Applications of Artificial Intelligence To Space Shuttle Mission Control

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ABSTRACT

Real time expert systems have been developed by the National Aeronautics and Space Administration (NASA) to monitor telemetry data from the Space Shuttle. These systems have been used during Space Shuttle flights. This represents the first use of expert systems to make flight decisions in a real space mission. This paper describes the requirements that led to the development of the expert system, the architecture used to obtain real – time performance, and the payoffs from the system.

INTRODUCTION

The successful launch of Discovery in September 1988 represented a bright new beginning for NASA. It also represented a bright new beginning in the Mission Control Center (MCC) at the Lyndon B. Johnson Space Center. For the first time knowledge – based. systems were used at this critical facility which is the focal point for Space Shuttle flight operations. Knowledge – based systems were used to monitor the Space Shuttle, detect faults and advise flight operations personnel. This is the first use of knowledge based systems technology in a NASA spaceflight operational environment. Flight management decisions were made directly based on the results of knowledge – based systems. This is a milestone in the application of artificial intelligence.

In the past, the MCC has relied on mainframe – based processing and display techniques which emphasized the use of highly skilled personnel known as flight controllers to monitor data, detect failures, analyze system performance, and make changes to flight plans. Figure 1 shows the working environment of the MCC and Figure 2 shows an example of the displays provided by this system. This worked well for programs of short – duration, but as NASA looks to operating long duration programs such Space Station Freedom, techniques are being explored to automate mission monitoring, display and analysis functions.

During the recovery from the Challenger accident, two real time expert systems were implemented and certified for use in making flight – critical decisions. This work was performed by a team of flight controllers and knowledge engineers from a combined NASA – industry team using commercial hardware and software. These two expert systems which monitor Space Shuttle communications and the Space Shuttle Main Engines were successfully used in the STS – 26 Discovery flight.

THE PROBLEM

The MCC information systems are vital to the safety and success of manned space flights conducted by the United States. The centralized system currently employed presents only raw data to flight controllers with very little interpretation. All processing is contained in a single large

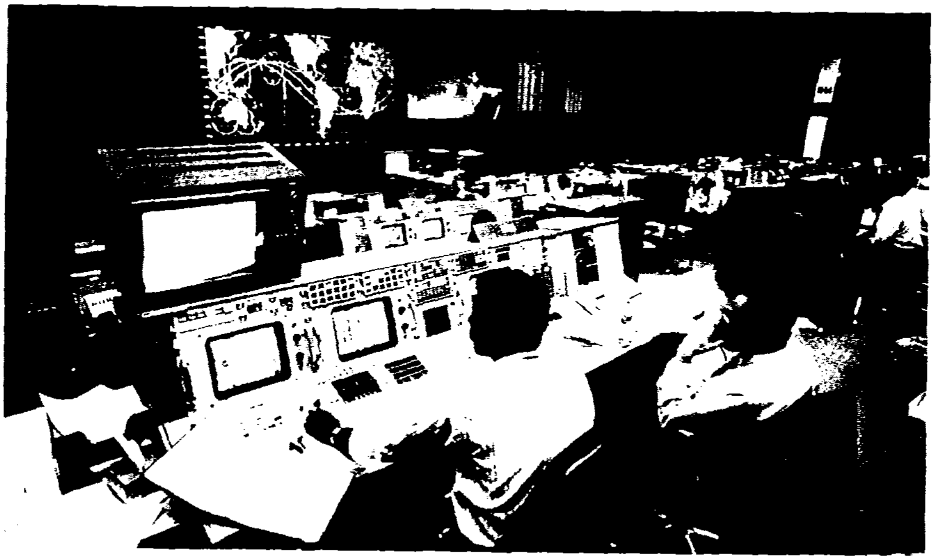

Figure 1 – Space Shuttle Mission Control

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 F/V   26/103                  COMM MANAGEMENT                RR0920:CH009
OGMT 271:22:10:20 OMET 271:22:10:20 SITE MIL OI 129     GN  44
RGMT 271:22:10:20 UD RT 1 SM     M    MBFS     MSM     D    BF     D
 - S-BAND PM ---------- KU-BAND -------- NSP. COMSEC ---------- GCIL ------
UL SS          0   |UL SS       -102.1 |  SELECT              |CONFIG PNL
STDN  SS  -150↓    |TDRS SEL       D  D|BIT SYNC              |KU FS   DABL
WEST       /       |WST          /     |FRM SYNC              |PM PNL   TV PNL
EAST       /       |EST          /     |COM SYNC              |PL PNL   FM PNL
RCVR LCK           |RF POWER     0     |SOURCE                |KU PNL
PH ERR        0    |ANT MODE         M |U/L RATE              |----DEU---------
COHERENT           |SEARCH          D  |     CODE             |  MF   DISP PWR
ANT  SEL   ER1     |DETECT          D  |D/L RATE              |1 GNC  9011 ON
  MODE     MAN     |TRACK           D  |     CODE             |2 GNC  9011 ON
  ELEC             |KU OPER          D |ENCR U/L CLR CLR      |3 GNC  9011 ON
  BEAM             |216 SYNC        D  |       D/L CLR CLR    |4    S    0SOFF
XPDR SEL           |DATA GD          D |     RCDR NSA NSA     |----FM----------
  MODE    INVL     |R/L HDR OFF        |RCDR V                |SS        -113↓
PRE AMP            |      LDR OFF      |ERROR R  0.2 0.2      |MODE  OFF
HEATER    1    2   |B-MODE           D |------CCTV------------|ANT SEL ER
PA     OFF   OFF   |  ANGLE         D  |D/L SEL               |  MODE  GPC
 TEMP  -80   -80   |--------UHF--------|  TEMP                |SYS SEL
 RFL    2.1   0.7  |MODE - - - ---     |VCU MN                |----SECURE TV---
---- SPC ---- TEC -|296-622 259-979    |DWNLINK    ENA        |ADU PWR ?
 SM       D     D  |279-987 243-24T    |GAM SEL    NORM       |TYPE     ?
BFS       D        |                   |ALC                   |OUTPUT   ?
------------RECORDERS--------------------------------------DDH--------------
OPS MODE TK %TP DIR SPMTN  TEMP        |DDH 1  271:22:10:20  FR/S  100
 1   STBY  1   0 REV 1  STOP   98      |DDH 2  271:18:53:33  FR/S    0
 2   STBY  1   0 REV 1  STOP   88      |DDH 3  271:22:10:20  FR/S  100
P/L  STBY  1   0 REV 1  STOP   91      |DDH 4  271:22:10:20  FR/S  100
FAULT        BCE STRG 3  STKR          |GPC 1234    TIME 271:05:28:10.07
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Figure 2 – Typical MCC Mainframe Display

mainframe computer with software which is difficult to change and verify. This system presents data to the flight controllers, but not information. It is the job of the flight controllers to convert this raw data to information that can be used to manage the mission. Teaching flight controllers to perform this task is a major training problem which typically takes two to three years to complete. The nature of the mainframe – based MCC system, which mostly provides monochrome text displays, causes even the most highly trained and motivated flight controllers to make occasional monitoring errors. In the problem domain of the MCC, a flight controller error can lead to grave consequences.

The problem of ensuring high – quality decisions by the flight control team using this minimal information processing capability is further complicated by NASA's unique bi – modal age distribution. Due to the hiring freezes between the Apollo and Space Shuttle programs, the majority of NASA personnel fall into two distinct groups: the younger "Shuttle – only" group under 35 years of age and the more experienced "Apollo – era veterans" of greater than 45 years of age. These veterans represent a dwindling supply of corporate knowledge and experience as they are promoted, retire or move on to other activities.

As NASA moves into the Space Station era, it is further confronted by the requirement to continuously operate the station for its twenty year lifetime. It is not reasonable to expect that we will be able to maintain a large work force of highly skilled flight controllers to perform the demanding workloads that are imposed by our current style of systems monitoring over that amount of time.

NASA'S SOLUTION

Artificial Intelligence is a natural source of techniques for converting data into information, capturing corporate knowledge, and lowering operator training and response time. In 1987, Mission Operations Directorate at the Lyndon B. Johnson Space Center started a project to apply the techniques and methodologies of AI such as expert systems and natural language interfaces to real space mission operations problems.

The first task of this project was to provide an "intelligent associate" to the flight controller monitoring the Space Shuttle's communications and data systems. The associate expert system is named after the first flight controller position selected for automation and is called the Integrated Communications Officer (INCO) Expert System. Development was started in August 1987 and the system was placed in the MCC in April 1988. Approximately eight person years worth of effort and $400,000 of hardware were required to field this system. This system was placed next to the INCO console which allows operators to compare results of the conventional console to those of the expert system (Figure 3). This system was used during the STS – 26 flight of Discovery in September 1988.

The INCO Expert System was implemented on a conventional color graphics engineering workstation. The Masscomp 5600 with the Unix operating system was chosen to be compatible with other workstations in the MCC.

Automated monitoring was performed by both algorithmic and heuristic techniques. Knowledge was represented both procedurally in C language code and in rules. The representation for specific knowledge was driven by the complexity of the knowledge and required rate of execution. In the Masscomp environment, conventional C programming generally executes faster than the interpreter in a rule – based system.

The procedural representations were built in a structured natural language and translated into C. This was done by a tool created by the project called Computation Development Environment (CODE). CODE allows flight controllers to specify monitoring algorithms in a high – level language and then generates the C code necessary to perform the algorithm. The rule – based representation for both algorithms and heuristics were built using the CLIPS expert system tool developed by the Mission Planning and Analysis Division at the Lyndon B. Johnson Space Center.

One of the requirements placed on the INCO Expert System is to advise flight controllers in real time. This typically means failure detection within five seconds of an event. This requires the expert system to have direct electronic access to the real time telemetry from the Space Shuttle. A major requirement on the INCO Expert System was also that it be isolated from all of the

Figure 3 – Expert System Workstation Installed Next To Conventional Console in MCC During STS – 26

existing MCC systems so that problems in the stand – alone expert system could not affect flight critical mainframe processing. The combination of these two requirements forced us to build a completely independent real time telemetry processing capability into the INCO Expert System.

The stringent demands of executing processes supporting real time telemetry processing while operating under an unmodified Unix led to the development of an innovative architecture for meeting real time knowledge – based system needs. The architecture was based on a four layer model (Figure 4). Raw data enters the first layer; as it moves up through the layers, it is converted to higher quality information.

The first layer performs basic data acquisition tasks such as telemetry decommutation. This layer is performed by a commercial telemetry hardware device which transfers data into the Masscomp via a Direct Memory Access (DMA) interface.

The second layer contains generic data conversion algorithms that do not require domain – specific knowledge. For example, algorithms that convert telemetry data between different floating point formats are contained in this layer. This layer is performed in C on the Masscomp workstation.

The third layer uses procedural techniques to implement domain – specific knowledge. This knowledge is entirely algorithmic in nature. For example, in this layer the system may monitor a voltage and signal an alarm if the voltage is below a required level. These algorithms were built using CODE.

The fourth layer uses rule – based techniques to represent both algorithmic and heuristic knowledge. It is often easier to implement complex algorithms, such as those that perform overall systems analysis, in the rule base rather than in the layer three procedures. This must be balanced with speed of execution concerns. Items that had to execute once every second were implemented using the layer three procedural techniques.

Rules execute as an embedded component of the entire system. Rule based components are only called into operation when the failure detection algorithms at the third layer detect a significant change in the system status. In this way we improve overall system performance. The rules are implemented in CLIPS and communicate with layer three procedures via shared memory

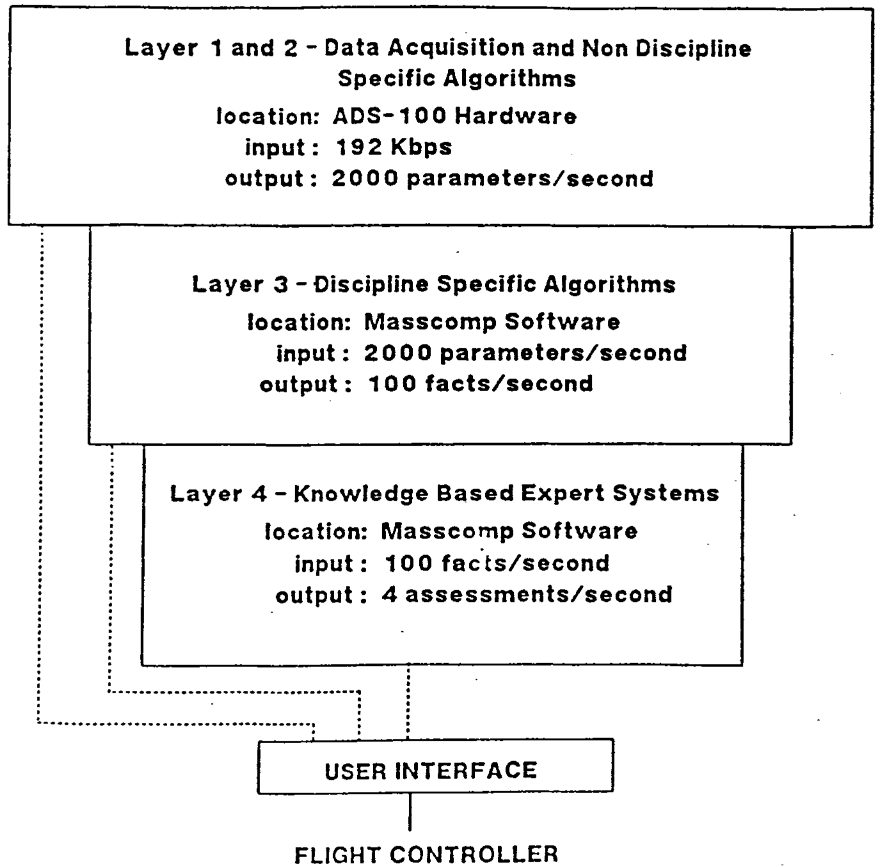

Figure 4 – Layered Architecture of INCO Expert System

An interesting characteristic of this layered approach is that as data moves up the layers, the total amount of data decreases, but the information value of the data increases. For example 192,000 bits of information enter layer one, but the rule – based expert system only operates on 350 facts generated by the layer three algorithms. These 350 facts contain important verified information about the system, where the raw telemetry bits by themselves do not uniquely identify conditions on the spacecraft.

Failures are detected by the system and flagged to the operator via a color graphic interface in less than five seconds. Figure 5 shows a typical display. This contains all of the information contained in the display from the mainframe system shown in Figure 2.

On several occasions during ground simulations and shuttle flights, the system has detected failures that were undetected by the flight control team. Sufficient confidence in the system has been gained so that conventional equipment is beginning to be replaced by expert systems and some manpower reductions will occur.

EXPERIENCE AND PAYOFF

When work was started on this expert system there was considerable debate on the expected payoff. Viewpoints centered around three potential payoff areas. Each of these three views required different emphasis during the expert system development.

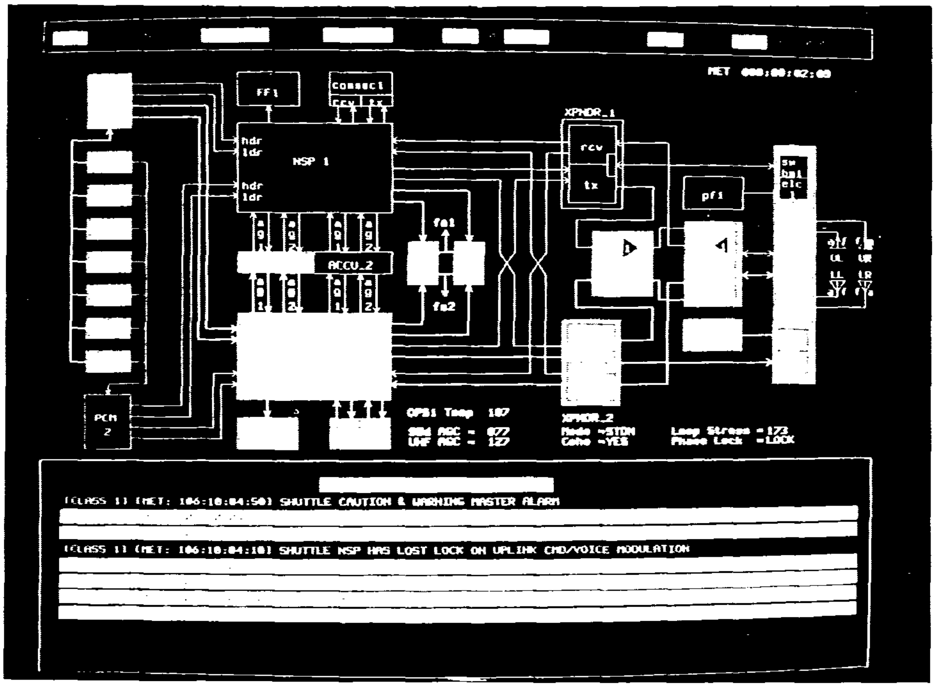

Figure 5 – INCO Expert System Schematic Display

The first view was to increase the quality and productivity of our current experienced personnel. Proponents of this viewpoint believed that the expert system should be developed to allow an experienced operator to make better flight decisions. This could be done by developing a system capable of continuously analyzing all incoming telemetry to a depth that would be impractical even for an expert operator.

The potential dollar value of this payoff is difficult to quantify. A single good decision which allowed completion of a several hundred million dollar mission would clearly pay for a large amount of expert system work, but it is difficult to say that the good decision was completely the result of the expert system. Developing an expert system to meet this goal requires the incorporation of deep knowledge about a given spacecraft monitoring task.

The second view was to use expert systems to allow less experienced personnel to perform at the level of more senior personnel. This has a measurable cost benefit in that it allows shorter training times. This viewpoint requires an emphasis on breadth of knowledge as well as improved human – computer interfaces.

The third view was that the use of expert systems should allow true manpower reductions by automating part of the systems monitoring job. This view requires deep knowledge about specific tasks as well as concentration on fault annunciation software and reliability issues.

In Mission Control we have taken the approach that our first priority is quality of decisions. The INCO expert system was designed initially to allow an expert INCO to function more productively by relieving him of the mechanical tasks associated with scanning data. Our second priority was in presenting data to operators so that less experienced operators could operate at high proficiency levels. Our lowest priority was in reducing manpower. The INCO expert system does meet all of these goals to a varying extent.

The INCO expert system captured deep knowledge about monitoring the Space Shuttle and in fact does allow operators to perform a more thorough job of monitoring telemetry. It contains knowledge about the monitoring task that is probably only shared by five or six experts, allowing even experienced INCO's to operate with the benefit of this expertise.

Based on the experience with INCO, we feel that it is possible to reduce the training time for a "first – time" flight controller from 2 years to approximately 1.5 years. Four operators are in training at any time in the INCO area resulting in a potential payoff of approximately 1 person – year per year (approximately 80,000 per year).

Unfortunately we will not be able to achieve this benefit as long as it is required to train the flight controllers in both the conventional mainframe system and the expert system. We are trying to increase the reliability and operator confidence in this system to allow for total committment to the expert system approach. In support of this goal we have removed two mainframe monitors from the conventional INCO consoles and have replaced them with display units from expert system workstations. These expert system workstation displays will be used as primary tools by the INCOs for the STS – 29 mission scheduled in March of 1989. After STS – 29 we will remove two more mainframe display units. We plan to start using the workstations as the prime flight controller tool in late 1989 and to start to see some training benefits in early 1990.

In late 1989, the INCO expert system will allow us to reduce the size of the INCO monitoring team from 4 operators per shift to three operators per shift. Because we currently have five teams of operators this will allow us to save approximately 5 person – years per year (approx $400,000 per year).

It is important to realize that this payoff will not result in lower operations costs or lower levels of staffing. The Shuttle program is under constant pressure to fly more often and to exact more performance from any flight. This requires more manpower. The personnel reduction from the expert system will be "re – invested" to form a sixth INCO flight control team. This will allow us to meet the demands of the 1990 Shuttle flight schedule. Use of the expert system has made a new source of trained flight controllers available, which we can apply to new problems and higher flight rates. The system has allowed us to "Do more for the same money" rather than "Do the same for less money".

The INCO expert system hardware investment was $400,000 and approximately 8 man – years of effort ($480,000) over two years. With the reduction of the INCO team scheduled for late 1989, we will achieve a cost – payback in approximately two years. The cost – payback however is not nearly as important as the fact that the the system will allow us to better use our precious and scarce resource of experienced personnel.

OPERATOR ACCEPTANCE

The real measure of success for this enterprise is the acceptance of real time expert system technology by the mission operations community. Because the system was developed primarily by flight controllers, acceptance in mission operations occurred almost immediately. A rapid prototyping methodology which allowed us to react rapidly to changes suggested by the flight control team also increased acceptance. On several occasions when the mainframe complex has failed during simulations, flight controllers did not hesitate to use the expert system as their only basis for flight decisions.

The degree of acceptance was dramatically demonstrated by the chain of events that led to our second expert system. In May 1988 the shuttle flight controllers responsible for monitoring the main engines determined that there were several failure modes of the main engines that required automated fault detection. Flight controllers could not manually perform calculations and assessments fast enough to meet the demands of monitoring this high performance system in dynamic flight.

The necessary fault detection routines were designed and built using the first three layers of the INCO Expert System. All of the knowledge in this main engine system was algorithmic in nature and of low complexity. The nature of the knowledge combined with the high – speed requirements for decisions during ascent led to a decision to place all of our efforts in the first three layers.

Development started in May 1988 and the system was certified for use in August 1988. Three full time personnel were assigned to this task, termed the Booster Expert System. The Booster Expert System provided a new and significant capability to Mission Control. Booster was certified for use in making flight – critical decisions and used during the STS – 26 flight. This is a major payoff to NASA because it is a large improvement in the quality of flight decisions during the dynamic ascent phase.

FUTURE EFFORTS

Based on the STS – 26 experience, this effort is being expanded into multiple new disciplines such as mechanical systems, electrical power and guidance,navigation and control. In at least two areas, successful implementation of the expert system will result in small manpower reductions. Each of these new systems represents new monitoring challenges, but the basic layered architecture of the INCO expert system will be used.

The general applicability of this architecture was proved in 1988 when the system was used by NASA and the United States Air Force for monitoring telemetry from experimental aircraft at the NASA Dryden Flight Research Facility and the Air Force Flight Test Center at Edwards Air Force Base. In each of these cases telemetry data from an experimental aircraft was incorporated into the INCO structure. In both cases the system was modified to the aeronautics applications in less than 48 hours. Use of this structure will allow operations personnel at these facilities to concentrate on expert system knowledge base issues, rather than forcing them to develop another real time environment.

The different expert systems will be connected by an Ethernet in late 1989. This will allow us to experiment with cooperation between multiple expert systems. Just as the various flight controllers communicate and work together in a control room, the local area network will provide us with the opportunity to allow the expert systems to work together.

Part of the human – computer interface for the Guidance, Navigation and Control Expert System will include graphic displays of the astronaut's flight instruments on ground workstations by reconstructing the displays from telemetry. The Attitude Direction Indicator (ADI) or astronaut's "artificial horizon" instrument emulation is already complete and will be used during STS – 29 in March 1989.

The INCO Expert System project is the first significant operational use of knowledge – based systems technology in a NASA operational environment. It has shown that expert systems can play an integral role in manned space flight operations. As NASA moves forward in future space activities, expert systems will be there.

ACKNOWLEDGEMENTS

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