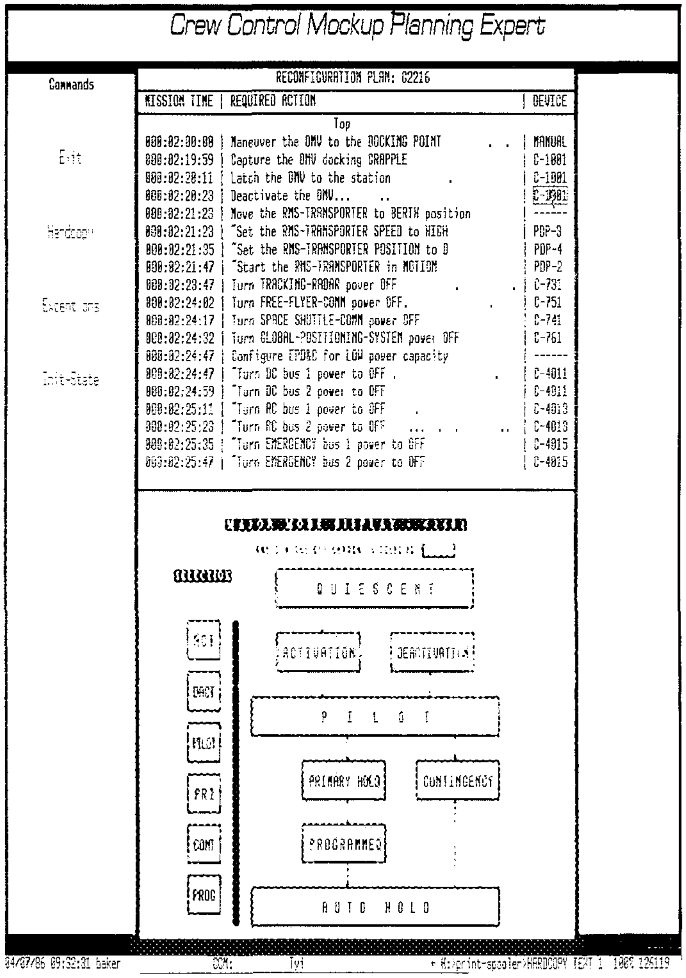
The initial expert system was developed on a Symbolics computer using ART and then ported to the LMI Lambda. The LMI workstation is located within the CCM adjacent to the subsystem controls and displays. The LMI is interfaced to the simulations through Ethernet.

Participants: S. Babb/JSC (contact), T. Baker and D. Herold/LEMSCO.

Power Subsystem Analysis and Diagnosis Expert System

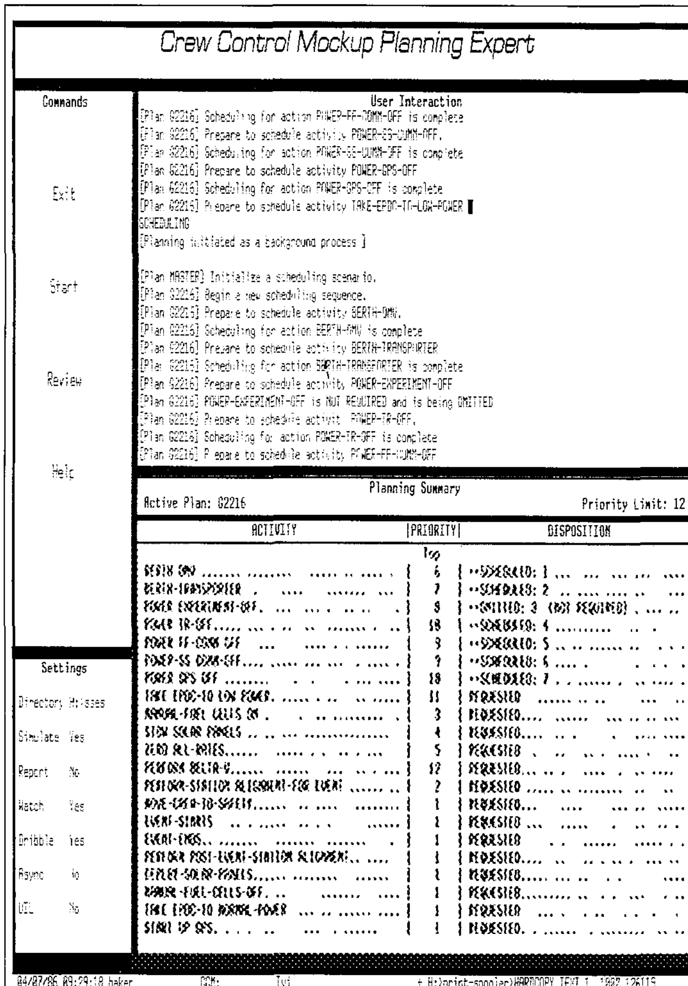
This expert system is implemented in OPS5 and executes on a VAX 11/780 in conjunction with a simulation of the power subsystem. The expert system analyzes and diagnoses faults that could occur in an H2/02 production and storage system typically found in a space power subsystem. The expert system reads parameters of the power subsystem once a second and determines if a "failure" flag is set. The parameters correspond to various subsystem sensor values for temperature, pressure, voltage, and so on. If a flag corresponding to a bad parameter value is set, the expert system analyzes the current system state and informs the operator of its analyses. If the expert system determines that certain units need to be replaced, it makes these requests known to the operator and simultaneously reconfigures the system. The expert system is designed to handle multiple, as well as single, faults.

In most cases, the expert system does not simply replace a unit if the parameter flag is set. (Some sensors indicate that a unit is bad regardless of other sensor states.



Reconfiguration Plan and
OMV Mode Control Display

Figure 8



Reconfiguration Planning in Progress

Figure 9

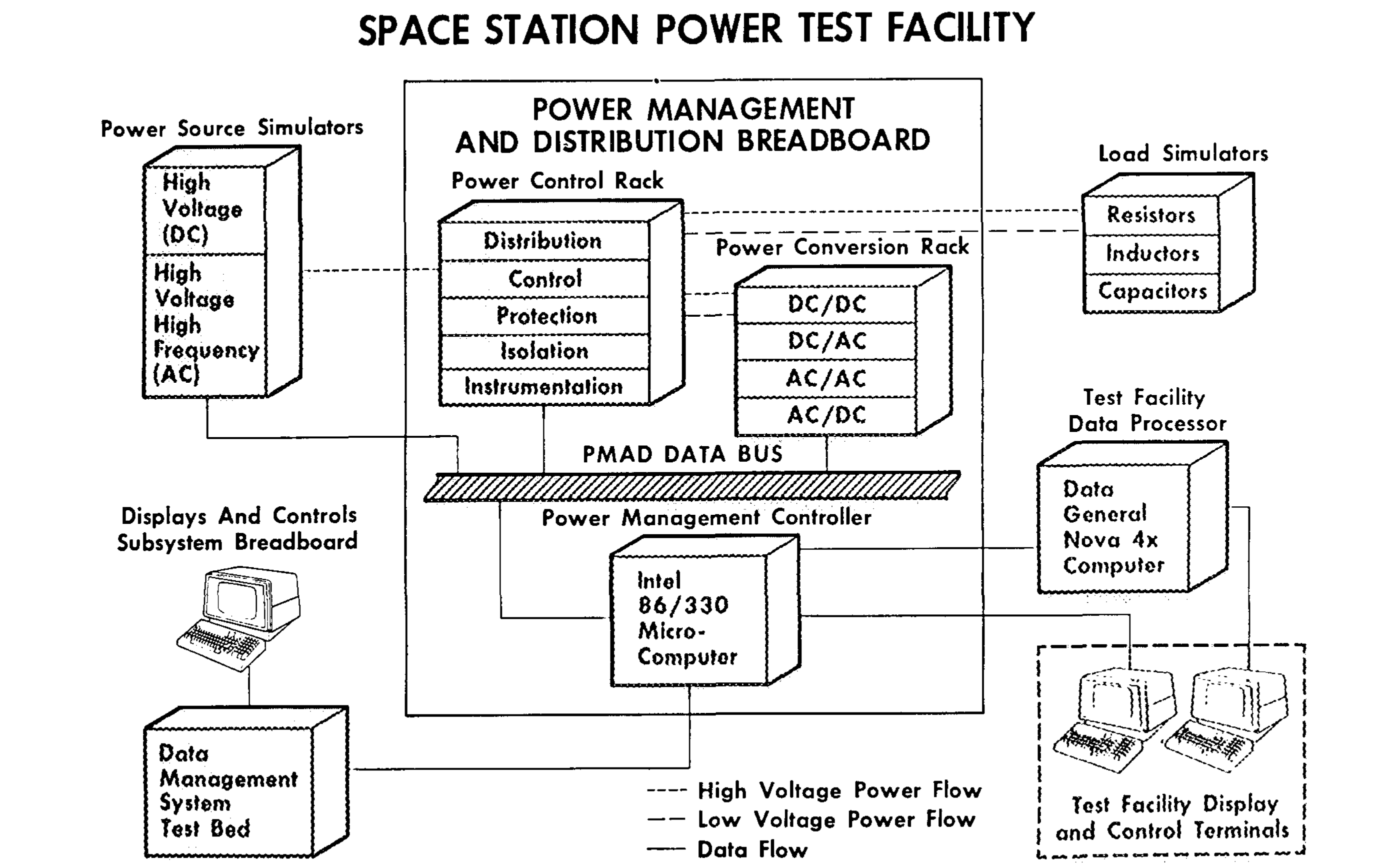
These indications require immediate action and notification of the operator. After the operator is notified, a complete failure analysis is conducted to ensure that the original diagnosis was correct.) Instead, the expert system performs a complete analysis by reading all of the parameters that affect the unit, both "up stream" and "down stream" of the affected unit, and tests the reasonableness of the failed parameter. If the other parameters do not reflect a state that could activate the flag, the operator is warned that the sensor itself might be suspect, and corrective action needs to be taken. Furthermore, the expert system can detect the failure of a component without sensors or a situation such as a blocked fluid line. Additionally, the expert system can detect the occurrence of a set of conditions that it does not understand, in which case the operator is notified.

Units of the subsystem are examined according to their probability of failure. The priorities can be changed as the expert system "learns" more about the history of the failure modes. At the end of a cycle in which a flag is noted, the expert system prints a complete analysis of the failure, including the "reasoning" used to make the final decision.

Participants: A Wetterstroem/JSC (contact), Dr. D. St. Clair, and V. Johnson/University of Missouri at Rolla.

Avionics Systems Division

The Avionics Systems Division (ASD) initiated a modest AI effort during the latter part of 1985. A Symbolics 3640 computer was purchased, and upgrades are planned for the ensuing years. Currently, an AI node is being installed on the ASD space station data management system test bed. It will be used to gain hands-on experience with potential space station on-board AI architectures. AI applications for generating initial conditions for large programs for analysis of integrated guidance, navigation, and control systems are also being investigated. This activity will



Space Station Power Test Facility

Figure 10

support both the shuttle program and the space station program. Other activities include the development of an expert system for electric power management and distribution, the development of advanced displays for inhabited spacecraft, and an investigation of general perception representations.

General Perception Representation

In developing techniques for computer perception, the usual approach has been to examine the observations for structure. Such techniques are frequently not enough. Vision processing, speech understanding, and tactile sensing are examples of computer perception. The purpose of this task is to identify the elements common to all types of perception and to represent them in a way that allows different kinds of observations to be used to form an estimate. Such an estimate would take the form of a probability distribution over the space of all possibilities.

Participant: Arland Actkinson (contact).

References: Actkinson (1985).

Expert System for Management and Distribution of Space Station Electric Power

The four manned spacecraft systems in the NASA program (Mercury, Gemini, Apollo, and Orbiter) have all utilized distribution systems for the electric power without automatic features except for the protection provided by fuses and circuit breakers. Crew input controlled all other functions. This method has been acceptable because of the relatively simple systems used in these vehicles, the short length of the missions, and the comparatively light work loads of the crew. However, the mission and scope of the space station program causes manual control of the electrical power management and distribution (PMaD) system to be totally impractical. The size and complexity of the space station control would demand far too much of the crew's time and effort if, indeed, it were feasible at all. Some responses to system operations might require speed that surpasses human capability and, therefore, must be performed automatically. With these requirements in mind, AI technology was investigated as a means of supplementing the planned automation of the system.

The space station PMaD is a utility. To serve the mission of the program it should be as nearly transparent to the crew as possible. The ideal system would operate under normal circumstances without assistance from the crew and would be able to inform the crew or the ground of its operating status on request. The crew and ground support personnel should be able to function with the assurance that they will be alerted to any change in the condition of the PMaD with immediacy based on the criticality of the change. The PMaD should be able to operate through minor contingencies without outside help, requiring crew assistance only when repair or replacement of failed components is necessary It is obvious from the foregoing that an expert system must be developed to accomplish these ends; consequently, the ESEP program was initiated

When it is fully developed, the ESEP will automate the operation of the space station PMaD during all stages of buildup and throughout its operational life. It will be capable of utilizing the multitude of power sources, accommodating various types of sources as the space station is updated, providing maximum power to a variety of ever-changing loads, and assuring optimum operation under various contingencies without human intervention or assistance. ESEP must evolve gradually, perhaps in the orbiting vehicle, but certainly during development of the PMaD design. It is essential that AI technology be incorporated at every available opportunity during the PMaD design and that provisions be made to allow the insertion of additional AI capabilities in the future.

ESEP will have to prove that it can provide control of the life-sustaining functions of the vehicle reliably and consistently. To assure this, the program must be able (1) to explain to the operator the logic behind a particular decision, (2) to incorporate new knowledge and accommodate PMaD modification, and (3) to learn from experience. The program, when in use, will evolve through four stages:

Appraisal. Its conclusions will be weighed against those of an expert.

Assistance. It will assist the crew and ground support personnel in troubleshooting system problems.

Selected Control. It will control operation of non-critical hardware and functions.

Critical Control. It will gradually take over control, with proper lockouts and overrides, of critical functions on board the vehicle.

To comply with the performance requirements, development of the ESEP program must begin concurrently with, or in advance of, the design of the space station PMaD itself; consequently, it must be designed to provide for updating, modifying, and reconfiguring

The specific goal of the ESEP is the development of an expert system for the space station PMaD However, the program itself is planned as a series of tasks, taking into consideration the expertise of the personnel involved, the hardware and software available, and the changing design of the PMaD. In Phase 1 a simple expert system was developed to aid in initializing the PMaD breadboard support and to test equipment. This program acquainted personnel with the more important aspects of expert systems. The program must be revised as the laboratory and breadboard are updated in the same way the space station ESEP will be revised—through periodic updating and reconfiguring (see Figure 10).

Phase 2 incorporated troubleshooting. If a problem arises ESEP leads the operator through a troubleshooting procedure and provides an adapted configuration. Future enhancements require the use of a more sophisticated expert system and hardware integration of the ESEP computer with the breadboard instrumentation system.

Participants. Bob Hendrix (contact), and Laura Staples.

Advanced Displays for Inhabited Spacecraft

As human-inhabited spacecraft become larger and more complex, there is a continuing trend toward increased complexity in both flight and ground subsystems that is causing higher and higher display—and control—integration expenses and crew and operator training costs. At JSC effort is being directed at the development of hardware and software technology that will support a generic display system which can represent a variety of spacecraft subsystems. Interactive responses will be hierarchically tiered to the current state of the subsystems. A proof-of-concept system is being developed that consists of three major components: a high-frequency control loop for a typical spacecraft subsystem such as electric power distribution, a lower-frequency loop that establishes and monitors subsystem trends, and a high-frequency display loop coupled with a voice input-output system for crew member interaction The three control loops will be constructed as dual-direction inference engines which operate on their respective knowledge bases as nodes on a global network that simulates the flight data system of the space station. The capability of the display node will include the generation of dynamic human images to provide visual representation of a subsystem expert.

Participants: Charles R. Price (contact), Richard D. Burghduff, and Andrew Farkas.

Tracking and Communications Division

The Tracking and Communications Division is involved in the development of an automated space station communications and tracking control and monitoring subsystem and in the development of vision systems for space applications.

Automated Communications and Tracking Inferencing Operations Nucleus (ACTION)

Under current operation, the space shuttle Orbiter C&T system is primarily controlled and managed from the ground. Dozens of communications and tracking "experts" on the ground monitor the hundreds of telemetry measurements, select the on-board equipment to be used, and configure it to support the current operational requirements. Thousands of procedures have been developed by the ground control "experts" to establish and maintain various C&T capabilities. These procedures are normally executed manually from the ground. The on-board crew can assume on-board control if the communications link to and from the ground is not available. However, when on board control is assumed, the crew must rely on previous training or on on-board C&T flight procedure manuals to manage the complex system.

To meet the requirement for autonomous C&T operation on board the space station, the crew will be expected to manage the C&T system with only occasional assistance from the ground "experts." The potential burden on the crew to meet this requirement could be immense because the space station C&T system will be much larger and more complex than that for the space shuttle orbiter. One solution is to integrate the C&T system management procedures into the software of the C&T control and monitoring subsystem (CMS). This enables the CMS computers to perform the routine management of the C&T system and, thus, assist the ground and on-board crew in performing this complex task.

The center of ACTION is a knowledge base of procedures to automate the configuration control and status monitoring functions.

Status Monitoring and Failure Management. The CMS will maintain a status base for the C&T system. Each measurement will be scanned before it is placed in the database to see if it is within the normal range of expected values. If not, the automated status keeper (ASK) function is called into action. The alleged abnormal measurement is validated, if possible, by checking other related sensor and performance measurement trend data. If a problem cannot be verified, the out-of-limit measurement is flagged, and no corrective action is taken. When a problem is verified and procedures are available in the rule base, immediate corrective action is taken, such as switching to a redundant unit, and the problem and corrective steps are reported to the crew and ground. If the corrective procedure is ineffective in returning the function to a normal state, the CMS will generate a caution and warning message to alert the ground or on-board crew. All software-automated functions will be designed so that they can be manually overridden.

Configuration Control. New C&T configuration requests will be selected from a display by the crew. The request will be received by the automated configuration control effector system software (ACCESS) and validated. If the request is authentic, the sequence of subcommands necessary to achieve the desired configuration will be generated from the procedures base and transmitted to the necessary equipment. The new configuration status will then be reported to ground and on-board crew through the status database.

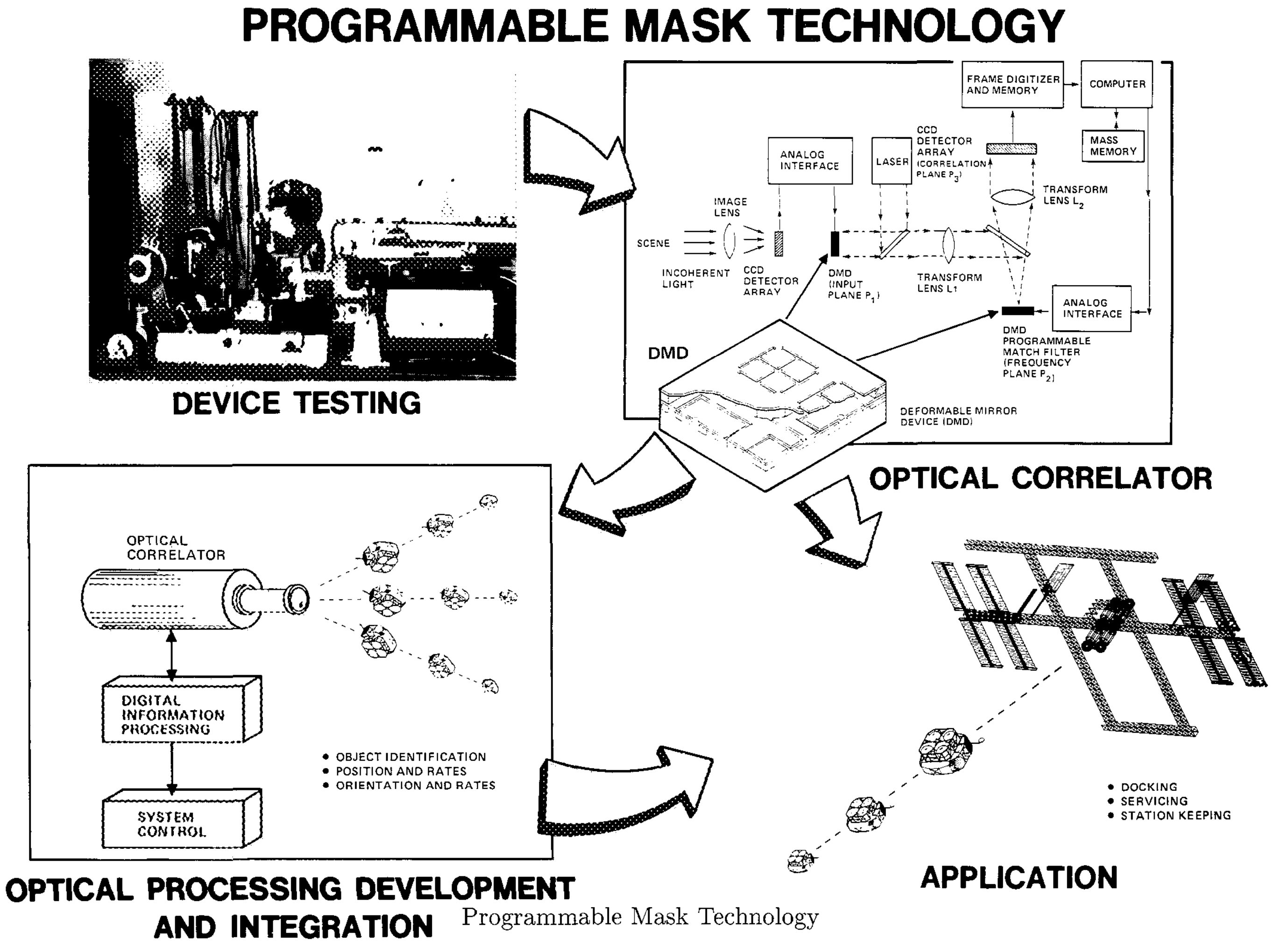
Participant: Oron L. Schmidt (contact).

Programmable Mask Technology

The objective of this program is to develop a vision system for space applications using the massively parallel capabilities of optical (coherent light) information processing. Areas pursued include development of suitable programmable mask devices (and of associated impulse deconvolution methods) and the development of a hybrid distributed-processing system (see Figure 11).

Generic categories that can benefit from optical information processing are pattern recognition, robotic vision, and Fourier transform analysis. Until recently, information-processing techniques for vision were based primarily on digital computers and numerical processing. The inherently parallel nature of optical information processing, coupled with the easy and natural optical Fourier transform analysis and the programmable masks, can obviate numerical processing for a substantial number of problems. The masks are used to modulate the optical Fourier transform of an input scene; an optical retransform then allows direct detection of, say, the mathematical correlation between the viewed scene and the reference image whose mask was placed at the location of the optical Fourier transform. Thus, any image computation that can be cast in the form of a correlation (or, equivalently, a convolution) between object and reference images is a candidate for optical processing, and this is a broad and powerful set of problems. Programmable masks are, as yet, in a rudimentary state, and methods of using them in vision systems also need development. The effects of the diffraction pattern of a single element and methods of compensating for them are one focus of the program. Another is the development of devices that have minimal effects for which to compensate. Yet another is the implementation of optical-processing masks for various vision problems (for example, discrimination and position estimation).

Finally, a hybrid system that mimics nature by distributing the information processing to best advantage between the system's "retina" and the optical correlator will be constructed The hybrid system will have flexibly specified digital spatial mapping from a high-resolution imager to the input modulator in the correlator. Insensitivity to scale and rotation of a viewed object will be the result of one form of mapping, allowing one to use only spatial dither in tracking the object. The elimination of two dimensions of dither (scale and rotation) greatly increases the speed of the vision system for its use in any sort of control network. Experiments with various mappings will



Programmable Mask Technology

Figure 11

result in design of very large scale integration (VLSI) cameras whose receptor patterns are best suited to drive a subsequent optical correlator.

Major contracted efforts in 1985 were the development of the Texas Instruments spatial light modulator (SLM) and a correlator including that device as the optically active element. One version of the new SLM configuration was tested. In-house efforts were made in the design of adaptive methods of using real devices and in the design of the programmable retina. All these efforts will come together in March 1986 with the delivery of the correlator system and its integration into the programmable retina at JSC. Joint research efforts with the U.S. Army are under way and are being sought with the U.S. Air Force and the National Bureau of Standards. Results and plans were presented in 1985 to the NASA Technology Utilization Office and to the armed services, with encouraging results.

Participants: R. Juday and K. Krishen (contact).

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