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NAVARES: A Prototype Expert System For NAVASTAR Anomoly Resolution

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ABSTRACT

The purpose of this research was to demonstrate the applicability of expert systems to the domain of satellite command and control, specifically, NAVSTAR Global Positioning System anomaly resolution. A prototype expert system was developed which successfully diagnoses many Attitude, Velocity and Control Subsystem and Electrical Power Subsystem anomalies. The project was sponsored by Air Force Space Command's 2nd Space Wing and was developed at the Air Force Institute of Technology.

INTRODUCTION

The operational NAVSTAR Global Positioning System (GPS) satellite system is operated by U.S. Air Force military personnel. The "Blue Suit" satellite engineers must meet the challenge posed by on-orbit anomalies without the extensive contractor technical support available to satellite systems in the past. These engineers are generally less experienced than their contemporaries in other systems, and most importantly they will take their expertise with them when they leave for a new assignment.

The objective of this research was to demonstrate the ability of expert systems to maintain corporate knowledge and aid inexperienced satellite engineers in the satellite command and control problem domain.

The NAVSTAR Anomaly Resolution Expert System (NAVARES) is a rule-based expert system prototype that successfully diagnoses many anomalies in the Attitude, Velocity and Control Subsystem (AVCS) and the Electrical Power Subsystem (EPS) of the GPS satellite. Anomaly resolution procedures and heuristics are represented in the knowledge base with rules and procedural code. The user interacts with NAVARES by answering queries about the satellite status. NAVARES uses its expert knowledge to diagnose the satellite anomaly and recommend a remedy.

WHY EXPERT SYSTEMS?

Artificial Intelligence encompasses many active research areas such as machine vision, robotics, natural language understanding, and knowledge-based or expert systems. The area which appears to have the greatest near term potential for satellite command and control applications is expert systems [Schumaker, p. 29]. Kruchten has identified two major satellite command and control problem areas, people and time, that expert systems may be able to solve [Kruchten, p. 1]

The people problems stem from several sources. It takes years to train an individual to be an expert in resolving anomalies aboard a given satellite. As satellite lifetimes increase, it becomes more difficult to retain these experts. The increasing number of satellites in orbit compounds this dilemma. Lastly, the Air Force is transferring command and control of many satellite systems from the developing command, Air Force Systems Command, to the operating command, Air Force Space Command. The operators are military officers who will rotate positions frequently, taking their expertise with them.

The time problem stems from the fact that some satellite failures may take weeks to resolve. A two-week wait might be acceptable for resolving an anomaly aboard a scientific research satellite, but systems that play a vital role in our nation's security must be returned to normal operations immediately. Furthermore, as we become more dependent on space systems, the time spent on anomaly resolution will become more critical.

KNOWLEDGE ENGINEERING

The NAVSTAR/GPS is a space-based radio navigation system designed to provide U.S. and Allied land, sea, and air forces with world wide, three dimensional position and velocity information. It also has a Nuclear Detonation detection capability.

Satellite support includes the daily uploading of navigation information and the monitoring, diagnosis and reconfiguration of the satellites. Each satellite is provided three navigation uploads per day. Normally a contact with the satellite also includes a state-of-health (SOH) support which entails monitoring the telemetry that indicates the satellite's health. SOH supports must be accomplished four times per day.

Table I summarizes the anomaly resolution activities and the responsibilities of each individual. A typical contact would consist of a navigation message upload and a SOH support. The Satellite Analysis Officer (SAO) would prepare the navigation message for sending prior to the pass, while the Satellite Operations Officer (SOO) would prepare to transmit. During command transmission, the SOO monitors critical points and calls upon the Satellite Engineering Officer (SEO) if there are any indications of a possible problem aboard the satellite. The SEO monitors all the telemetry points for possible problems and records data for short term trend analysis. If there is a problem identified, the anomaly resolution process begins.

There are three NAVSTAR anomaly resolution categories:

	USERS	SAO	SEO	SOO	SE (EMS)	CREW CMDR
ISSUE REQUIREMENTS	X					
MONITOR AND MAINTAIN NAV PAYLOAD		X				
MONITOR SV HEALTH IN REAL-TIME			X			
PERFORM EMERGENCY ANOMALY RESOLUTION (CAT 1)			X			
PERFORM SHORT TERM TREND ANALYSIS			X			
COMMAND SATELLITE				X		
PERFORM LONG TERM TREND ANALYSIS					X	
ON CALL FOR EMERGENCY ANOMALY RESOLUTION (CAT 1)					X	
PRIMARILY RESPONSIBLE FOR CAT 2 ANOMALY RESOLUTION					X	
PRIMARILY RESPONSIBLE FOR CAT 3 ANOMALY RESOLUTION					X	
APPROVES ALL COMMANDING						X

TABLE I. NAVSTAR Anomaly Resolution

1. Category 1 - Satellite life threatening
2. Category 2 - Satellite mission threatening
3. Category 3 - All others

Contingency actions to correct anomalies are identified as Type A, if the appropriate response to the anomaly is defined in an operational directive or the Orbital Operations Handbook, or Type B, if the response is not documented.

For example, if there was an anomaly detected in the Electrical Power Subsystem such that the satellite would permanently lose its operational capability if it were not corrected immediately, then this would be a Category 1 anomaly. If there is a documented procedure for resolving this anomaly, then this procedure would be a Type A contingency action. On the other hand, if the anomaly was not anticipated by the satellite designers or not seen previously and successfully resolved, then it would be a Type B contingency action.

The SEO is the crew member that performs the first level of anomaly resolution. First, the SEO verifies that an anomaly exists. If so, the SEO checks for an approved anomaly resolution procedure (Type A). If no approved procedures are available, the SEO follows the Type B contingency action procedures. Depending on the seriousness of the anomaly, the SEO may recommend immediate action, request support from the on-call Satellite Engineer (SE) or simply make note of the condition so that the appropriate subsystem SE can later investigate the anomaly. Since the SEO's knowledge is typically more general and shallow, the SEO is usually required to call in the SE.

The SEs do not work on the operational crews except to maintain proficiency as an operator. They typically spend the majority of their time increasing their knowledge and understanding of their assigned subsystems, performing long term analysis of the assigned subsystems, supporting the operational crews by developing contingency plans for possible anomalies, and last, but certainly not least important, resolving anomalies.

The SEs use a variety of microcomputer software to perform their trend analysis and trouble-shooting. Often, they can anticipate problems using trend analysis, or go back to the trend analysis when they are investigating an anomaly. They may also rely on the Orbital Operations Handbook, but are more likely to use their knowledge of the satellite's history and basic engineering skills. For this reason SEs must be considered the best source of anomaly resolution knowledge.

A particularly good record of the SE's knowledge can be found in the anomaly case reports. Whenever there is a significant satellite anomaly, one SE is assigned to lead the anomaly resolution effort. This SE will produce a report that contains a narrative description of the events, the conclusion, and the logic supporting the conclusion.

EXPERT SYSTEM TOOL SELECTION:

Based on the knowledge engineering effort, five major requirements were identified for the expert system development tool. The expert system shell must

1. interface with IBM-PC compatible data bases and spreadsheets,

2. be user friendly, i.e., have a good explanation capability and allow easy addition or modification of rules,

3. have development help facilities, i.e., trace functions and error messages,

4. be relative inexpensive,

5. and have growth capability to accommodate all nine GPS satellite subsystems.

Of the tools evaluated, GURU, an IBM-PC compatible expert system development tool by Micro Data Base Systems, best met the requirements and was selected (Rampino, pp. 37-40).

SYSTEM DESIGN

Introduction. Rapid prototyping was the design strategy used to develop NAVARES. First, several small systems were developed to explore GURU's capabilities. Next, a rule set was developed to handle the AVCS. As proficiency with the tool increased, procedural code was added for control, and the remaining rule sets were developed. Design was an evolutionary process.

Figure 1 illustrates three levels of knowledge that are desired in the operational NAVARES system. The first level is the knowledge in the Orbital Operations Handbook. The second level is the anomaly case reports described in the knowledge engineering section. The third level, model base knowledge, is knowledge derived from mathematical or symbolic models of the GPS subsystems. The current NAVARES implementation handles only the AVCS and EPS and does not include any model base knowledge.

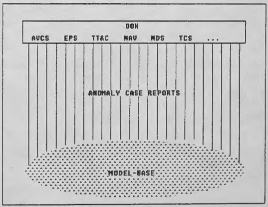

Figure 1. System Design Concept

<u>Knowledge Representation</u>. The knowledge engineering process revealed that experts do not use a standard anomaly resolution approach. The experts use their experience and knowledge to analyze each anomaly as a unique challenge. Therefore, a structure for representing NAVARES's knowledge was developed from the Orbital Operations Handbook and several past anomaly reports. This structure is represented in Figure 2. At the top of the illustration are the potential anomalous subsystems that the user may select. If "Unknown" is chosen, then the system will consider all the possible anomalies. If the AVCS or EPS is chosen, then the system restricts its search for a disorder to the selected subsystem knowledge base.

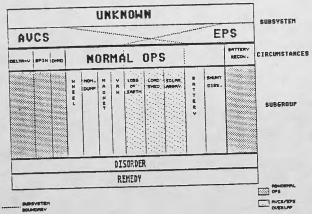

Figure 2. Implemented System Design

Next, there are five different anomaly circumstances. The majority of NAVARES' knowledge falls in the "Normal Ops" area. Under the AVCS, the user may also specify Delta-V Maneuver Execution, Spin Stabilization, or Dual Magnet Momentum Dump as the circumstance. Under the EPS, he may select Normal Ops or Battery Reconditioning. The four circumstances outside of Normal Ops are logically separate subsets of rules that apply only to these particular circumstances (indicated by the darker shaded areas). Figure 3 shows a sample rule from this layer of the knowledge base.

Under Normal Ops, there are nine subgroups. These subgroups correspond to component groups or narrow areas for the system to search for a disorder. The three lighter shaded

```
RULE:     epsld
          READY:     once
                     @ 3,1 ?"What were the circumstances of the
                            anomalous event?"
                     event = MENU(epsmenu,1,2,7,22,5,36,1)
                     @ 24,1 ?"Thinking... please wait."
          IF:        event = 1
          THEN:      askl = true
                     clear
                     @ 3,1 ?"Please narrow the problem to one of
                            the following categories."
                     normvent = MENU(normenu,1,5,5,21,3,38,1)
                     @ 24,1 ?"Thinking... please wait."
                     if normvent ne 5 then epsrun = true
                          perform smallkbs
                     endif
          REASON:    Narrowing search for disorder to particular
                     circumstances.
```

Figure 3. Sample Circumstance Rule

subgroups, (i.e., Loss of Earth, Load Shed and Solar Array), are areas where the EPS and AVCS overlap. This overlap is indicated by the dotted lines. To the left and right of the lighter shaded subgroups are those Normal Ops subgroups which logically fall under the AVCS and EPS, respectively.

The bottom two layers, "Disorder" and "Remedy," consist of rules which match anomaly evidence to a disorder and then match a disorder to a remedy. Figures 4 and 5 show a sample rule from each of these layers.

```
RULE:     mdump4
          IF:        chkhow = true and
                     momhigh = "Y" and
                     mdlon = "Y" and
                     (howflag = "Y" or
                     tbedtemp = "Y")
          THEN:      disorder="uncommanded thruster dump"
                     clear
                     ?"The SV may have experienced an uncommanded"
                     ?"thruster dump.  (See MCS-9794-01)"
                     d1="The SV may have experienced an uncommanded"
                     d2="thruster dump.  (See MCS-9794-01)"
          REASON:    If the momentums on the previous passes were
                     high and building, and the Momentum Dump Logic
                     (MDL) was on, and we had either a flag in the
                     HOW word or high thruster bed temperatures,
                     then we may have had an uncommanded thruster
                     dump.  See MCS-9794-01.
```

Figure 4.

Sample Evidence to Disorder Rule

```
RULE:     bat8r
          IF:        disorder="probable battery failure"
          THEN:      remedy = true
                     ?"";?""
                     ?"Turn off the charger to the failed battery."
                     r1="Turn off the charger to the failed
                          battery."
          REASON:    See OOH Figure 3.8.2.3-3.
```

Figure 5.

Sample Disorder to Remedy Rule

Data Management. The GURU data management capabilities are used to maintain records of past anomaly report titles so that, regardless of NAVARES' success in finding a remedy to the problem at hand, the user may request a list of relevant past reports. Reports are retrieved on the basis of satellite number, anomaly circumstance, and anomaly subgroup (see Figure 2). These reports may be useful in providing the satellite engineer clues to the source of an anomaly.

SAMPLE SESSION:

Once NAVARES has been initialized in the GURU environment the user may begin an anomaly resolution session. The initial questions request the user's name, the date, and the satellite number. Next the user must determine the anomalous subsystem (Figure 6); the user may choose to narrow the search for a solution or enter "Unknown."

```
Does this anomaly seem to be in the AVCS or EPS?
    1.  Attitude, Velocity and Control Subsystem
    2.  Electrical Power Subsystem
    3.  Unknown
```

Figure 6. Subsystem Menu

For the purposes of this discussion, assume the AVCS was selected. The next menu prompts the user for the circumstances under which the anomaly occurred (see Figure 7).

```
What were the circumstances of the anomalous event?
    1.  Normal Operations
    2.  Delta-V maneuver
    3.  Spin stabilization
    4.  DHMD execution
```

Figure 7. Circumstances Menu

Assuming that "Normal Operations" was selected, the user is then requested to narrow the problem to a particular subgroup (see Figure 8). For this example, "Loss of Earth" was selected.

```
Please narrow the problem to one of the following
categories.
    1.  Loss of Earth
    2.  Magnet related
    3.  Reaction Wheel related
    4.  Momentum dump related
    5.  Yaw related
    6.  Unknown
```

Figure 8. Subgroup Menu

Once the subgroup is selected, the user is presented a series of questions to help NAVARES reach a solution. Figure 9 shows a sample sequence of questions and answers (underlined).

```
Are the pitch and roll error less than or equal to
2 degrees? (Y/N)  N
(new screen)
Is the pitch and roll override enabled? (Y/N)  N
(new screen)
The SV has experienced loss of earth.
No attempt should be made to diagnose the SV until it is
safed.
Press any key to continue.
(new screen)
Has Load Shed 2 occurred? (Y/N)  Y
(new screen)
Is the solar panel gimbal angle appropriate for the position
in the SV's orbit where Load Shed 2 occurred? (Y/N)  N
```

Figure 9. Sample Query Sequence

This particular sequence of questions leads to a solution which is displayed after the last question is answered. The system also displays a block diagram of the subsystem indicating the anomalous component. NAVARES' final output is shown in Figure 10. It gives an assessment of the satellites malfunction (DISORDER) and a suggested solution (REMEDY) and lists relevant past reports. If NAVARES fails to recommend a remedy, the user may still request the relevant past reports.

```
NAME:                                    DATE:                  SVN:
Lt Pam Neal                              14 March 1988          1

DISORDER:
     It is possible that the Solar Array Drive went to hold mode
because of a "bit hit" from cosmic radiation or some other cause.
(See DR SCF 5111-78).

REMEDY:

     If it can be determined that one Solar Array Drive channel is
more susceptible to space charge than the other, then switch to
the less vulnerable channel.  Otherwise, no corrective action can
be suggested.  (See DR SCF 5111-78)


Reports by SVN:
     TITLE

DR SCF 5111-21
DR SCF 5111-35
DR SCF 5111-78


Reports by anomaly type:
     TITLE

DR SCF 5111-78
```

Figure 10. Sample NAVARES Output

EVALUATION

An extensive verification and validation evaluation was performed on NAVARES (Rampino, pp. 51-58). The most interesting aspect of the evaluation was the use of user test scenarios that were not provided to the developers during the knowledge engineering phase. The 2nd Space Wing supplied three anomaly scenarios used to qualify SEOs for operational crew duty. These three scenarios, which pertain only to the AVCS and the EPS, were:

- Scenario 1: Excessive discharge during Battery Reconditioning/Failure to auto-terminate
- Scenario 2: Cosmic radiation caused bit change in Magnet Control Electronics
- Scenario 3: Loss of Earth without Load Shed 2 occurrence

NAVARES correctly solved Scenarios 1 and 2, but could not reach any conclusions for Scenario 3. Scenario 1 was covered in the portion of the Orbital Operations Handbook that had been included in the knowledge base and Scenario 2 was included in a anomaly report also represented in the knowledge base. As for Scenario 3, NAVARES' knowledge base about Loss of Earth was too limited. However, the scenario information was subsequently easily added to the knowledge base.

CONCLUSION

The evaluation process has shown NAVARES to be a successful research prototype. If the knowledge is expanded to all nine GPS subsystems, it can be a useful decision aid in resolving NAVSTAR anomalies. One of the greatest challenges during the development process was determining the best organizational structure for satellite vehicle anomalies knowledge. The structure presented in this paper appears valid and provides a firm foundation for expanding the knowledge base.

Knowledge engineering was difficult in this technical and specialized domain. The transition of NAVARES to an operational system will require close interaction between the satellite engineers (experts) and the developers. Having patient and willing experts, and developers well versed in the technical aspects of NAVSTAR operations and the GPS satellite design, will dramatically increase the likelihood of success in developing an operational system.

REFERENCES:

Kruchten, Major Robert J., "Artificial Intelligence and Satellite Autonomy," Proceedings of the Second Aerospace Applications of Artificial Intelligence Conference (AAAIC-86), Dayton, Ohio, October 1986.

Micro Data Base Systems Inc., <u>GURU User's manual, Version 1.1</u>, Lafayette, Indiana, 1987.

Rampino, Michael A., <u>NAVARES: A Prototype Expert System for NAVSTAR Anomaly Resolution</u>, Masters Thesis, Air Force Institute of Technology, December 1987.

Schumaker, Randal P., and J. Franklin, "Artificial Intelligence in Military applications," <u>Signal</u>, June 1986, pp. 29-48.