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Intelligent systems in aerospace

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Abstract

An overview of research in the areas of aerospace applications of artificial intelligence, expert systems, neural networks and robotics is presented. Challenges associated with aerospace projects require increasingly complex aerospace systems which in turn demand automation and fault tolerance. We have addressed these issues and provided a survey of the research on intelligent systems that has been carried out in an attempt to meet these challenges. The application areas we have overviewed include fault monitoring and diagnosis, generation and management of power in space, efficient and effective command and control, operations and maintenance of space stations, planning and scheduling, automation, and cockpit management.

1 Introduction

Research in the areas of aerospace applications of artificial intelligence, expert systems, neural networks, and robotics has resulted in numerous successful projects. The United States National Commission on Space plans "to lead the exploration and development of the space frontier, advancing science, technology and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars". As asserted (Ballhaus, 1987) such challenges demand an aggressive research program in artificial intelligence (AI) technologies, leading to the development of autonomous and intelligent systems. These systems will employ knowledge in order to reason, apply past experiences to solve complex problems, learn from their environment, acquire knowledge from human experts, and communicate with human counterparts. These systems will have fault tolerance as well as self-validation capabilities. These developments will lead to reconfigurable and fault-tolerant aerospace transportation systems and automated flight and air-traffic management systems which are less sensitive to human-induced errors. Achieving the objectives successfully will certainly require the combination of aerospace and AI technologies and the development of large-scale engineering system testbeds.

In United States research work in such testbeds has already started. Autonomous Land Vehicle Demonstration sponsored by DARPA and NASA Systems Autonomy Demonstration Project for Space Station are a few examples of such testbed development. As reported later, The University of Tennessee Space Institute (UTSI) has developed and applied several prototype expert systems to aerospace applications; several other organizations like Rockwell International, GE, General Dynamics, Lockheed, McDonnell Douglas, Boeing, Martin Marietta, TRW, Mitre Corp., Gruman, GTE, Hughes Aircraft, Westinghouse, Raytheon, MIT, Carnegie Mellon, and the US Airforce, Navy and Army have also been involved in applying AI/expert system technology to aerospace.

Europe is also intensifying its research and development in artificial intelligence for aerospace applications (Owen, 1989). As Owen states, builders of aircraft and spacecraft are among the leaders in harnessing the power of AI and expert system technology. Both national and international research programs have been launched in these areas. For example, information technology research programs are carried out under Britain's five-year Alvey program and the

European Community's Esprit project. Applications of AI and expert system technology to space operations are sponsored by the European Space Agency (ESA). Several other European organizations like Edinburgh University, British Aerospace, Smith Industries, GEC, Ferranti, Marconi, Germany's MBB, France's Matra, and Aerospatrali-Broguet are also involved in applying AI/expert system technology to aerospace.

Since it is impossible to describe all the projects involved in applying AI/expert system technology to aerospace, we will provide an overview of selected projects in some specific areas at selected organizations. An extensive bibliography will be provided for the readers who would like to further study the field. A survey of space-related AI projects is also available (Macintosh, 1989) for further study.

2 Fault diagnostic systems

2.1 Space shuttle main engine

Operating the SSME is very challenging since the engine is by far the most complex and most power dense propulsion or power generation system. It has performed reliably and safely for many shuttle missions. However, some failures have occurred during launches, launch attempts and ground testing (Cikanek, 1987). Ground testing of the SSME is planned and executed in order to ensure reliable and safe flight operation of the engine. The detection of engine anomalies and the subsequent shutdown to prevent major damage has been implemented by a multifaceted detection/shutdown system. The system consists of sensors, automatic redline and other limit logic, redundant sensor and controller voting logic, conditional decision logic, and human monitoring. Typically, on the order of 300 to 500 measurements are sensed and recorded for each test, while approximately 100 are used for control and monitoring. In spite of this extensive detection system, 27 major incidents have occurred since 1975. Although this is a very small number compared to over 1200 successful hot fire tests, the resulting costs and schedule delays of an incident can cause a significant impact. Based on examinations of the data and failure investigations of these incidents, Rocketdyne developed an advanced failure detection algorithm (Norman, 1988; Nguyen et al., 1988). The algorithm was tested on low frequency sensor measurements taken from five tests. In some cases the algorithm detected an anomaly earlier than the redline cutoff currently implemented. Since the algorithm was developed and tested on low frequency data, it does not have general utility.

Most of the present day knowledge-based fault diagnostic systems are not capable of performing fault diagnosis in real time. Many of them use a large number of production rules that make the system response slow. Also, the interactions among the rules make addition and deletion of rules difficult. Furthermore, a number of these diagnostic systems perform shallow reasoning that fails to diagnose faults which require deep level knowledge. A number of these systems also suffer from a major drawback, namely, the user is expected to understand the fault symptoms because of the lack of facilities to acquire knowledge automatically from the sensor data. Since these diagnostic systems are generally unsuitable for real-time diagnostic applications, alternative approaches for developing real-time diagnostic systems are needed.

The expert system, called LEADER (Gupta & Ali, 1989), has high potential for real-time fault diagnosis. A prototype of this system has been successfully tested to analyse rocket engine data. LEADER has been designed and implemented for automatic learning, detection, identification, verification and correction of anomalous propulsion system operations in real time. LEADER employs a set of sensors to monitor engine component performance, and to detect, identify and validate abnormalities with respect to varying engine dynamics and behaviour. Two diagnostic approaches are adopted in the architecture of LEADER. In the first approach fault diagnosis is performed through learning and identifying engine behaviour patterns. LEADER, utilizing this approach, generates a few hypotheses about the possible abnormalities. These hypotheses are then validated based on the SSME design and functional knowledge. The second approach directs the processing of engine sensory data and performs reasoning based on the SSME design, functional knowledge, and the deep-level knowledge, i.e. the first principles (physics and mechanics) of SSME subsystems and components.

The architecture of LEADER is divided into two diagnostic subsystems and an integration subsystem. One of the diagnostic subsystems performs fault diagnosis based on the analysis of SSME behaviour, whereas the other diagnostic subsystem analyzes SSME design and functions to diagnose SSME faults. Each of the diagnostic subsystems performs diagnosis independently of the other by sharing the processor time, or whenever possible by running in parallel. The two diagnostic subsystems allow LEADER to perform SSME fault diagnosis.

LEADER's architecture is divided into the following three subsystems:

A. Engine Behaviour Analysis Based Diagnostic Subsystem (BABS).
B. Engine Design Analysis Based Diagnostic Subsystem (DABS).
C. Integration Subsystem (IS).

The three subsystems, their modules, and the overall control strategy and approaches used to design and develop LEADER are described below.

BABS performs diagnosis by analysing the SSME behaviour data representing various abnormal conditions. SSME behaviour is analysed by learning the discriminant behaviour-patterns associated with various SSME faults, and using them to diagnose unknown faults by matching the learned fault-patterns with unknown fault patterns. The results of this subsystem indicate that this subsystem performs fault diagnosis fast and successfully, if the unknown fault indeed represents one of the fault categories present in the training data. The machine learning module of this subsystem associates each fault with a set of relevant sensor characteristics. The diagnostic module uses a neural network based pattern matcher that has been trained with the behaviour patterns obtained from the machine learning module. The network is trained to associate a particular set of relational sensor behaviours with a particular fault. During the diagnosis phase, the neural network performs matching of patterns associated with the faults with which it was trained to the patterns associated with the unknown fault. As a result of this pattern analysis and matching, the system derives several possibilities of faults in terms of hypotheses and their estimated likelihood of occurrence. These are available for further analysis and validation by the hypothesis validation module which is responsible for validating the fault hypotheses resulting from the diagnostic module in the light of SSME design. It determines if the events associated with a hypothesis and described in terms of SSME design indeed occurred, and are supported by the sensor data of the fault currently being diagnosed by the diagnostic module. If the events associated with a hypothesis are all found to have occurred as deduced by direct or inferred evidence, the corresponding hypothesis is considered to be a valid diagnosis, representing the fault currently being diagnosed.

The strategy used by the hypothesis validation module involves knowing the events associated with the hypothesis being validated and using the processes of event-justification and event-contradiction to determine whether the events associated with a hypothesis have occurred or not. The processes of event-justification and event-contradiction use the unknown fault sensor data and SSME design to infer the knowledge or evidence that would conform or deny the occurrence of events associated with the hypothesis being validated.

DABS performs diagnosis using design based reasoning. Design and functional knowledge pertaining to SSME subsystems, components, and subcomponents are employed for performing forward reasoning to infer the causes, location and associated events of a given unknown fault by utilizing the unknown fault sensor data.

Ke and Ali (1988) simulated human perception, comprehension and interpretation of rocket engine data analysis. In their research, efforts have been made to define and employ heuristic as well as algorithmic rules to conceptualize data produced by normal and faulty jet and rocket engine behaviour examples. These rules have been employed in developing the machine learning system called MLS. The input to MLS is examples which contain data of normal and faulty engine behaviour. These data include sensor values in time, start and end points of the significant variations in the sensor values, and first and second derivatives of these variations. MLS first transforms the data into discrete selectors. Partial descriptions formed by those selectors are then generalized or specialized to generate concept descriptions about faults. The concepts are represented in the form of characteristic and discriminant descriptions, which are stored in the knowledge base and are employed to diagnose faults. To enhance the capabilities of MLS, Ke and Ali employed an inductive learning technique, called Task-Oriented Clustering (TOC), which uses attribute vectors combined with symbolic conceptual descriptions to deal with the structural object domain. The modified new system is called "The Learning and Diagnosis System (LDS) (Ke & Ali, 1989). The representation combining numerical attribute vectors and symbolic descriptions makes it easier in LDS to apply various domain knowledge and to improve the time-efficiency of the diagnosis task as well as the incremental learning process. Prior known knowledge and partially learned knowledge is used to build a hierarchy of clusters and to guide the process of learning. This method of learning emphasizes the improvements in the effectiveness and efficiency of its task through incremental learning. The computational model of TOC makes incremental learning more time efficient than other methods.

Cikanek reported a series of experimental plume observations (Cikanek et al., 1987) which were made during single engine space shuttle main engine (SSME) tests. The analysis of these observations provides information useful to detect SSME anomalies associated with plume. The observations were conducted from the 220 nm wavelength in the ultraviolet out to the 15 micron wavelength in the infrared. Four types of instruments were employed including analogue autoranging narrow band radiometers, optical multichannel analyzers, mechanical scanning and film plate spectrometers, and imaging cameras. It has been reported that these observations present a range of opportunities to improve understanding of engine performance, operation, degradation, and failure. The SSME failure study indicated that in eight of the twenty-seven major failures, visible evidence of anomalous plume activity was correlated to events within the failure sequence. Cikanek conjectured that an automatic plume monitor could be very helpful in detecting SSME anomalous operations.

2.2 Aerospace vehicles

Expert systems have been employed in complex monitoring and diagnosis of space systems. Lockheed developed (Read et al., 1986) a communicating expert system for fault diagnosis and fault correction in a prototype for the Space Station Air Revitalization System (ARS). The system consists of three communicating expert systems: one for oxygen generation, one for carbon dioxide removal, and a supervisor for overall control. The three expert system modules communicate via mailbox. The main goal of developing this prototype was to explore the construction and use of communicating expert systems. Related work in this area covering meta-level control and coordination in distributed problem solving systems (Hahn, 1983; Yang et al., 1985; Corkill & Lesser, 1983), employment of distributed heuristic agents (Sawigral, 1983), and control and coordination in distributed expert systems (Smith, 1979) has also been reported.

Aggarwal and his associates (Aggarwal et al., 1986) reported the results of a feasibility study of using knowledge-based diagnostic systems for gas turbine engine rotordynamic diagnostics. Typical rotordynamic faults observed in gas turbine engines were surveyed to assess the extent of knowledge required to diagnose rotordynamic faults. A fault tree was developed for a set of representative rotordynamic faults observed in gas turbine engines. It was concluded that a nonconsultative diagnostic system was the best approach and that fault trees were the best way to represent rotordynamic diagnostic knowledge. The report provides a system configuration for an expert rotordynamic diagnostic system. The recommended system configuration includes a capability to monitor the performance of sensors in the diagnostic system and to detect sensor malfunctions or failures.

Caglayan & Lancraft (1984) studied the design and digital simulation of an integrated fault tolerant system using analytical redundancy for avionics sensors of NASA–LRC's transport system research vehicle. The objective of the fault tolerant system is to provide reliable estimates for aircraft position, velocity, and altitude in the presence of possible failures of ground-based navigation aids and on-board flight control and navigation sensors. The estimates provided by the system are used by a fully automated guidance and control system to land the aircraft along a prescribed path. Sensor failures are identified by utilizing the analytic relationship between the various sensor outputs arising from the aircraft equations of motion. Schutte and Rajagopalon (Schutte & Abbott, 1986; Rajagopalon, 1984) have also applied an AI approach to aircraft applications.

Research on knowledge-directed, sensor-based fault diagnosis in the flight domain has been reported by Ali and Scharnhorst (1985). They identified and adopted four important criteria in sensor-based diagnosis. First, because the sensors themselves are sometimes more unreliable than the airplane components, sensor data are always verified by using available global information. Second, the processing of faults is prioritized so that dangerous faults are checked for before those with less impact on the performance of the aircraft. Similarly, faults that are highly unlikely to occur are not checked for until after more likely possibilities are eliminated. Third, distinctions are made between fault causes and fault symptoms. Fourth, an accurate model of the status of the aircraft is maintained at all times. Their model includes beliefs regarding which components are currently inoperative and the justifications for those beliefs. Ali et al. (1986) have also developed a Flight Expert System (FLES) for diagnosing and recovering from in flight faults. In developing FLES, they found it helpful to examine the characteristics of faults, and to identify what types of faults occur in the flight domain. Early on, they recognized that some faults are due to improperly adjusted controls. Typical examples of this are extended flaps during flight, insufficient throttle during takeoff or excessive airspeed on approach. They refer to this type of fault as a maladjustment. A second type of fault, a malfunction, exists when a component is no longer able to perform its intended task. Examples of malfunctions include electrical shorts, hydraulic fluid leaks and engine flame-outs.

Another observation was of the relationship between faults and the times at which they occur. They have noticed that maladjustments are sensitive to the phase of flight that the aircraft is in. The flap positions, for example, vary depending on whether the plane is trying to take off, land, cruise, etc. This means that to detect a maladjustment in the flaps, the system must be aware of their current setting and the current flight phase. They found this to be true for each type of maladjustment. This is in sharp contrast to malfunctions, which are largely independent of the flight phase. A short in an electrical bus, for example, is obviously a fault at any time. Although there are exceptions to this independence (e.g. the degree of danger associated with each malfunction may vary considerably from phase to phase), it has been useful to maintain the distinction between malfunctions and maladjustments.

Dietz and Ali (1987) investigated qualitative and temporal reasoning to analyse engine behaviour and to diagnose faults in jet engines. Engine parameters monitored during engine operation were used to generate qualitative and temporal representations of actual engine behaviour. Similarities between the representations of failure scenarios and the actual engine behaviour are used to: (1) diagnose fault conditions which have already occurred, or are about to occur, (2) increase the surveillance by the monitoring system of relevant engine parameters, and (3) predict likely future engine behaviour. The stored failure representations include both sudden failures and slowly developing fault conditions. As a result, the system can detect developing faults which have not yet caused a parameter to exceed safety limits. Three important diagnostic objectives were focused in their system. First, the diagnostic system must respond appropriately to slowly developing faults which may not have yet caused any parameter in the system to exceed operational limits. A second objective was that the diagnosis be performed in real time, so that appropriate compensating measures could be performed to alleviate the fault condition. A third objective was that the diagnostic methodology accommodate the occurrence of multiple faults.

Gupta and Ali (1988) developed an intelligent learning system which analyses the engine fault data given as a training set of engine behaviour examples and generates characteristic and discriminant descriptors for the identification of these faults. Four engine parameters and their temporal and qualitative relationships were employed to represent jet engine behaviour. These parameters are rotational speeds of the low and high pressure turbine assemblies referred to as N1 and N2 respectively, exhaust gas temperature EGT, and combustion temperature COMBT. Normally, these parameters show stable readings. Faulty conditions like fuel interruption or bearing loss cause significant variations in the values of these parameters. These variations have been transformed into structural representations involving instances and events. Every instance node is associated with a moment in time when a significant change occurs in the value of a parameter, and the node stores information related to this moment. An event stores information related to the happenings between two instances. The analysis of engine behaviour under normal and faulty conditions has illustrated several important features called descriptors which contribute significantly to diagnosing and predicting faults. These descriptors are generated from temporal and qualitative features derived from sensor data and from relationships between these features. For example, a temporal sequence of instances and events created by a parameter variation forms a pattern. These temporal patterns and their interparameter relationships are described by descriptors. Similarly, inter-parameter and intra-parameter qualitative relationships are described by descriptors. The learning system described in this paper (LEBEX) first extracts these descriptors from normal and faulty engine behaviour examples and represents them hierarchically in the knowledge base. The processes of generalization and specialization (by comparison) are applied to these descriptors to finally produce characteristic and discriminant descriptors. These descriptors are represented hierarchically in the knowledge base and later employed by the expert system to detect, diagnose and predict abnormal engine conditions and faults in real time conditions.

Bickmore & Yoshimato (1987) developed an approach to satellite diagnosis which can integrate evidence from a variety of diagnostic strategies encompassing expertise including knowledge of design rationale and sensitivities, development history, test methods, test history, fault history and other indications of pedigree, and operational scenarios and environments. The system utilizes a structural and behavioural model of the satellite, and uses a form of spreading activation to perform the diagnostic procedures on the model. The various sources of diagnostic evidence are combined using a specially-tailored Dempster–Shafer based utility for modelling uncertainty.

Marsh (1985) developed an Integrated Status Assessment (ISA) expert system to perform space station failure diagnosis. The initial domain of the expert system was the KU band portion of the communication and tracking system. ISA was designed as a hybrid expert system using different methodologies: object oriented programming, rule-based programming using both shallow and deep reasoning, and qualitative modelling.

3 Space station applications

3.1 Power management

Ohler and Hall are developing a prototype of the electrical power management system on the NASA Space Station (Ohler & Hall, 1986). The goal of the project is to develop a generic power control system that could be adapted to a wide range of proposed electrical power distribution architectures while maintaining the automated nature of the system. The system is a loosely coupled distributed AI system composed of four cooperating components, three of which are planning agents that develop plans in parallel. The fourth component, the fault management agent, is a diagnostic system which responds to faults in the distribution network and identifies, isolates, and recovers from faults. The planning agents are the load scheduling agent, the resource managing agent, and the power allocation agent. The system is still in the developmental phase.

McClure (McClure et al., 1986) discussed the implementation issues associated with autonomous management of the space station electric energy system. They proposed a system to handle the scheduling and real time control of the energy system. The major components of this system are a user interface, an executive subsystem, a scheduler for the loads and storage, and a real time controller. Nguyen and Chiou employed two expert systems (Nguyen & Chiou, 1986) to demonstrate the concept of parallel symbolic manipulation for power distribution management and dynamic load planner/scheduler in the simulated space station environment.

Bernard et al. (1988) explain the need for nuclear energy in spacecraft. They report that the implementation of nuclear energy in space will not be achieved by the mere transfer of the technology that has been developed for terrestrial applications because of the difficulties associated with the rejection of heat in space and the need to minimize system mass for economical spacecraft launching. Their paper provides an overview of a research programme on reactor control.

3.2 Other applications

A space station will be a complex and closed system managed by a small crew. Decisions will be required concerning the operation and maintenance of all the elements of the station. Several researchers have employed expert system technology for various applications associated with space stations. Nease & Fulwider (1988) summarize some of these applications. Jamar & Schur (1986) developed a system for automated control of the space station environmental control and life support system called ASCLSS. In this system, basic controllers manage subsystem processes like CO_2 concentration, O_2 generation, and CO_2 reduction for the air checking, mode changes, and fault management. Crone et al. (1987) described the use of expert system technology for the management of the communication and tracking system for the space station. They developed the Control and Monitoring Equipment Resource Allocation (CAMERA) Expert System to minimize crew workload in managing the communications of the space station. CAMERA provides a facility for automatic management of communications resources, diagnosis of faults, and reconfiguration to restore communications automatically. It utilizes a man–machine interface to allow high level end-to-end service requests. It interprets the requests, determines the equipment required to implement the service, and assigns the appropriate equipment to the service. CAMERA then establishes the service automatically at the time requested and monitors the operation of the simulated system to diagnose faults and determine the appropriate procedures to restore the service. Healy also described some applications (Healy, 1988) of advanced automation to space stations' operations management.

Loftin et al. (1987) developed an autonomous intelligent training system for use by Mission Control Center Flight Dynamics Engineers to perform payload-assist operations. The system, called Pam Deploy Intelligent Computer-Aided Training (PD/ICAT), integrates expert system technology with teaching/training methodologies.

Cox (1988) is developing an intelligent operator aid, called the Telemetry Analysis Logic for Orbiting Spacecraft (TALOS), by using the Lockheed Satellite Telemetry Analysis in Real-time (L*STAR) expert system tool to support real-time, ground-based health and safety monitoring. TALOS will assist the operators of NASA's Hubble Space Telescope (HST) which is a complex, modern satellite system. Two aspects of the HST motivated the TALOS development: first, to reduce the continuous analysis of thousands of telemetry data points in order to perform health and safety monitoring, and second, to represent and employ an enormous quantity of design data and engineering knowledge and expertise which accumulated during the development of the HST.

4 Intelligent aids for flight crew tasks

The performance and complexity of aircraft have increased dramatically in all dimensions. The increasing complexity of cockpits makes it necessary to provide enough support so that the aircrews will be able to effectively manage the substantial resources at their command. An effective solution of this problem is to develop an intelligent cockpit management system which is capable of reasoning with the stored knowledge and providing the aircrew with the information which is most critical to the success of the mission at a given time. The objective of the automated system is not to take full control of the aircraft but to provide the pilot with a structured selection of options which include over-riding the automated system (Johanson & Rouse, 1981; Hammer & Rouse, 1982; Curry, 1985; Weiner, 1985). Because of the wide range of possible applications in the area of artificial intelligence techniques, one can conceive of a wide range of possible applications in the area of intelligent aids for flight crew. Sheldon and Feehrer reported the results (Sheldon & Feehrer, 1985) of a study aimed at developing a basis for applying AI to the flight deck environment of commercial transport aircraft. In particular, the study comprised four tasks: (1) analysis of flight crew tasks, (2) survey of the state-of-the-art of relevant AI areas, (3) identification of human factors issues relevant to intelligent cockpit aids, and (4) identification of AI areas requiring further research.

Modern warfare places enormous demands on combat pilots, particularly those who operate single-seat tactical fighters. The increasing complex mission environment surpasses human ability to respond effectively in real time because a pilot is expected not only to achieve mission objectives but also be alert to changes in the external and internal situations. A pilot must also respond to eliminate or avoid threats. AI technology has been employed to aid pilots of fighter aircraft through a system that both organizes the workload in the cockpit and increases the current capabilities of the aircraft onboard systems (Anderson et al., 1984, 1985).

Recently a few prototypes of avionics expert systems have been developed by Boeing Military Airplane Company, Advanced Decision Systems and Lockheed as a part of the "Pilot's Associate System". Boeing's primary system was a Crew Station Information Manager (CSIM) which operates on information from three supporting subsystems including a situation assessor, a mission planner and integration controller. Shelnutt et al. (1986) described the general architecture used for the expert system and the specific knowledge representation and control reasoning techniques used to implement the Crew Station Information Manager. Pohlmann & Payne (1986) presented an overview of the Boeing project, looked back to describe some of the lessons learned during the project, and looked ahead to describe potential future research directions for avionics expert systems.

5 Intelligent control systems

Expert system technology has provided the capability to build and operate more efficient and effective command and control systems, especially for performing functions that require the analysis and solution of complex problems (Lightfoot, 1986). In this section we will highlight the aerospace application of expert systems.

Many space station operations involve continuous control of real-time processes. These processes include electrical power system monitoring, propulsion system maintenance, checkout and maintenance of space suits and environmental and life support systems, on-board manufacturing, and servicing of attached vehicles such as satellites, shuttles, orbital maneuvering vehicles, orbital transfer vehicles and remote teleoperators. Leinweber & Perry (1986) described the requirements for real-time expert systems in space station control and developed a prototype of space station expert control procedures by employing PICON, a real-time expert system shell. The potential applications of their prototype include altitude control, electrical power control, environmental and life support functions, propulsion, monitoring of docked vehicles and payloads, and manufacturing process control.

Dwyer (1987) proposed a reconfigurable non-linear control system design methodology to automatically correct computed slew torque commands of space-based painting systems in slew-induced structural deformations. The torque corrections are generated from structural sensors as well as from higher derivatives of command boresight angular rates. Structural control forces are generated from higher angular slew rates to shape the slew-induced structural excitations. Automatic selection of slew torque and structural actuator correction signals, as well as automatic correction for tracking error gains can be managed by a supervisory controller that tests required effort levels against actuator ratings. The simulated implementation of the control system for a space-based laser beam expander on a silicon graphics IRIS system is reported.

Sztipanovits et al. (1988) described a model-based approach for the design and implementation of intelligent controllers by employing a "Multigraph Architecture" which is a layered system and includes a parallel, graph computation model, the corresponding execution environment, and software tools supporting the interactive, graphical building of knowledge-bases.

Merrill & Lorenzo (1988) proposed an architecture of an Intelligent Control System (ICS) for reusable space propulsion systems. ICS has the potential to produce enhanced performance with increased reliability, durability and maintainability. Ali & Crawford (1988) provided the design of an expert system for automatic detection, verification and correction of anomalous rocket engine operations through interfacing with an intelligent adaptive control system. The design of their intelligent propulsion control and monitoring system includes the architecture of an Integrated Expert System (IES) serving as the core component. The IES functions include automatic knowledge acquisition, integrated knowledge base, and fault diagnosis and prediction methodology. The results of fault analysis and diagnostic techniques are presented. These faults are based on a fault example in the SSME main combustion chamber injectors. The authors claim that the on-board expert system would help the propulsion system's intelligent controller to focus on the sources of faults and increase the effectiveness of its attempts to correct them. However, they also recognize that a majority of the rocket engine component failure modes will not be correctable by control system actions and will require immediate engine shut-down to prevent serious or catastrophic failure of the engine. In these situations the expert system will look for an alternative mechanism and its components' lifetimes to provide the needed support.

An expert system approach has also been followed in the design of reconfigurable flight control systems for airplanes. Several architectures have been proposed (Handelman, 1983; Belkin & Stengel, 1987) to detect and recover from malfunctioning flight systems. In case of recoverable malfunctions, the proposed systems counterbalance the effect of a failed primary control effector, such as an aileron, with a secondary control effector, such as a trailing-edge flap.

6 Intelligent planning and scheduling systems

Expert system technology has been recently been applied to perform innovative planning and efficient scheduling. Gargan & Tilley (1987) are developing a system, called Payload Hardware and Inventory Tracking System (PHITS), which is capable of creating and stimulating the execution of launch site payload processing plans. In these plans experiments are manifested, prepared for launch, and integrated into a shuttle for transporting to the space station for operation. During the execution of this procedure PHITS will track the utilization and location of all resources and hardware items used to implement the processing such as the pressurized laboratory experiment equipment rocks. The focus of PHITS will be to concentrate on problems like: (i) the planning and scheduling of new flights; (ii) the determination of requirement dates for relevant material; and (iii) the tracking of all resources in the system. Pearson (1989) has developed a collection of planning and scheduling tools called the Integrated Mission Planning System (IMPS) to perform satellite coverage analysis, mission planning and performance analysis for satellite and ground station systems and constellation trade-off analysis for candidate missions. IMPS creates dynamic events among spacecraft, fixed targets, moving targets, and geographical areas of interest and displays these events to provide real-time animation of a mission. Hewett et al. (1988) described the development of an automated flight test management system (AIMS) which will provide a flight engineer with a set of tools to assist in flight test planning, monitoring and simulation. Flight test planning is implemented at several levels. At the highest level, the flights required for an entire program are established by the project requirements. At the lower levels, flight plans are determined by a more detailed analysis of the project requirements and are partitioned according to similarity of prerequisites, flight envelope requirements, and test needs to establish an orderly progression of flight plans satisfying the high-level project requirements. Raman (1988) described a system, called SCENGEN, being developed at Boeing with an objective of providing a system which utilizes the tools and problem solving heuristics employed by the flight deck engineers in developing flight mission scenarios.

Dietz, Ferber and Ali developed the SSME Component Assembly and Life Management Expert System (CALMES) to assist the engine assembly and scheduling process and to insure that these activities utilize available resources as efficiently as possible. The need for CALMES arose because of the reusability of the space shuttle system which introduces many problems related to testing, reliability and logistics. Components must be assembled from parts inventories in a manner which will most effectively utilize the available parts. Assembly must be scheduled to efficiently utilize available assembly benches while still maintaining flight schedules. Assembled components must be assigned to as many contiguous flights as possible in order to minimize component changes. Each component must undergo a rigorous testing program prior to flight. In addition, the testing and assembly of flight engines and components must be done in conjunction with the assembly and testing of developmental engines and components. The development, testing, manufacture, and flight assignments of the engine fleet involve the satisfaction of many logistical and operational requirements, and are subject to many constraints. Tyically, a priori knowledge consists only of parts inventories and a proposed flight schedule. Using this input, CALMES performs four basic functions: (1) determining how components may be optimally assembled from the parts inventory, (2) assigning components to flights, (3) scheduling component testing, and (4) scheduling component assembly. The first function deals exclusively with component assembly, while the remaining functions are considered to be scheduling operations.

7 Automation and robotics

The requirements of aerospace applications of robots differ radically from those of earth-based robots. The constraints of the availability of power and repair facilities require new techniques and design criteria. Roston (1986) provides an overview of the desired features for space robot manipulators. A description of problems which will be encountered in the development of telerobotic systems for space applications such as the flight telerobotic systems is given in Jenkins (1987).

A space station is planned for on-orbit assembly in the 1990s by NASA. The space station will include several extravehicular robotic systems. A remote manipulator, similar to the shuttle RMS but mounted on a mobile transport vehicle which crawls along the station truss structure, will allow handling of large equipment. Other crane-like manipulators will also be used. A description of these telerobotic systems is given in Campbell (1988).

The European Space Agency is developing a "Service Manipulator System" (SMS) whose principal goal is to automate the mundane details of operating the manipulator as much as possible. The details of the project are given in Donzelli et al., 1987 and Smith, 1988. Several space applications can be greatly enhanced by the use of robotics and automation. Examples of such applications are collision-free navigation, rendezvous and docking, satellite retrieval and servicing, orbital inspection, maintenance, refurbishment and repair, and navigation of remotely piloted vehicles. Total or partial automation of space systems will enhance safety, reliability, productivity and adaptability. It will also reduce the overall cost of space missions (Cohen & Erickson, 1985). The feasibility of realistic autonomous space manipulation tasks using multisensory information is shown in Abidi et al. (1988).

In 1985, NASA initiated a major programme of robotics research and development for technology applications to space station construction, maintenance, repair, on-orbit servicing, and remote exploration. A focal point within this program has been the development of a ground-based telerobot testbed. Designed to prove technology concepts for supervised automation of increasingly unstructured and complex tasks, the testbed has reached an initial stage of integration. Schenker et al. (1988) have reported on several testbed experiments including the visual tracking and grapple of a satellite, dual arm spatial coordination and manipulator control, force-reflecting teleoperations, and simulated task planning for a satellite servicing scenario. The Telerobot

Interactive Planning System (TIPS) is the highest level of autonomous control of the integrated testbed (Peters, 1988). TIPS will perform overall task planning of a satellite module replacement task, including gross motion spatial planning and on-line error recovery.

The applications of artificial intelligence technology in the Flight Telerobotic Servicer (FTS), particularly in the automation of operator and supervisory control, are described in Smith et al. (1987), Oberright (1987) and Goforth & Doming (1988). It is expected that the use of expert system in the FTS design will relieve and/or lighten the teleoperations crew of slow, and tedious tasks are prone to human fatigue and error. There are several facets or dimensions to consider in attempting to apply AI technology in a system such as the FTS. For example, which phase of mission operations or teleoperations is the most likely place to insert this technology? How should the automation of off-line, planning activities be coordinated with on-line or real-time operational activities? Goforth & Doming (1988) address some of these issues.

8 Neural network based systems

Neural networks have properties which seem to offer solutions to some of the difficult problems encountered in machine learning, vision, speech, pattern recognition, resource planning, control and real-time systems. One of the important features of neural networks is their ability to recall stored patterns using fuzzy or incomplete cues in time. This ability is independent of the number of stored patterns. Neural network features are very significant in aerospace applications where aircraft, space vehicles and military weapon systems operate in increasingly difficult situations. These systems are also becoming increasingly complex with the advancement of technology and need neural networks to make them autonomous, flexible, adaptable and self-learning in highly dynamic environments.

TRW has been working on the "Adaptive Network Cognitive Processor" (ANCP). The objective of this program has been to develop a prototype system which builds an inner model of its environment in the form of cognitive maps and to use this model for reasoning, planning, and problem solving. The exact problem domain is a high level situation assessment and response system for pilot aiding. Booz-Allen & Hamilton, Inc. and Texas Instrument are working on the "Adaptive Network Sensor Processor" which applies neural network associative memory and pattern recognition technology to a military radar warning system for providing identification, categorization, and classification of previously experienced and novel radar signals in a noisy environment.

Dietz et al. (1988, 1989b) employed neural network technology to develop diagnostic expert system methodologies based on the analysis of patterns of behaviour of jet and rocket engines. In their approach fault diagnosis is conceptualized as the mapping or association of patterns of input data to patterns representing one or more fault conditions. Their neural network methodologies offer several powerful and useful features, including: (1) general mapping capabilities, (2) resistance to noisy input data, (3) the ability to be trained in a supervised learning mode, and (4) the capability of operation with incomplete input. Although the performance of their earlier diagnostic system was quite good, it was not free of the usual neural network drawback and needed an improvement. The most important improvement dealt with how the networks respond to fault classes for which the networks have not been specifically trained. The networks were trained to categorize inputs representing known fault conditions. However, there was no method whereby a network could be trained to recognize when an input pattern corresponded to a previously unobserved, i.e. unknown, fault condition. When presented with sensor patterns representing an unknown behavioural scenario, the networks would sometimes incorrectly categorize the patterns as a known fault condition. As a result, the diagnostic system rarely produced false negative results (i.e. reporting no fault condition when given a set of patterns indicative of a known fault condition), but would sometimes produce false positive results when given input patterns representing a behavioural scenario for which the networks were not specifically trained. In the new and improved system they developed and employed a neural network topology (Dietz et al., 1989c) which effectively addresses these problems. The network topology is autoassociative, i.e. the network input and output is identical when properly trained, and hence learning is unsupervised. Classification of input patterns is accomplished by examining the activations of the nodes in the hidden layer.

A range of training examples indicative of a particular fault class will result in hidden node activations which map out a surface in N-dimensional space, where N is the number of hidden nodes. An unknown input example presented to the network for classification will invoke hidden node responses which can be conceptualized as a point in N-space. If the hidden node activation lies near a surface corresponding to a particular fault, the input pattern will be associated with that fault. If, on the other hand, the resultant hidden node activation lies away from any surfaces defined by the training set, the input will be classified as an unknown pattern. Therefore, an input pattern produces a hidden node response which is sufficient to either (1) associate the input with a known fault scenario, or (2) reject the input altogether as not representative of any known fault condition for which the network has been trained. If an input is associated with a fault condition, the hidden node activations will also serve to identify the severity and duration (i.e. rapidity of fault onset) of the fault.

Another improvement to the system concerns the number of networks required for diagnosis. The earlier system required five networks for each sensor; one to diagnose the fault type, and two additional networks to identify fault severity and duration for each fault. Two main faults were considered; as a result, the entire system required 20 networks. Adding another fault type to the system's diagnostic capability required the training of twelve additional networks. With the new approach, a single network can be trained to respond accurately to input examples from all sensors; as a result, a single network performs the functions of all 20 networks required in the earlier system. In the present approach, a single network is trained to identify and categorize all fault conditions. As a result, adding the capability of identifying additional faults requires the training of only a single network.

9 Conclusion

The significance and importance of intelligent systems research and their aerospace applications can be judged by the large number of projects being carried out as well as by the number of conferences organized. We have reviewed only a small number of aerospace applications and projects in this paper. The bibliography includes only a subset of selected papers. Limited space in this special issue of the journal resulted in excluding the review of many interesting projects associated with intelligent aerospace systems. Many papers were excluded from the bibliography for the same reason. Reasons for such a tremendous amount of work in this area have been the past and present successes and future potential in applying intelligent systems to aerospace applications. In spite of the enormous interest of a large number of researchers, we believe the past and present work is only a tip of the iceberg.

9.1 Summary of work to date

Current research in the areas of aerospace applications of artificial intelligence, expert systems, neural networks, and robotics has resulted in a wide range of successful projects covering fault diagnostic systems, space station applications, pilot associate systems, control systems, and planning and scheduling systems. The American agencies participating in the research and development include DARPA, NASA, the US Air Force, Navy and Army, Rockwell International, General Electric, General Dynamics, Lockheed, McDonnell Douglas, Boeing, Martin Marietta, TRW, Mitre Corp., Grumman, GTE, Hughes Aircraft, Honeywell, Harris Corp., Westinghouse, Raytheon, MIT, The University of Tennessee Space Institute (UTSI), Carnegie Mellon University, University of Cincinnati, Auburn University, University of California, SRI International, Jet Propulsion Laboratory, Rice University, and University of Michigan. The

European organizations include the European Space Agency (ESA), Edinburgh University, British Aerospace, Smiths Industries, GEC, Ferranti, Marconi, Germany's MBB, France's Matra, and Aerospatrali-Broguet. Japan's leading industrial organizations have also started pursuing research in this area recently. Some of these successful projects have been reviewed in this paper and an extensive bibliography has been provided for the readers who would like to study the field further.

9.2 Current and future trends and themes

The objective of research in this area has been to develop autonomous, fault-tolerant, and intelligent aerospace systems capable of reasoning, using the available knowledge, acquiring and employing past experience, and formulating and utilizing new insights, heuristics and knowledge to solve the complex problems which are faced by aerospace vehicles. Examples of such problems include high level controls, management of information, resources and activities, monitoring, diagnosis and servicing of anomalies, tactical maneuvering, navigation in unfriendly and unseen situations. Current advancements in intelligent systems technology have been very encouraging in formulating potential solutions; however, the technology is still in the early stage of development. Therefore, the successes in achieving solutions to these complex problems have been demonstrated only on overly simplified problems in narrowly defined domains of expertise. For example, man–machine communication with these systems has been in a rudimentary form. Research on knowledge comprehension and on human factor considerations of automated systems have not progressed very far. Most systems developed so far are only in prototype forms which were designed with no possible extensions to the real-time response required for real life complex problems. Future intelligent systems will address these problems and will emphasize integrated and hierarchical processing in which top-level controllers will interact and coordinate multiple expert systems for integrated problem solving and resource allocation. Such systems will be capable of acquiring, understanding and utilizing local as well as global knowledge in a dynamic environment. Man–machine communication will include continuous speech, natural language, pattern and image understanding and recognition, and multi-dimensional graphics. Acquisition, understanding, representation and integration of information derived from multiple sensors will also be important. Parallel and distributed processors capable of very fast symbolic processing will be critically important in the future generation of intelligent systems. It is expected that in the future emphasis will shift from developing prototypes to actually developing operational systems for solving real life problems in a real-time environment. This trend has already started and a few systems are being developed which have potential of being operational. We predict a tremendous growth in this area.

References

Abidi, MA, Green, WL, Chandra, T and Spears, J, 1988. "Multisensor robotic system for autonomous space maintenance and repair" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 104–113.

Adams, TL, 1986. "Model-based reasoning for automated fault diagnosis and recovery planning in space power system" *Proceedings of 21st Intersociety Energy Conversion Engineering Conference,* Vol. 3, American Chemical Society, pp 1763–67.

Adorf, HM, 1986. "Artificial intelligence applications within the space telescope—European coordinating facility" *Report from ST-ECF, ESA.*

Aggarwal, B, et al., 1986. "AI gas turbine rotor diagnostics" *Final Report, AFWAL-TR-86-2072.*

Ahlf, PR, 1985. "The shuttle trajectory and launch window expert system" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Albrecht, R and Russo, G, 1986. "Hubble space telescope data analysis in Europe" *Proceedings of SPIE Conference,* Vol. 628, Tucson, Arizona.

Ali, M and Scharnhorst, DA, 1985. "Sensor-based fault diagnosis in a flight expert system" *Proceedings of the Second Conference on Artificial Intelligence Applications,* December 11–13, Miami Beach, FL.

Ali, M, Scharnhorst, DA, Ai, CS and Ferber, HJ, 1986. "A flight expert system (FLES) for on-board fault monitoring and diagnosis" *SPIE Proceedings* Vol. 635, pp 58–61.

Ali, M and Crawford, R, 1988. "Rocket engine control and monitoring expert system" *AIAA 24th Joint Propulsion Conference,* July 11–13, Boston, MASS.

Anderson, BM, Cramer, NL, Lineberry, M, Lystad, GS and Stern, RC, 1989. "Intelligent automation of emergency procedures in advanced fighter aircraft" *Proceedings First Conference on Artificial Intelligence Applications,* December, pp 496–501.

Anderson, BM, Beal, JM, McNulty, C and Stern, RC, 1985. "Knowledge engineering for a flight management expert system" *Proceedings National Aerospace and Electronics Conference,* May, pp 1431–1435.

Austin, A and Laffery TJ, 1983. "Knowledge-based analysis of telemetry data on the Hubble space telescope" Communication from Lockheed Artificial Intelligence Center.

Bahrami, KA, Biefeld, E, Costello, L and Klein, JW, 1986. "Space power system scheduling using an expert system" *Proceedings of 21st Intersociety Energy Conversion Engineering Conference,* Vol. 3, American Chemical Society, pp 1813–18.

Baker, TC, Lennington, RK, Herold, RW and Bennett, WP, 1986. "An expert system for space station activity scheduling" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 1–4.

Ballhaus, WF, 1987. "AI and the aerospace frontier" *Aerospace America,* January, p 6.

Baruah, A and Campiche, JB, 1986. "An expert system for electrical power automation on a spacecraft" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 317–326.

Becker, J, 1985. "Expert systems take off at NASA" *Expert Systems User,* April, pp 12–13.

Belkin, BL and Stengel, RF, 1987. "Cooperative rule-based systems for aircraft control" *Proceedings of the 26th Conference on Decision and Control,* Los Angeles, CA, December.

Bernard, JA et al., 1988. "Autonomous control of spacecraft nuclear reactors" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 28–45.

Bickmore, TW and Yoshimoto, GM, 1987. "An evidential approach to model-based satellite diagnosis" *SPIE Proceedings of Space Station Automation,* Vol. 851, pp 178–185.

Boarnet, M, Culbert, C and Savely, RT, 1987. "AI applications for the space station" *Proceedings of the 1987 IEEE International Conference on Robotics and Automation,* Vol. 1, Washington: IEEE, pp 131–6.

Bose, P, Meng, AC and Rajinikanth, M, 1987. "KAMPR: knowledge based approach to mission planning and replanning" *Proceedings of IEEE National Aerospace and Electronics Conference,* Vol. 4, New York: IEEE, pp 1434–41.

Branets, VN, Legostaev, VP and Cheriod, BY, 1988. "The system of the MIR station motion control" *Proceedings of the 39th Congress of the International Astronautical Federation,* Vol. IAF-88-334, Bangalore, India, October.

Britt, DL, 1986. "The role of expert systems in space station power management" *Proceedings of 21st Intersociety Energy Conversion Engineering Conference,* Vol. 3, American Chemical Society, pp 1776–79.

Caglayan, AK and Lancraft, RE, 1984. "A fault tolerant system for an integrated avionics sensor configuration" *Report No. NAS1-16579,* Bolt Beranek and Newman, Inc.

Cameron, JM, Doshi, RS and Holmes, KG, 1987. "Route planner development workstation" *JPL Report: D-2733, NASA.*

Campbell, R and Kohn, W, 1985. "RMS-MRMS intelligent end effector automatic task interpreter" *Space Station Operations and Technology,* Vol. 10, Houston, Texas: AIAA.

Campbell, PD, 1988. "Teleoperation and autonomy in space station robotic systems" *SPIE Proceedings of Space Station Automation,* pp 56–62.

Chamis, CC, 1986. "Probabilistic structural analysis methods for space propulsion system components" *Proceedings of the Space Systems Technology Conference.*

Ciarlo, A, Donzelli, P, Katzenbelsser, R and Moller, BA, 1987. "Satellite on-board applications of expert systems" *ESA Journal* **11** 31–44.

Cikanek, HA, 1987. "Characteristics of space shuttle main engine failure" *23rd Joint Propulsion Conference,* June 29–July 2, 1987.

Cikanek, HA et al., 1987. "Space shuttle main engine plume spectral monitoring preliminary results" *AIAA 23rd Joint Propulsion Conference,* June 29–July 2, San Diego, California.

Clemons, P, Culbert, C and Wang, L, 1985. "Development of an expert system to assist monitoring mission control center software status" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 113–115.

Cohen, A and Erickson, JD, 1985. "Future use of machine intelligence and robotics for the space station and implication for the US economy" *IEEE Journal of Robotics and Automation,* **RA-1** (3) pp 117–123.

Contreras, VJ and Ferguson, JC, 1986. "Knowledge management: A system for controlling the AI development environment for an expert system which performs satellite anomaly resolution" *MILCOM 86—IEEE Military Communications Conference,* Vol. 1, New York: IEEE.

Conway, SM, 1987. "A model based approach to fault diagnosis and health maintenance in a spacecraft power subsystem" *AIAI Project Report: AIAI-PR-9,* Artificial Intelligence Applications Institute, University of Edinburgh, Edinburgh.

Corkill, DD and Lesser, VR, 1983. "The use of meta-level control and coordination in a distributed problem solving network" *IJCAI.*

Cornell, M, 1986. "Knowledge based automatic test equipment" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 327–333.

Courtin, JP, Thuaire, A, Lemoine, JM and Monasterolo, A, 1988. "Failure diagnosing expert system for the TDF-1 satellite's power supply system" *Proceedings of Human–Machine Interaction & AI in Aeronautics and Space,* Toulouse, France, September, 1988, pp 229–240.

Cox, PA, 1988. "Knowledge based systems for the Hubble space telescope" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 86–91.

Crone, MS, Julich, PM, Dash, EG and Wavering, WD, 1987. "Expert system technology for the space station communications and tracking system" *SPIE Proceedings of Space Station Automation,* Vol. 851, pp 31–38.

Crouse, KJ and Spitzer, JF, 1986. "Design knowledge bases for the space station" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 5–11.

Culbert, C, 1985. "The role of artificial intelligence and expert systems in increasing STS operations productivity" *R&D Productivity,* pp 378–382.

Culbert, C, Wang, L and Flinn, H, 1985. "ESFAS: An intelligent user interface for the flight analysis system" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 215–220.

Curry, RE, 1985. "The introduction of new cockpit technology: A human factors study" *NASA TM 86659,* NASA Ames Research Center, Moffett Field, California.

Dapeng, Z and Zhongrong, L, 1986. "The design of a smart sensor system for real-time remote sensing image processing on board satellite" *Proceedings of SPIE Int. Soc. Opt. Eng. (USA),* Vol. 657, pp 164–70.

Delaune, CI, 1985. "A monitor and diagnosis program for the shuttle liquid oxygen loading operation" *"ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Dickey, FJ and Toussaint, AL, 1984. "ECESIS: An application of expert systems to manned space stations" *IEEE Conference on AI Applications,* Vol. 1, pp 483–489.

Dietz, WE and Ali, M, 1987. "Qualitative and temporal reasoning in engine behavior analysis and fault diagnosis" *Third Annual Conference on Artificial Intelligence for Space Applications,* November 2–3, Huntsville, AL.

Dietz, WE, Kiech, EL and Ali, M, 1988. "Pattern-based fault diagnosis using neural networks" *Proceedings of The First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* Tullahoma, TN, June 1–3, pp 13–23.

Dietz, WE, Ferber, HJ and Ali, M, 1989a. "Space shuttle main engine component assembly, assignment, and scheduling expert system" *Proceedings of The Second International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* June 6–9, Tullahoma, TN, pp 356–363.

Dietz, WE, Kiech, EL and Ali, M, 1989b. "Jet and rocket engine fault diagnosis in real time" *Journal of Neural Network Computing,* **1** (1) pp 5–18.

Dietz, WE, Kiech, EL and Ali, M, 1989c. "Classification of data patterns using an autoassociative neural network topology" *Proceedings of The Second International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems"* Tullahoma, TN, June 6–9, 1928–1036.

Dolce, JL and Faymon, KA, 1986. "Automating the US space station's electrical power system" *Opt. Eng.,* **25** (11) pp 1181–5.

Donqelli, P, Cortinovis, R and Massari, S, 1987. "Robotic intelligence issues for space manipulator monitoring, control, and programming" *First European In-Orbit Operations Technology Symposium,* Darmstadt, Germany, September.

Doyle, RJ, Atkinson, DJ and Doshi, RS, 1986. "Generating perception requests and expectations to verify the execution of plans" *JPL Report: D-3394, NASA,* April 1.

Drew, DL and Yoshimoto, GM, 1986. "Space station system coordinator and anomaly handler" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 243–252.

Drummond, M, Currie, K and Tate, A, 1987. "Contingent plan structures for spacecraft" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Dudziak, MJ, 1987. "SOLON: an autonomous vehicle mission planner" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Durfee, EH and Lesser, VR, 1987. "Incremental planning to control a blackboard-based problem solver" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Dwyer, TA, 1987. "Automatically reconfigurable control for rapid retargetting of flexible pointing systems" *SPIE Proceedings of Space Station Automation,* Vol. 851, pp 75–82.

Elfving, A and Ferse, W, "Simulation tools for the development of an autonomous rendezvous and docking system" *Intelligent Autonomous Vehicles,* Amsterdam, The Netherlands: Elsevier, pp 31–46.

Erickson, JD, 1987. "Intelligent systems and robotics for an evolutionary space station" *Journal of the British Interplanetary Society,* **40** (10) pp 471–481.

Erickson, JD, 1987. "Manned spacecraft automation and robotics" *Proceedings of the IEEE,* Vol. 75, IEEE, pp 417–426.

Ferguson, JC, 1985. "Star Plan: A satellite anomaly resolution and planning system" *Report from Ford Aerospace.*

Ferrara, F and Rosenga, G, 1984. "SCAN: Consultant systems for satellite communication antennas" *Eletronica e Telecommunicazioni,* **33** pp 189–93.

Finnerty, DF, Martin, J and Doms, PE, 1987. "ASSETT: An application in mission automation for science planning" *Journal of the British Interplanetary Society,* **40** (10) pp 461–470.

Firschein, O, et al., 1985. "NASA space station automation: AI-based technology review" *SRI Project Report 7268,* SRI International. Prepared for NASA Ames Research Center.

Firschein, O (ed.), 1986. *Artificial Intelligence for Space Station Automation,* Noyes Publications.

Fraser, J, Conway, SM, Currie, K, Drummond, M, Lockwood, RM, Macintosh, AL and Tate, A, 1988. Using onboard AI to increase spacecraft autonomy" *Proceedings of Human–Machine Interaction and AI in Aeronautics and Space,* Toulouse, France, September, pp 173–185.

Friedland, P, 1988. "AI research at NASA Ames Research Center" *Proceedings of Human–Machine Interaction and AI in Aeronautics and Space,* Toulouse, France, September, pp 187–210.

Friedman, L, 1983. "Research at Jet Propulsion Laboratory (JPL)" *The AI Magazine,* AAAI, Winter, pp 58–59.

Gale, FCT and Wolff, M, 1988. "Artificial intelligence in the Columbus crew work station" *Proceedings of Human–Machine Interaction & AI in Aeronautics and Space,* Toulouse, France, September, pp 97–124.

Gargan, RA and Kovarik, V, 1986. "An expert system for mission scheduling and conflict resolution" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 179–188.

Gargan, RA and Tilley, RW, 1987. "Mission planning and simulation via intelligent agents" *SPIE Proceedings of Space Station Automation,* Vol. 851, pp 23–30.

Georgeff, MP and Lansky, AL, 1986. "A system for reasoning in dynamic domains: fault diagnosis on the space shuttle" *SRI Technical Report: 375,* SRI International.

Goforth, A and Doming, R, 1988. "AI, automation and the flight telerobotic servicer" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 2–11.

Golden, M and Siemens, RW, 1986. "An expert system for automated satellite anomaly resolution" *Report from Ford Aerospace.*

Goodwin, MA and Talisman, BI, 1986. "A prototype real-time system to monitor space shuttle rendezvous navigation" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 165–172.

Gupta, UK and Ali, M, 1988. "Hierarchical representation and machine learning from faulty jet engine behavioral examples to detect real-time abnormal conditions" *Proceedings of The First International Conference on Industrial and Engineering applications of Artificial Intelligence and Expert Systems,* Tullahoma, TN, June 1–3, pp 710–720.

Gupta, UK and Ali, M, 1989. "LEADER—An integrated engine behavior and design analysis based real-time fault diagnostic expert system for space shuttle main engine (SSME)" *Proceedings of The Second International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* Tullahoma, TN, June 6–9.

Hammer, JM and Rouse, WB, 1982. "Design of an intelligent computer aided cockpit" *Proceedings of the International Conference in Cybernetics and Society,* New York, pp 449–453.

Handelman, DA, 1983, "An application of artificial intelligence theory to reconfigurable flight control" *Proceedings of NASA/FAA Conference No. 2451,* Atlantic City, NJ.

Hankins, GB, Jordan, JW, Mulvehill, AM, Dumoulin, JM and Ragusa, JM, 1985. "EMPRESS—expert mission planning and replanning scheduling system" *Report from Mitre: M85-23,* September.

Haziza, M, 1988. "Towards an assistant expert system shell for fault diagnosis of geostationary satellites" *Proceedings of Human–Machine Interaction & AI in Aeronautics and Space,* Toulouse, France, Sepbember, pp 211–228.

Healey, KJ (ed.), 1986. "AI research and applications at the NASA Johnson Space Center" *AI Magazine,* **7** (2) pp 101–115.

Healey, KJ (ed.), 1986. "AI research and applications at the NASA Johnson Space Center" *AI Magazine,* **7** (3) pp 146–152.

Healey, KJ, 1988. "The systems autonomy demonstration project: Catalyst for space station advanced automation" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 210–217.

Heer, E and Lum, H, "Raising the AIQ of the space station" *Aerospace America,* January.

Hewett, MD, et al., 1988. "The development of an automated flight test management system for flight test planning and monitoring" *The First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Experts Systems,* June 1–3, Tullahoma, TN, pp 324–333.

Highland, F, 1985. "Flight controller—A prototype expert system for shuttle ground control" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Holmes, KG, Wilcox, BH, Cameron, JM, Cooper, BK and Salo, RA, 1986a. "Robotic vechicle computer aided remote driving" *JPL Report: D-3282,* Vol. 1, *Concept Demonstration,* NASA.

Holmes, KG, Wilcox, BH, Cameron, JM, Cooper, BK and Salo, RA, 1986b. "Robotic vehicle computer aided remote driving" *JPL Report: D-3282,* Vol. 2, *Technical Reference,* NASA.

Holmes, KG, Cooper, BK, Salo, RA and Cameron, JM, 1986c. "Robotic vehicle—route planning/navigation fusion" *JPL Report: D-3790,* Vol. 1, *Concept Demonstration,* NASA.

Huhns, MN, et al., 1983. "Control and cooperation in distributed expert systems" *Proceedings IEEE SOUTHEASTCON,* pp 241–245.

Jamar, PG and Schur, A, 1986. "Impact of intelligent systems on space station man–machine interface (MMI) design" *SPIE Proceedings of Space Station Automation,* Vol. 729, pp 218–224.

Jenkins, LM, 1987. "Telerobot experiment concepts in space" *SPIE Proceedings of Space Station Automation,* Vol. 851, pp 92–102.

Johannsen, G and Rouse, WV, 1981. "Problem solving behavior of pilots in abnormal and emergency situations" *Proceedings of the European Conference on Human Decisions and Manual Control,* Delft University, The Netherlands.

Jongert, J, 1988. "Operationalising and expert system for satellite control" *ESTEC Workshop on AI Applications on Space Projects,* November.

Kaiser, DL, 1985. "Use of a man machine interface in the development of two expert systems for space station applications" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Kane, P, Yuen, V, Hopping, K and Kohn, W, 1985. "An expert system for configuration and design in a multiprocessor—shared memory computer architecture" *Space Shuttle–Space Station Operations and Technology,* Vol. 10, AIAA.

Katz, B and Brooks RN, 1987. "Understanding natural language for spacecraft sequencing" *Journal of the British Interplanetary Society,* **40** (10) pp 451–460.

Ke, M and Ali, M, 1988. "MLS, a machine learning system for engine fault diagnosis" *Proceedings of The First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* Tullahoma, TN, June 1–3, pp 721–727.

Ke, M and Ali, M, 1989. "A learning representation and diagnostic methodology for engine failure diagnosis" *Proceedings of The Second International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* Tullahoma, TN, June 6–9, p 824–830.

Koch, RH, 1986. "LRS: A knowledge based approach to launch resource scheduling" *Air Force Institute Report No.: AFIT/GSO/ENS/86D-4,* Air Force Institute.

Kohn, W, 1985. "A symbolic expert system for the design of digital controllers for space vehicles" *Lockheed Symposium on AI,* pp 13–19.

Kohn, W, Van-Valkenburg, J and Dunn, C, 1985. "Automatic procedures generator for orbital rendezvous maneuver" *SPIE Cambridge Symposium, Space Station Automation,* Vol. 580, pp 40–52.

Kohn, W. and Healey, 1986. "Trajectory planner for an autonomous free-flying robot" *IEEE Transactions on Robotics and Automation,* November.

Korf, RE, 1982. "Space robotics" *CMU-RI-TR-82-19,* Pittsburgh: CMU Robotics Institute.

Kornell, J, 1986. "A satellite with a good attitude: An expert system for stationkeeping" *Proceedings WESTEX-86 IEEE Western Conference on Knowledge Based Engineering and Expert Systems,* June, 1986, IEEE, pp 111–17.

Krishen, K, deFigueiredo, RJP and Graham, O, 1987. "Robotic vision/sensing for space applications" *Proceedings of the 1987 IEEE International Conference on Robotics and Automation,* Vol. 1, Washington: IEEE, pp 138–150.

Lea, RN and Giarratano, J, 1986. "An expert systems program using fuzzy logic for shuttle rendezvous sensor control" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 327–330.

Lea, RN and Goodwin, MA, 1986. "Use of fuzzy logic to determine navigation filter convergence during space shuttle rendezvous" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 331–334.

Lee, DJ, 1986. "Computers in space" *Spaceflight News* **12** pp 34–43.

Leinweber, D, 1986. "Real-time expert systems for space station process control" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 237–242.

Leinweber, D and Perry, J, 1986. "Controlling real-time processes on the space station with expert systems" *SPIE Proceedings of Space Station Automation,* Vol. 729, pp 11–19.

Leinweber, D, 1987. "Expert systems in space" *IEEE Expert,* Spring.

Lightfoot, P, 1986. "AI challenges for spacecraft control programs" *Telematics and Informatics,* **3** (3) pp 159–163.

Linick, RD, 1985. "Spacecraft command for unmanned planetary missions: the uplink process" *Journal of the British Interplanetary Society,* **38** pp 450–457.

Lockwood, RM, 1987. "An expert system to monitor and control the imaging device on a satellite" *AIAI Project Report: AIAI-PR-10,* Artificial Intelligence Applications Institute, University of Edinburgh, Edinburgh.

Loftin, RB, Wang, L, Baffes, P and Rua, M, 1987. "An intelligent training system for payload-assist module deploys" *SPIE Proceedings of Space Station Automation,* Vol. 851, pp 83–89.

Loganathan, M and Thomas, KV, 1988. "A prototype PC expert for station keeping of geostationary satellites" *Proceedings of the 39th Congress of the International Astronautical Federation,* No. IAF-88-031, Bangalore, India, October.

Macintosh, AL, Fraser, J, Currie, K, Drummond, M and Tate, A, 1989. "Survey of space related AI projects" *AIAI-TR-65,* AIAI, University of Edinburgh.

Mahmoudi, M, 1985. "Conceptual system design for servicing the satellites in space" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Maletz, M and Culbert, C, 1985. "Monitoring real-time processes using the automated reasoning tool (ART)" *Aerospace Applications of Artificial Intelligence,* pp 350–360.

Malin, JT and Lance, N, 1985. "An expert system for fault management and automatic shutdown avoidance in a regenerative life support subsystem" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Marsh, CA, 1985. "RBMS—An expert system for modeling NASA flight control usage" *Artificial Intelligence and Simulation,* San Diego: Society for Computer Simulation, pp 47–50.

Marsh, CA, 1988. "The ISA expert system: A prototype system for failure diagnosis on the space station" *Proceedings of The First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* Tullahoma, TN, pp 60–74.

Marshall, MM, 1981. "Goals for air force autonomous spacecraft" *JPL Report: 7030-1,* Issue 1, Jet Propulsion Lab, Caltech.

McClure, J, et al., 1986. "Autonomous management of the space station electric energy system" *SPIE Proceedings of Space Station Automation,* Vol. 729, pp 90–97.

McLaughlin, W, 1987. "Space at JPL" *Spaceflight,* **29** pp 38–44.

Meenen, RJ, Grant, TJ and Jongert, JJ, 1988. "The N202 expert system for man-in-the-loop spacecraft cabin pressure control" *Handout on BSO/Aerospace N202 Expert System Experiment, Crew Workstation Test-Bed, ESTEC.*

Merrill, WC and Lorenzo, CF, 1988. "A reusable rocket engine intelligent control" *AIAA 24th Joint Propulsion Conference,* July 11–13.

Miller, RH, Minsky, ML and Smith DMS, 1982. "Space applications of automation, robotics and machine intelligence systems (ARAMIS)—Executive summary" *NASA Report: CR-162079.*

Moravec, HP, 1987. "Certainty grids for mobile robots" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Mount, FE and Woolford, BJ, 1985. "A representative space station expert system for maintenance scheduling" *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Nachtsheim, PR, Gevarter, WB, Stutz, JC and Banda, CP, 1985. "Knowledge based expert system for scheduling of airborne astronomical observations" *NASA Amés Report, NAS 1.15:88194; A-86054; NASA-TM-88194,* NASA.

Nease, A and Fulwider, R, 1988. "Implementation of expert system technology on the space station" *SPIE Proceedings of Space Station Automation,* Vol. 729, pp 212–217.

New, E, 1985. "Schematic generation for NASA's LOX expert system' *ISA Workshop on Robotics and Expert Systems,* Vol. 1, pp 185–193.

Newell, JF, 1987. "Composite load spectra for select space propulsion structural components" *LRC Structural Integrity and Durability of Reusable Space Propulsion Systems,* NASA, pp 175–187.

Nguyen, TA and Chiou, WC, 1986. "Cooperating expert systems for space station power distribution management" *SPIE Proceedings of Space Station Automation,* Vol. 729, pp 7–10.

Nguyen, KD, Cole, DH, Perry, J and Norman, AM, 1988. "An integrated laboratory test bed for rocket engine health monitoring experimentation" *AIAA 24th Joint Propulsion Conference,* July 11–13, Boston, MA.

Norman, A and Taniguchi, 1988. "Development of an advanced failure detection algorithm for the SSME" *24th Joint Propulsion Conference,* July 11–13, Boston, Massachusetts.

Norsworthy, R, Kohn, W and Arellano, J, 1985. "A symbolic package for analysis and design of digital controllers" *Space Station Operations and Technology,* Vol. 10, AIAA.

Oberright, J, 1987. "Space station flight telerobotic servicer program review" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Oberright, J, McCain, H and Whitman, RI, 1987. "Space station flight teleobotic servicer functional requirements development" *SPIE Proceedings of Space Station Automation,* Vol. 851, pp. 169–172.

Ohler, PC and Hall, SB, 1986. "Distributed AI systems for dynamic allocation and management of power (DAISY-DAMP) testbed" *SPIE Proceedings of Space Station Automation,* Vol. 729, pp 67–88.

Olalainty, B, Gulberg, J and Fuchs, JJ, 1988. "Applying AI techniques to generate spacecraft mission plans" *Proceedings of Human–Machine Interaction and AI in Aeronautics and Space,* Toulouse, France, September, pp 297–312.

Orlando, N, Abbot, K and Rogers, J, 1984. "AI research at NASA Langley Research Center" *The AI Magazine,* AAAI, pp 79–80.

Owen, K, 1989. "AI gets a boost" *Aerospace America,* July, p. 16.

Pazzani, MJ and Brindle, AF, 1986. "Automated diagnosis of attitude control anomalies" *Annual AAS Guidance and Control Conference,* San Diego: American Astronautical Society.

Pearson, G, 1987. "Mission planning for autonomous systems" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Pearson, G, 1989. "A blackboard system for planning space missions" *Proceedings of The Second International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* June 6–9, Tullahoma, TN, pp 409–416.

Peters, SF, 1988. "Autonomy through interactions: The JPL telerobot interactive planning system" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 173–178.

Pohlman, LD and Payne, JR, 1986. "Pilot's associate demonstration one: A look back and ahead" *IEEE National Aerospace and Electronics Conference,* Dayton, Ohio.

Rajagopalan, R, 1984. "Qualitative modeling in the turbojet engine domain" *CSL Tech. Rept. T-139,* Dept. of Elect. Engineering, Univ. of Illinois, Urbana, IL, March.

Raman, S, 1988. "Flight mission scenario generation with knowledge-based system" *The First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* June 1–3, Tullahoma, TN, pp 341–343.

Raulefs, P and Thorndyke, PW, 1987. "An architecture for heuristic control of real-time processes" *Space Telerobotics Workshop,* JPL, NASA, January.

Read, JY, et al., 1986. "Use of communicating expert systems in fault diagnosis for space station applications" *SPIE,* Vol. 729, *Space Automation II,* October 28–30, Cambridge, MA, pp 30–39.

Rosenthal, D, 1986. "ST proposal entry processor: Grotto specs" *Report from ST ECF, ESA.*

Roston, G, 1986. "A technique to aid in the design of optimal robots for use in space applications" *SPIE Proceedings Space Station Automation,* Vol. 729, pp 161–169.

Russo, G, Richmond, A and Albrecht, R, 1986. "The European scientific data archive for the Hubble Space Telescope" *Proceedings of the Erice Workshop on Data Analyusis in Astronomy,* April.

Sanderson, AC, Peshkin MA and Hoem-de-Mello, LS, 1987. "Task planning and control synthesis for robotic manipulation in space applications" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Scarl, EA, 1984. "Applications of a non-rule knowledge based system to NASA scheduling and monitoring problems" *Proceedings of IEEE Intersociety Energy Conversion Engineering Conference,* San Francisco, CA.

Scarl, EA, Jamieson, JR and Delaune, CI, "A fault detection and isolation method applied to liquid oxygen loading for the space shuttle" *Proceedings of the 9th International Joint Conference on AI (IJCAI-85),* Los Angeles, CA.

Schenker, PS, French, RL and Smith, DB, 1988. "NASA telerobot testbed development and core technology demonstration" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 132–144.

Schmidt, OL, 1986. "Expert system for the control and monitoring of the space station communications and tracking system" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 155–159.

Scheutzle, JG and Zoch, DR, 1986. "A hierarchical planning system for mission support" *IEEE Expert Systems in Government Symposium,* October 22–24, pp 210–220.

Schutte, PC and Abbott, KH, 1986. "An artificial intelligence approach to onboard fault monitoring and diagnosis for aircraft applications" *Presented at AIAA Guidance and Control Conference,* Williamsburg, VA, August 18–20.

Sheffield, JW, Kher, RP and Raghav, P, 1986. "Thermal aspects of future spacecraft thermal management systems" *AFWAL Report No. AFWAL-TR-86-2021,* Air Force Wright Aeronautical Labs.

Sheldon, B and Feehrer, C, 1985. "An analysis of the application of AI to the development of intelligent aids for flight crew tasks" *NASA Contractor Report 3944, BBN,* Cambridge, Massachusetts.

Shelnutt, JB, Stenerson, RU, Nelson, PC and Marks, PS, 1986. "Pilot's associate demonstration one: A look inside" *IEEE National Aerospace and Electronics Conference,* Dayton, Ohio.

Skapura, DM and Zoch, DR, 1986. "A real-time production system for telemetry analysis" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6.

Smith, RB, 1979, "A framework for distributed problem solving" *IJCAI,* pp 836–841.

Smith, JH, Gyamfi, MA, Valkmer, K and Zimmerman, WF, 1987. "The space station assembly-phase: Flight telerobotic services feasibility" *JPL* **I and II** September.

Smith, RE, 1988. "Task planning issues for an in-orbit service manipulator" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 71–78.

Solloway, C, 1987. "Description of current research – AI research group JPL" *Proceedings of the NASA Workshop for Space Station Telerobotics,* Jet Propulsion Lab, Caltech, January 20–22.

Sorenson, C and Lockhart, D, 1986. "The rendezvous trajectory assistant (RTA) expert system" *Proceedings of ROBEXS '86, The Second Annual Workshop on Robotics and Expert Systems,* Instrument Society of America, Research Triangle Park, North Carolina, June 4–6, pp 303–306.

Sawizral, HA, 1983. "Experiments with distributed heuristic agents in Rosie" *Proceedings of the International Conference on Systems, Man, and Cybernetics,* Bombay, Vol. 1, pp 355–358.

Spector, A and Gifford, D, 1984. "The space shuttle primary computer system" *Communications of the ACM,* **26** (9) pp 874–900.

St Clair, DC and Wetterstroem, A, 1986. "UIL-ESP-AD: An expert system for analyses and diagnoses of a space station power subsystem" *Proceedings of the ACM 14th Annual Computer Science Conference.*

Sztipanovits, J, Biegl, C, Karsai, G and Purves, RB, 1988. "Model-based approach for intelligent control" *SPIE Proceedings of Space Station Automation,* Vol. 1006, pp 46–55.

Touchton, RA, 1986. "Common module dynamic payload scheduler expert system" *Proceedings of 21st Intersociety Energy Conversion Engineering Conference,* Vol. 3, American Chemical Society, pp 1785–90.

Toussaint, AL and McFall, ME, 1985. "Spacecraft application of expert systems" *IEEE AES Magazine,* May, pp 2–5.

Vachtevanos, G, Hexmoor, H and Purves B, 1986. "On the intelligent control of the space station common module thermal system" *Proceedings of the 21st IEEE International Conference on Systems, Man, and Cybernetics,* Vol. 2, pp 1390–4.

Vachtevanos, G and Davey, K, 1987. "Fault diagnostics for the space station thermal control system using a hybrid analytical/intelligent approach" *Proceedings of the IEEE International Symposium on Intelligent Control,* Washington: IEEE, pp 54–8.

Vere, SA, 1983. "Planning spacecraft activities with a domain independent planner" *Proceedings ofAIAA Computer in Aerospace Conference.*

Wagner, RE, 1983. "Expert system for spacecraft command and control" *Report from Ford Aerospace.*

Wagner, RE, 1983. "Automated spacecraft health and status" *Report from Ford Aerospace.*

Ward, N, Murdoch, J and Edwards, E, 1986. "A study of expert systems applied to space projects" *ESA Report No. TP 8247,* British Aerospace Ltd.

Wechsler, DB and Crouse, KR, 1986. "Approach to design knowledge capture for the space station" *NASA Report No. NAS 1.15:89272; NASA-TM-89272.*

Weeks, DJ, 1985. "Application of expert systems in the common module electrical power system" *SPIE, Proceedings of Space Station Automation.*

Wiener, EL, 1985, "Cockpit automation: A field study of flightcrew transition" *NASA CR-17333,* NASA Ames Research Center, Maeffett Field, California, July.

Wilcox, BH and Gennery, DB, 1987. "A Mars Rover for the 1990s" *Journal of the British Interplanetary Society,* **40** (10) pp 483–488.

Wolfe, WJ and Raney SD, 1987. "Distributed intelligence for supervisory control" *Space Telerobotics Workshop,* JPL, NASA.

Yang, JYD, Huhns, MN and Stephens, LM, 1985. "An architecture for control and communication in distributed artificial intelligence systems" *IEEE Trans. on Systems, Man, and Cynbernetics,* **SMC-15** (3).