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An Expert System for Satellite and Instrument Data Anomaly and Fault Isolation

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A prototype Generic Payload Operations Control System (GPOCC) is being developed at the NASA Jet Propulsion Laboratory to provide a low-cost command and control processing center for science instruments and small payloads. The GPOCC supports the difficult transition from integration and test to flight operations. The prototype will incorporate four expert systems to perform telemetry, command, and mission planning functions as well as telecommunications scheduling. The first of these expert systems to be developed will perform telemetry data analysis and fault isolation, as well as propose corrective action.

This Data Analysis Module (DAM) will monitor telemetry data and perform continual data monitoring and trend analysis based on a knowledge base and historic data archived on an optical disk storage device. The system maintains a continuous "knowledge" database of past system performance characteristics.

The Data Analysis Module will be partitioned into four stages:

MONITORING - monitoring and interpreting instrument and satellite behavior.

DIAGNOSIS - determine origin of system malfunctions inferred from knowledge base.

PREDICTION - inference of predicted performance based on historic performance and current trends.

RECOMMENDATION - developing and prescribing corrective action for diagnosed problems.

The goal of the Data Analysis Module is to achieve consistent, dependable and validatable performance, to demonstrate thorough, reliable and fast reasoning, and to reduce the concentration demanded of flight analysis personnel.

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Introduction

The Data Analysis Module (DAM) is a project of the Institutional Computing and Mission Operations division of the California Institute of Technology, Jet Propulsion Laboratory. The Data Analysis Module is an expert system element intended for future incorporation in a purposed Generic Payload Operations Control Center (GPOCC). The purpose of the DAM project is the design and development of an expert system to monitor spacecraft and science instrument telemetry data, isolate and diagnose faults, pinpoint the probable fault location and recommend corrective action.

Background

The Jet Propulsion Laboratory is a lead center for NASA's program of planetary exploration and earth science. In support of this role JPL has pursued areas of technology associated with the advancement of the spacecraft and science instrument operations environment. To concentrate emphasis efforts in new areas of technology the Laboratory established the Office of Space Science and Instruments (OSSI) and the Office of Technology and Applications Programs (TAP). *[JPL Annual Report 1988]*

The concentration of the Laboratory on technology in the mission operations domain has centered on automation of instrument and spacecraft command and control functions. Automation in the mission environment is significant for three reasons. First, carefully selected automation reduces the workload of the operations personnel. Second, automated and verifiable computer-based tools *[Harmod 1987]* improve the accuracy of data processing and assist space flight and instrument control engineers in monitoring of spacecraft and mission sensors where operating data rates may greatly exceed the ability of individuals to monitor successfully. And third, as the number of missions increases, the number of trained and experienced flight support personnel cannot keep up with the extreme demands caused by information overload. Automated aids and operator assistance allow for productivity enhancement and maintaining the required level of flight support. *[Hansen 1988]*

To automate the flight and instrument integration and control process, the Laboratory has directed a major effort toward the incorporation of artificial intelligence into spacecraft sensor and space vehicle integration and test, and flight operations areas.

This effort has led to the development of several knowledge-based systems to improve the JPL spacecraft and instrument command and control process. Specifically these expert systems are:
SHARP, the Spacecraft Health Automated Reasoning Prototype, is one

of a number of Mission Operations Productivity Enhancement Program (MOPEP) activities. SME, Spacecraft Monitoring Environment, is being incorporated into the satellite integration and test domain. EPDM, the Electrical Power Data Monitor, is being designed to monitor the Voyager spacecraft power systems, and DAM, Data Analysis Module.

The Spacecraft Health Automated Reasoning Prototype (SHARP)

The Spacecraft Health Automated Reasoning Prototype has been designed to incorporate the experience of the lead Voyager spacecraft telecommunications engineer into a useable knowledge base. Data from this knowledge source is assimilated in a knowledge base that will be used as an around-the-clock mission operations assistant in support of the Voyager spacecraft's upcoming Neptune Encounter. The LISP expert system shell was used in the development. Data Views provides the graphical interface. SHARP is implemented on a Symbolics 3670.

Spacecraft Monitoring Environment (SME)

The Spacecraft Monitoring Environment is being developed to aid in the Galileo spacecraft integration process. The SME will provide a real time autonomous spacecraft test sequencing and data monitoring of integration and test activity. SME resides on a Sun 386/i. Data Views is being used to provide high-level contextual graphic displays and windowing capability.

Electrical Power Data Monitor (EPDM)

The Electrical Power Data Monitor is currently under conceptual design. The EPDM will be designed to oversee the Voyager spacecraft power systems during the Neptune Encounter. The C Language Integrated Production Systems (CLIPS) developed by Johnson Space Center Mission Planning and Analysis Division's Artificial Intelligence Section, will be used as the expert system shell. The EPDM development will be on a Sun 3/260.

Generic Payload Operations Control Center (GPOCC)

The Generic Payload Operations Control Center is a concept being developed to apply automation to instrument and satellite testing, as well as a mission operations environment. The GPOCC will couple expert systems with high level contextual graphical data displays for ease of user interpretation. A modest prototype was developed on a Apple MacIntosh II to demonstrate user interfaces and functionality of the GPOCC concept.

The Generic POCC will apply expert system technology to four areas: 1) mission flight planning for science instrument and flight sequence planning, and command constraint checking; 2) control of on-board data storage devices, memory management, and memory comparison; 3) DSN 26-meter subnet and TDRSS telecommunications link scheduling; 4) satellite telemetry data monitoring, trend Analysis, prediction forecast, anomaly detection, fault isolation, diagnosis, and corrective action strategy. *[JPL D-5435 1988]*

The Generic Payload Operations Control Center effort is intended to support the arduous transitions between development, instrument and satellite integration and test, and flight operations.

However, lack of a funding source and development manpower restrictions has permitted only piecemeal development. For this reason, an implementation strategy was generated which provided for a phased progression of development. The Data Analysis Module was selected for initial implementation. DAM builds on the experience gained in development of telecommunications and power systems, and spacecraft integration and test systems. However, these systems were designed to be operated within a restricted domain of their own unique environment (i.e. telecommunications, powers systems). DAM is intended to develop an expert system that encompassed operation of all the subsystems of a complete spacecraft.

Other NASA Center Expert System Implementations

Several other NASA space centers have developed expert systems for use in a mission operations environment. All of the systems have been well thought-out and impressively implemented. The Goddard Space Flight Center has developed two such systems. The Communications Link Expert System (CLEAR) for Cosmic Background Explorer (COBE) developed by the GSFC Data Systems Applications Branch of the Data Systems Technology Division, *[Hughes 1987]* and MOORE (named after Mr. Bob Moore at TRW who was the knowledge source) a prototype expert system for diagnosing TDRSS spacecraft attitude control problems, developed by Westinghouse Electric for the GSFC. *[Howlin 1988]*

The Johnson Space Center Mission Planning and Analysis Division has developed an expert system called INCO, for the Instrumentation and Communications Officer prototype designed to monitor and analyze Space Shuttle telecommunications links. *[Madison 1988]*

Data Analysis Module

The Data Analysis Module will monitor telemetry data and perform continual data monitoring and trend analysis based on its knowledge base and historic data archived on an optical disk storage device. Because of cost constraints, an off-the-shelf hardware PCM decommutator will be used to frame synchronize and channelized the data stream instead of building a software frame synchronizer. The DAM prototype will include a worm-drive optical disk to maintain a continuous "knowledge" database of past system performance characteristics.

The Data Analysis Module contains four rule domains. These domains are:

MONITORING - monitoring and interpreting instrument and satellite behavior.

DIAGNOSIS - determine origin of system malfunctions inferred from knowledge base.

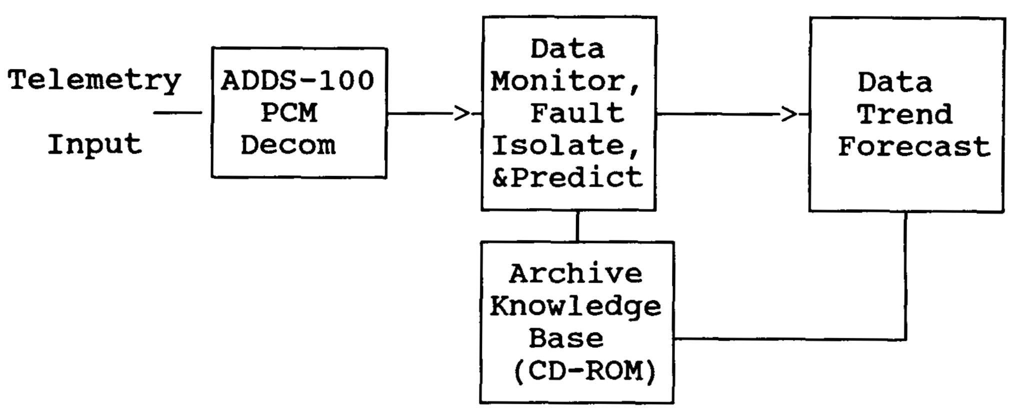
PREDICTION - inference of predicted performance based on historic performance and current trends.

RECOMMENDATION - developing and prescribing corrective action for diagnosed problems.

The goal of the Data Analysis Module is to achieve consistent, dependable and validatable performance, *[Stagner 1988]* to demonstrate thorough, reliable and fast reasoning, and to reduce sometimes-overwhelming loads placed on flight analysis personnel.

The DAM processing flow is show in figure 1.

Figure 1 Data Analysis Module Process Flow



Data Analysis Module Mission Domain

In implementing the Data Analysis Module, the science and mission user domain framed the overall structure and requirements of the DAM. DAM will function in an instrument test environment, a spacecraft integration and test environment, and lastly, in an actual mission operations environment.

In the instrument test environment the DAM will allow the instrument principal investigator or scientist to observe operating conditions during development in the same environment and equipment configuration as will be used in flight.

In the spacecraft integration and test environment the DAM must provide data-handling flexibility and integrated displays to lend itself to the task of releasing satellite integration and test personnel from constantly modifying a complex data handling system as system requirements change.

The DAM must support a mission operations environment which will be a natural progression from the instrument and satellite integration and test environment. The DAM support of the Mission Operations System (MOS) will differ little from the prelaunch Ground Data Systems testing and MOS training activities. The major difference is the addition of "live" flight telemetry data input to the input process. This similarity significantly aids in the transition from single-instrument integration to full-up on-orbit operations.

The DAM telemetry task will be coupled to a display systems design to provide more user-efficient data interpretation by use of symbolic representation including pop-up windows, scroll bars, graphics, colors representative of data states, and interactive icons.

Data Analysis Module Design Concept

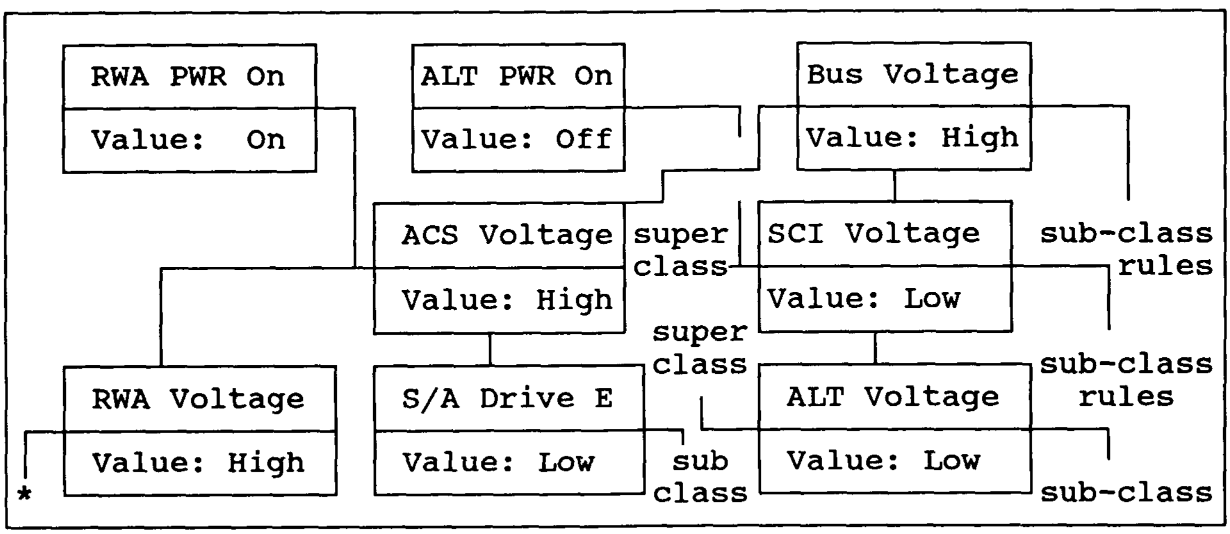
Knowledge representation is a central issue in the development of intelligent systems. While a number of knowledge representation formalities and techniques have been developed, most are based on semantic networks and frames. *[Barr 1981;Cho 1985]* These may have limited application domains which depend on complex deductive strategy.

Expert systems have been developed to provide telemetry data analysis. These systems have examined data related to a unique spacecraft subsystem (i.e. telecommunications, and power in SHARP and EPDM, respectively). The DAM examines the input telemetry stream on a criticality prioritized basis.

Early in system design each telemetry channel was assigned a criticality level. Once this was done, a relationship for each parameter was established. The level two relationship is flowed down through to sub-tier prioritized classes. The result was an interwoven tree of rule classes based on individual channel priority and importance. This entity-relation approach allows critical spacecraft and sensor faults to be monitored constantly and faults to be quickly detected.

Each prioritized telemetry channel is assigned a frame slot. These slots explicitly point downward to assigned subclasses, and up to super classes. This enables DAM frames (a knowledge representation scheme that associates features with an object in terms of various slots and slot values) to capture hierarchical taxonomies. An example of the DAM rule hierarchy is shown in figure 2.

Figure 2 DAM Rule Classes



Hardware Configuration

To reduce the cost of the initial implementation the conceptual testbed was established on an IBM PC/AT clone using CLIPS as the expert system shell. Simulated spacecraft telemetry was used for the data source. Formal prototyping will be done in the JPL Mission Operations Division's Operations Engineering Laboratory (OEL) on a SUN 4/260 using an Advanced Digital Data Systems ADDS-100. PCM decommutator to provide conditioning of the serial telemetry data stream.

The initial testbed configuration is:

System 1800 AT 80286 running at 8 MHZ
80287 co-processor
640 Kbyte RAM
2.5 Mbyte Extended RAM
with 80 Mbyte hard disk and 30 Mbyte auxiliary storage
1.2 Mbyte floppy disk drive
60 Mbyte streaming tape storage
VGA display with NEC Multisync II color monitor

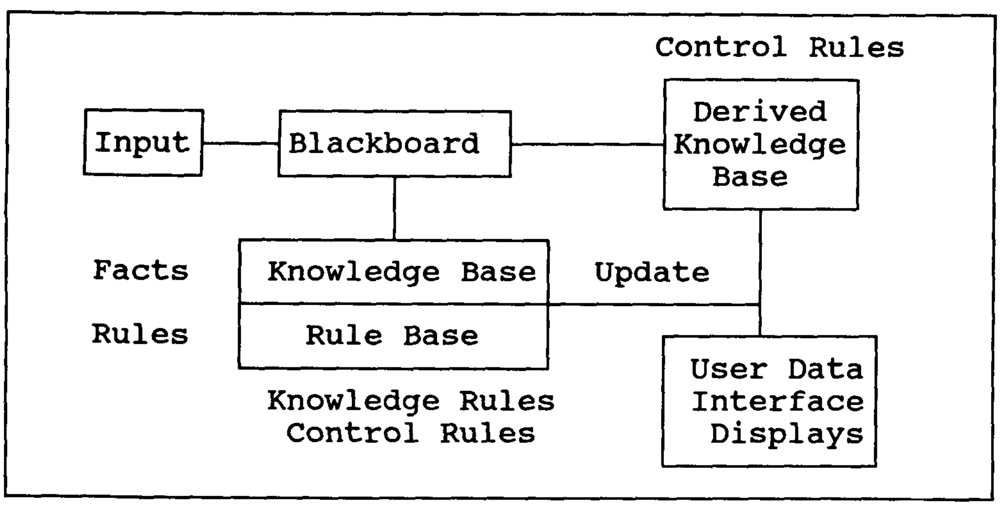
The formal OEL prototype configuration will be:
Sun 4/260 68020 running at 16 MHZ
8 Mbyte RAM
two 71 Mbyte hard disks
60 Mbyte streaming tape storage
1152 x 900 bit-mapped color display

<u>Development Approach</u>

The DAM will be implemented in two stages, a conceptual testbed, and a formal prototype. To validate the conceptual design of the Data Analysis Module a testbed consisting of approximately twenty five rules for the five spacecraft subsystems. Following the testbed demonstration a formal prototype will be implemented. The prototype will consist of roughly one hundred twenty five rules and will be configured as a flight support workstation.

The DAM testbed will be use to develop the initial telemetry channel hierarchial relations. The testbed will demonstrate our understanding of the telemetry problem domain. This initial testbed model will be a proof of concept. Once the testbed has shown our comprehension of the domain, prototype design will begin. Testbed development is expected to be completed by the end of the year. The conceptual design of the testbed is shown in figure 3.

Figure 3 DAM Testbed Conceptual Design



Both the testbed and the formal prototype will use CLIPS as the expert system shell. CLIPS was chosen for several key features: these include forward rule chaining, rule syntax, multi-field functions, embeddable in C programs, window and mouse interfaces, portability (testbed to prototype), tool set (rule break pointing, fact address comparisons, style checking and cross-referencing), and complete documentation.

The prototype will allow evaluation of the DAM hardware and software performance, as well as ferret out problems employing actual telemetry data sets. The formal prototype development will be completed by the end of 1989.

The monitoring, diagnosis, and recommendation rules are combined into a single task. The predictive model is generated from past and current data activity. The DAM will also log all expert system activity for later analysis.

System Architecture

The basic testbed architecture incorporates three components: the CLIPS expert system shell, the input data source, and the output user displays.

The ADDS-100 telemetry decom provides the DAM with simulated communications links from the Tracking and Data Relay Satellite System (TDRSS), White Sands Ground Terminal (WSGT) and the JPL Deep Space Network (DSN) 26-meter subnet. This telemetry source data is frame synchronized, and decommutated by the PCM hardware decommutator. The channelized data is archived.

The DAM expert system provides telemetry data monitoring and interpreting, and fault isolation. The DAM will then determine origin of system malfunctions inferred from the knowledge base and develop and prescribe corrective actions for the diagnosed problems.

The output user displays inform the user of current status and alert the user to any data irregularities.

Data Monitor

The Data Analysis Module monitors data values to detect faults. These faults are identified, a diagnosis is performed, and corrective action strategy proposed. As the DAM examines the input serial telemetry stream each data channel is placed in a predefined frame slot and compared against initial user defined expected data boundary value conditions. If a value exceeds the established boundary value the rules associated with that data channel fire. If a nominal value is present the current value is compared against previous data values.

Fault Diagnosis and Corrective Action Recommendation

When channel values exceed boundary conditions faults are isolated and corrective action recommendations are predicted by the compound rules classes governed by assertive clauses. For example:

```
(assert   (RWA run-away
           ACS Voltage High
           SCI Voltage Low
           S/A Voltage Low
           RWA PWR     On))
```

Predictive Modeling

While the DAM is performing continual data monitoring trend analysis based on historic data is preformed. Trend variations are examined for fault conditions, inference of predicted performance is made based on historic values and recommendations are made for corrective action. The system maintains a continuous "knowledge" base of past telemetry system performance characteristics.

Knowledge Representation

The DAM man-machine interface will be via easily interpreted contextual graphic displays. These interactive video displays will provide a direct representation of the intrinsic images associated with the instrument and satellite telemetry and telecommunications systems. Multiple display screens with pop-up windows and high resolution graphics will be linked through context and mouse-sensitive icons and text.

Implementation

The DAM design will insure that implementation meets the requirements specified in JPL software standards as well as software system integration and test standards. *[JPL D-4000; D-5000 JPL 1988]*

Summary

Based on the knowledge gained in the design and development of the Data Analysis Module, the Generic Payload Operations Control Center will provide for consistent, dependable and validatable performance. It will demonstrate reliable reasoning, and reduce the requirement for a large integration and test, as well as a mission flight support staff.

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