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Utilizing Expert Systems for Satellite Monitoring and Control

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Abstract

Spacecraft analysts in the spacecraft control center for the COBE (Cosmic Background Explorer) satellite are currently utilizing a fault-isolation expert system developed to assist them isolate and correct faults in the communications link. This system, named CLEAR (Communications Link Expert Assistance Resource), monitors real-time spacecraft and ground system performance parameters in search of configuration discrepancies and communications link problems. If such a discrepancy or problem is isolated, CLEAR alerts the analyst and provides advice on how to resolve the problem swiftly and effectively. The CLEAR System is the first real-time expert system to be used in the operational environment of a satellite control center at the NASA Goddard Space Flight Center.

CLEAR has not only demonstrated the utility and potential of an expert system in the demanding environment of a satellite control center, it has also revealed many of the pitfalls and deficiencies of the development of expert systems. One of the lessons learned from this and other initial expert system projects is that prototypes can often be developed quite rapidly, but operational expert systems require considerable effort. Development is generally a slow, tedious process that typically requires the special skills of trained programmers.

Due to the success of CLEAR and several other systems in the control center domain, a large number of expert systems will certainly be developed to support control center operations during the early 1990s. To facilitate the development of these systems, a project has been initiated to develop an integrated, domain-specific tool, named GenSAA (Generic Spacecraft Analyst Assistant), that will allow the spacecraft analysts to rapidly create simple expert systems themselves. By providing a highly graphical, point-and-select method of system development, GenSAA allow the analyst to utilize and/or modify previously developed rule bases and system components, thus facilitating software reuse and reducing development time and effort.

Introduction

The Goddard Space Flight Center is responsible for managing the operations of numerous low-earth orbit satellites. These scientific satellites either have a dedicated control center (e.g. LANDSAT and the Hubble Space Telescope) or share computer resources in the Multi-Satellite Operations Control Center (e.g. Cosmic Background Explorer and Earth Radiation Budget Satellite). In either case, highly trained personnel, called flight operations analysts (FOAs), are responsible for the proper command, control, health and safety of the satellite.

The satellite control centers operate round-the-clock throughout the lifetime of the spacecraft. There are typically multiple real-time communications events with each satellite daily. During these real-time communications events, the FOAs must:

- establish and maintain the telecommunications link with the spacecraft,
- monitor the spacecraft's health and safety,
- send commands or command loads to the satellite for on-board execution,
- manage spacecraft resources (including on-board memory, batteries, and tape recorders), and
- oversee the dumping of the scientific data from the on-board tape recorders to ground systems for processing and analysis.

To accomplish these activities, the analyst must combine a thorough understanding of the operation of the spacecraft and the ground systems with the current state of operations as indicated by numerous telemetry parameters displayed on the consoles. During an event, the analyst typically monitors hundreds of telemetry parameter values on multiple display pages that may be updating several times per second. The monitoring of the operation of these satellites is a demanding, tedious task that requires well-trained individuals who are quick-thinking and composed under pressure.

As spacecraft become more complex, the task of operating a satellite is becoming increasingly more difficult. The FOAs are reaching a level of saturation as more and more data must be monitored and analyzed during the real-time supports. The need to automate some of these functions is apparent.

The CLEAR System

The Communications Link Expert Assistance Resource (CLEAR) is the first attempt at the Goddard Space Flight Center to utilize an expert system to automate a spacecraft analyst's task. CLEAR is a fault-isolation expert system this is supporting real-time operations in the Payload Operations Control Center (POCC) for the Cosmic Background Explorer (COBE) mission. This system monitors the communications link between COBE and the Tracking and Data Relay Satellite (TDRS), alerts the analyst to any discrepancies or problems, and offers advice on how to correct them. It is the first expert system to become operational in a satellite control center at NASA/Goddard.

CLEAR is a forward chaining, rule-based system that operates in the COBE Mission Operations Room (MOR). It monitors over 100 real-time performance parameters that represent the condition and operation of the spacecraft's communications with the relay satellite. With this information, together with the knowledge of TDRS operations, COBE's on-board communications system and the expected configuration of the scheduled event, CLEAR can accurately portray the status of the communications link.

The CLEAR Expert System is currently supporting the COBE flight operations analysts for fault isolation. It is used routinely and is regarded as the fault-isolation "expert" for the COBE/TDRS telecommunications link.

The user interface for CLEAR utilizes textual and graphical output in a tiled-window format to provide the user with information about the status of the COBE/TDRS/ground communications links. A graphics window displays all of the elements of the communications network from the COBE Spacecraft to the POCC with green lines representing healthy links between elements. If the performance parameters indicate that the communications link or processing system is degrading or down, then the associated icon will turn yellow or red, respectively. This display enables analysts to assess the current status of the communications event in a quick glance.

When CLEAR isolates a problem, a short description of the problem is displayed in the "problems" window. If multiple problems are found, the problem descriptions are ranked and displayed in descending order of criticality. CLEAR suggests actions for the analyst to take in order to correct the problem; however, the system does not take any corrective action itself.

To further assist the analyst and to provide support for its advice, the CLEAR system provides an explanation facility. When the analyst selects a problem displayed in the problems window, CLEAR provides a detailed explanation of why the expert system believes that the problem exists. No backtracking or backward chaining is conducted since the system must continue to monitor the real time data and fire forward chaining rules. CLEAR maintains an event log to record histories and allow offline analysis of problems. The event log has proven to be quite useful for operational support of the mission and continued enhancement of the knowledge base.

The CLEAR System operates on any of the seven PC/AT-type workstations that are used for console operations in the MOR. It is written in the C language and uses the C Language Integrated Production System (CLIPS) and a custom-developed graphics library. It currently has approximately 160 rules. Additional rules may be added to monitor the tape-recorder dumps from the satellite to the Wallops ground station.

CLEAR isolates approximately 70 different problems. The types of problems include: non-reception of data within the control center (system or communication problems, or data reporting not activated); misconfigurations between the COBE MOR and the TDRS ground station (coherency/non-coherency, doppler compensation on/off, power mode, actual TDRS in use; antennae configurations); discrepancies in telemetry rate or format; inactive or non-locked links; and degrading or critical automatic gain control situations (signal strength).

The rule-based method of knowledge representation has proven to be quite powerful for this application. Rules provide a direct method of encoding the fault-isolation knowledge of a spacecraft analyst. The development of CLEAR would have taken much longer using conventional, non-rule-based programming techniques. Perhaps more importantly, the rule-based method of representation has provided the flexibility to easily adapt the knowledge base to unforeseen changes in the operational behavior of the spacecraft. For example, even though the operational nature of COBE was fairly accurately understood by the design engineers and flight operations team before the launch, slight behavioral variations and complications arose once the spacecraft was in orbit. Although the FOAs were able to adjust to such variations rather quickly, ground monitoring software systems required complex modifications. However, the required changes to CLEAR's rule-base were relatively straightforward and quickly implemented. After this modification, CLEAR provided consistent operational assistance. This situation demonstrates one of the advantages of the separation of knowledge and data in rule-based expert systems.

Although CLEAR has demonstrated the utility and potential of an expert system in the demanding environment of a satellite control center, it has also revealed many of the pitfalls and deficiencies of the development of expert systems. One of the lessons learned from this and other initial expert system projects is that prototypes can often be developed quite rapidly, but operational expert systems require considerable effort.

Early in CLEAR's development, the primary concern was the perceived difficulty of the knowledge acquisition effort. However, the knowledge engineering task was found to be relatively straightforward, albeit time-consuming. The development of the rule base was a lengthy process due to the interactive nature of the knowledge acquisition. Basically, the expert would describe a specific piece of knowledge to the "knowledge engineer" who would transcribe it into a rule, pass it back to the expert for validation, test it, and then, finally, release it for operational use. The involvement of various players in this process resulted in long turnaround times from the point at which a piece of knowledge was determined to be important until it was translated into a rule and placed into operation. Later in the project, it was determined that the translation of this type of expertise into rules is quite straightforward and can be easily performed by the expert himself.

The CLEAR development team learned that most of the development time for the system was spent on issues not directly related to the construction of the expert system and its rulebase. A surprising amount of the effort focused on the integration of the expert system with the data source and graphics display system. This required in-depth programming knowledge of the interfacing systems and the ability to trouble shoot problems within them. Tools are needed to simplify the complicated task of integrating expert systems with interfacing systems.

CLEAR is regarded as a successful attempt to automate a control center function using an expert system; several other missions have requested systems similar to it. Although this system is beneficial to the COBE flight operations analysts, additional benefits can be captured through retrospective analysis of the development process and focused application to future systems. The project described below represents the first steps taken that capitalize on a number of the lessons learned from the development of the CLEAR Expert System.

The GenSAA Approach

Partly due to the success of CLEAR, a considerable number of expert systems will be developed to support control center operations in upcoming missions during the early 1990's. To facilitate the development of these systems, a project has been initiated to develop an integrated, domain-specific tool, named GenSAA (Generic Spacecraft Analyst Assistant), that will allow spacecraft analysts to rapidly create simple expert systems without having to directly deal with the complicated details of the systems with which the expert system would have to interface. In addition, this tool will allow the expert system developer to utilize and/or modify previously developed rule bases and system components, thus facilitating software reuse and reducing development time and effort.

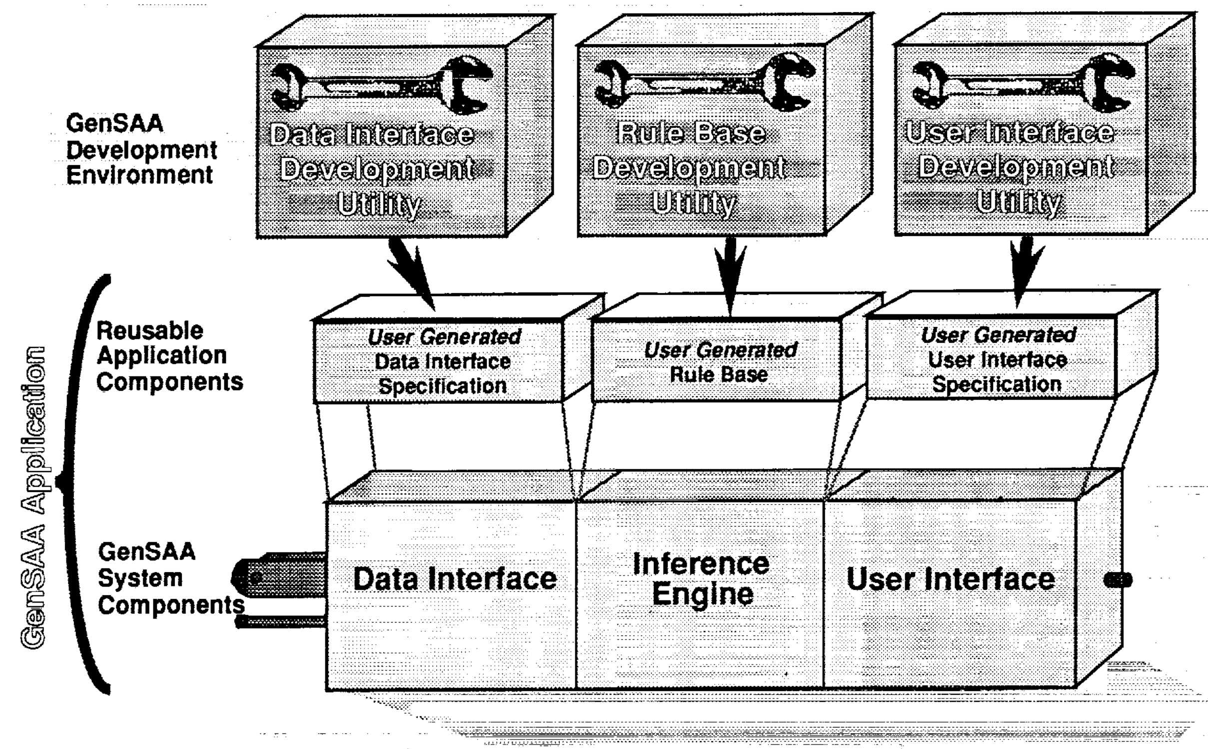

Figure 1- Elements of GenSAA

The GenSAA tool will consist of a development environment and system components (figure 1). The system components comprise of:

- the inference engine,
- the display driver, and
- a process that manages the reception of data.

The development environment is composed of three utilities:

- Data Interface Development Utility,
- Rule Base Development Utility, and
- User Interface Development Utility.

Collectively, these utilities will be used to create or modify an instance of an expert system.

The GenSAA development utilities will utilize a highly graphical, point-and-select method of interaction to facilitate use. The expert system developer will use the data interface development utility to select the telemetry parameters to be monitored, the rule base development utility to define the rules which will act on the values of these telemetry parameters, and the user interface development utility to layout a simple graphical representation of the subsystem or process being monitored and where the results of the rule executions will be displayed.

The components generated by the development utilities are called application-specific components. They will be integrated with the GenSAA System Components to create a GenSAA Application. A GenSAA Application is an expert system that will be executed during spacecraft contacts to monitor the selected telemetry parameters and to notify the flight operations analysts of faults inferred from this data.

To demonstrate the advantage of software reuse and to involve the user in the tool definition, the project team decided to initially focus on a class of missions managed by Goddard. A study of upcoming missions was conducted to identify a series of missions that have sufficient commonality to enable reuse of expert system software from mission to mission. The Small Explorer (SMEX) family of missions was determined to be an ideal target group due to the appropriate time frame of this program, the low-cost nature of the missions, the emphasis on system reuse, and the rapid turnaround between missions. All of these factors correlate closely with GenSAA's objectives.

GenSAA is intended to be used by FOAs in a POCC. In an effort to monitor the health and safety of a satellite and its instruments, FOAs monitor real time data looking for combinations of telemetry parameter values, trends, and other indications that may signify a problem or failure. The expert systems created with GenSAA will greatly assist the flight operations analysts with the tedious task of data monitoring thereby allowing them to focus on other, higher-level responsibilities during the real-time contacts with the satellite. This, in turn, will likely result in a more efficient and effective system of operations.

The behavior of a satellite is quite dynamic and often not well understood until the spacecraft is placed in orbit. To quickly create expert systems that can effectively monitor satellites, tools are needed that allow the analysts to formulate the rulebase easily without the intervention or delay of knowledge engineers and programmers. By eliminating these traditional developers, several benefits are expected. The analysts will be able to create rules quickly in response to unforeseen changes in spacecraft behavior or operational procedures. Also, knowledge translation errors will be reduced or, at least, more easily corrected. Knowledge translation errors are errors which are inadvertently introduced during the process of translating a piece of expert knowledge into rule form.

In addition to assisting the FOAs with real-time spacecraft operations, GenSAA will be useful as a training tool in two ways. First, by utilizing the playback utilities provided by the new control center ground system named TPOCC (Transportable Payload Operations Control Center), analysts will be able to replay a previous spacecraft communications event. Thus, a student analyst can observe how the expert system handles a specific problem scenario. Exercises like this will provide a realistic, hands-on environment for training flight operations analysts in a safe, off-line mode. Second, the development of rules used in an expert system is a beneficial mental training exercise for the FOA. Experience from previous expert system projects indicate that the actual formation of rules is a beneficial exercise in itself. By allowing the analysts to create rules themselves, they are forced to consider the alternatives more closely thus promoting a deeper understanding of the problem domain. This may allow the optimal method of fault isolation to be identified.

Another benefit of automating fault-isolation tasks with rule-based systems is that the resulting rulebase serves as accurate documentation of the fault-isolation method. Not only can the rulebase be studied by student analysts to learn about fault-isolation techniques, but, more importantly, mission operations can be better protected against the effects of personnel turnovers. POCC expert systems that capture fault-isolation knowledge preserve expertise from mission to mission and mitigate the impact of the loss of experienced, flight operations analysts.

Conclusion

As satellites become more complex, their operation is becoming increasingly difficult. Flight operations analysts who are responsible for the command, control, health and safety of these spacecraft are rapidly being inundated with the data coming at them at higher and higher rates. Understandably, they are quickly reaching a level of information saturation.
As demonstrated by the CLEAR Expert System, fault-isolation expert systems can help flight operations analysts monitor the flood of data. These systems can accurately monitor hundreds of real-time telemetry parameters, isolating discrepancies and anomalies the instant they can be detected, and alerting the analysts while providing advice on how to correct the problems swiftly and effectively. However, although these expert systems can be quite beneficial, the development of these systems is usually time consuming and costly, and the resulting system often cannot be easily reused by another mission.

Consequently, GenSAA is being developed for use by the flight operations analysts who work in satellite control centers. It is designed to provide quick and easy development of fault-isolation expert systems without the delay or costs of knowledge engineers and programmers. By facilitating the reuse of expert system elements from mission to mission, GenSAA will reduce development costs, preserve expertise between missions and during periods of personnel turnover, and provide a more accurate degree of command and control of our rapidly advancing satellites.

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