N94- 34060

PI IN THE SKY: THE ASTRONAUT SCIENCE ADVISOR ON SLS-2

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Abstract

The Astronaut Science Advisor (ASA, also known as Principal-Investigator-in-a-Box) is an advanced engineering effort to apply expert systems technology to experiment monitoring and control. Its goal is to increase the scientific value of information returned from experiments on manned space missions. The first in-space test of the system will be in conjunction with Professor Larry Young's (MIT) vestibulo-ocular "Rotating Dome" experiment on the Spacelab Life Sciences 2 mission (STS-58) in the Fall of 1993. In a cost-saving effort, off-the-shelf equipment was employed wherever possible. Several modifications were necessary in order to make the system flight-worthy. The software consists of three interlocking modules. A real-time data acquisition system digitizes and stores all experiment data and then characterizes the signals in symbolic form; a rule-based expert system uses the symbolic signal characteristics to make decisions concerning the experiment; and a highly graphic user interface requiring a minimum of user intervention presents information to the astronaut operator. Much has been learned about the design of software and user interfaces for interactive computing in space. In addition, we gained a great deal of knowledge about building relatively inexpensive hardware and software for use in space. New technologies are being assessed to make the system a much more powerful ally in future scientific research in space and on the ground.

Introduction

The Astronaut Science Advisor (originally called "Principal Investigator-in-a-Box", abbreviated [π]) project is an application of Expert Systems technology from the field of Artificial Intelligence to the conduct of space science experiements. It aim is to improve the quality and yield of experimental science on current shuttle missions and long duration missions of the type foreseen for the Space Station. It encapsulates in a computer program some of the experiment related knowledge and reasoning possessed by the Principal Investigator. The primary user of the system is the astronaut performing the experiment, but reference to the system by the Principal Investigator and possibly by the Mission Manager is also envisioned.

Scientific research is conducted to elucidate unknown quantities and processes in nature. The first step in doing research is the construction and recording of a hypothetical model (a theory) which might describe a process or define a quantity. An important feature of a good theory is that it should be *testable*. This means one should be able, based on one's theory, to suggest one or more experiments, the outcomes of which are clearly predicted in advance. The validity of the theory is then verified by the expected experimental outcome.

This rather simple description ignores the real complexity of doing modern scientific research. The systems under study today are almost always too complex to approach with a finished theory and some "make or break" experiment. Instead, scientists create a preliminary theory which can be tested "by parts" and "tuned". An experiment is carried out a few steps at a time, all the while noting whether the system is behaving in a way consistent with the predictions of the theoretical model. If the model seems correct, the experiment continues along the lines initially constructed from the theory. If there is disagreement between experimental observation and the theory predictions, the theory is *modified* by the scientist so it more closely predicts what has been observed. Such alteration of the system's model generally requires modification of the experimental procedure before continuing the investigation. The research process continues, iteratively, in this manner until the scientist is convinced no further information will be obtained with the current experiment. The resulting new theory is announced and, perhaps, new experiments are proposed based on it.

It is very difficult to do scientific research in space because most of the time the scientist(s) are not among the flight crew. Instead, a carefully chosen and highly trained "best fit" crew flies with the experiments while the scientists remain on the ground. When possible, real-time sent to the scientists while their experiments are active. However, as the size and complexity of the experimental environment increases, the availability of communication bandwidth for real-time ground data acquisition decreases. Furthermore, the scientist on the ground may not be able to communicate complex changes in an experiment protocol in time to have the crew implement them in the current experiment session. Finally, due to orbital geometry and the limited number of Tracking and Data Relay Satellites, there are periods of "loss of signal" during which no data are available on the ground. The recorded on orbit for later transmission, but generally does not become available until the night after the experiment was executed. Most of the time experiment protocols are performed in their original form because of these limitations. They are not executed in part and modified as is good scientific practice. If, as often happens, post flight analysis of the data indicates a requirement to change the theory describing a system, the only recourse available to the scientist is to propose another flight of the experiment in order to test the new model. This method of doing scientific research in space is both expensive and exasperatingly slow.

The Astronaut Science Advisor effort is a first step at circumventing these limitations and improving the scientific return from experiments done in space. The idea is to fly a computer system which has some of the expert factual knowledge and decision making ability of the scientist together with real time data acquisition for a large number of signals and a highly intuitive and informative human interface. It is effectively a limited alter ego of the Principal Investigator. This computer system contains a rudimentary representation of the theoretical model and a mechanism to make comparisons of observations (obtained via the data acquisition portion) with model predictions. It also contains a system to create and suggest alterations to the initial protocol if advantageous.

The version of the [π] being flown on SLS-2 is knowledgeable about Professor Larry Young's Rotating Dome Experiment. It will record all electronic data produced by the experiment and act as a "watch dog" to ensure the experimental apparatus is operating correctly and the not corrupted by malfunctioning equipment. It will analyze specific portions of the data with respect to a theoretical model and, on demand from the astronaut operator, suggest alternative protocols designed to maximize the utility of the information being produced. Finally, the computer is aware of the time allocated for the protocol and indicates how closely the experiment is keeping to its schedule. Should the experiment run significantly late, the astronaut can be provided with a revised protocol which is designed to gain the most important information possible in the remaining time.

The applicability of the technology being developed for the Astronaut Science Advisor is not limited to manned research in space. It can be applied to medical diagnosis and research (see [GRO92]). A remote data collection and monitoring facility such as might be used for oil wells which are not visited for long periods could benefit from this technology. We believe this kind of system can greatly increase the productivity of unmanned planetary explorer missions by increasing the ability of the system to quickly respond to environmental changes and by decreasing the telemetry load. The development of this technology is still in its infancy. It is clear other applications will appear as it matures.

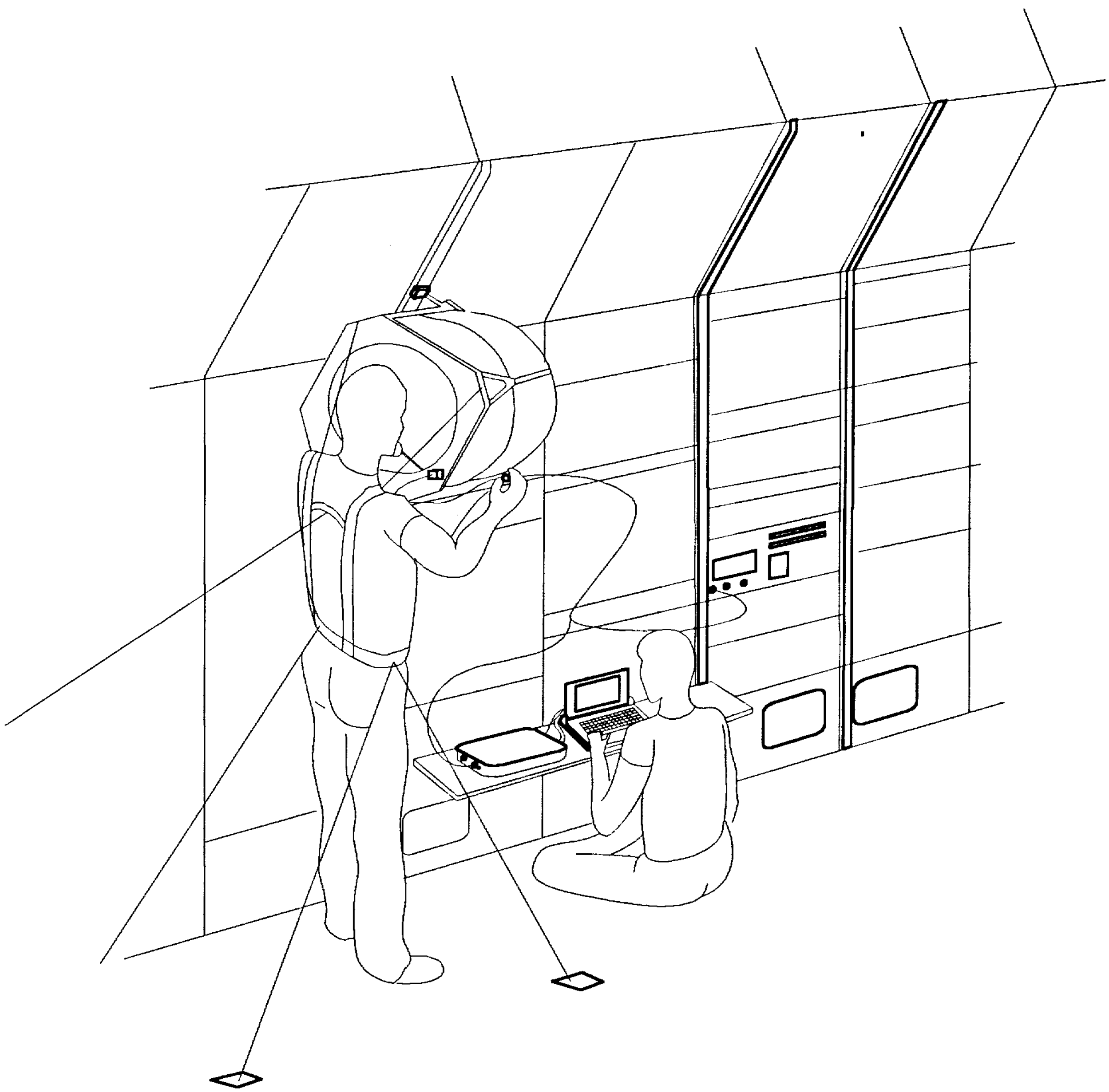

Figure 1

Background: The Rotating Dome Experiment

The Rotating Dome Experiment (see Figure 1) is designed to study the human balance system. The sensory inputs for balance are produced by the visual, vestibular, and *proprioceptive* systems. The proprioceptive sense indicates the relative positions of, and forces acting upon the various parts of the body. A model of the human balance system exists (see [YOU84]). However, the parameters of the model, particularly the weights of the different sensory inputs in the overall estimation of position, are not well defined. Even the general structure of the model is difficult to determine. The difficulty arises because it is practically impossible to decouple the different inputs to study the effect of one at a time.[1] Performing the experiment in the micro-gravity environment removes all but the visual and proprioceptive inputs, theoretically allowing a better determination of model parameters and structure.

Specifically, the experiment exposes a human subject to a rotating visual field in the roll axis. The roll axis passes approximately from the back of the subject's head through the tip of the subject's nose. To a varying degree, after a short time subjects begin to feel as if they are rotating while the visual field is perceived to slow or even stop. This perception of motion in the absence of real, physical motion is called *vection*. There are measurable subjective and physiological responses to roll vection, including involuntary twisting of the eyeball in its socket (ocular torsion), tilting of the head, and a general sway of the entire torso.

On orbit, the experiment will be carried out under three conditions: free-floating, the subject biting on the biteboard; tethered, the subject floating completely but held within a small volume of space by a set of loose tethers; and bungeed, weight upon the subject's feet simulated by attaching a set of bungee cords from the floor to a torso harness.

There is an additional reason for interest in performing the Rotating Dome experiment while on orbit. Many astronauts feel ill, and some become severely sick, while in the micro-gravity environment. This *space motion sickness* is expensive, dangerous, and poorly understood. It is thought a major cause of motion sickness is conflict among the position sensory inputs involved with balance. Indeed, some subjects of the Rotating Dome experiment experience motion sickness even while on the ground. A better model of the balance system might shed some light on ways to combat or eliminate space motion sickness.

Dome Data

Data collected during the experiment consist of:

1. Dome tachometer. The dome provides a coded square wave tachometer signal which allows determination of both its speed and direction of rotation.
2. Subjective estimation of vection. The subject is provided with a small one-dimensional, spring-centered joystick with which to indicate his or her relative level of vection. Full deflection indicates the subject feels the visual field (the dome) is not moving at all, while the subject is rotating. No deflection indicates the subject feels stationary while the visual field is moving.
3. Biteboard torque. Individually molded biteboards are anchored to a fixed truss in the dome by a strain gauge bridge. The subject may secure him- or herself in the dome by biting on the biteboard. Any tendency to tilt the head will be translated into changes in the strain gauge output.
4. Electro-myograph signals. Two skin contact electrodes are adhesively attached to each side of the subject's neck over the thickest part of the sterno-clavicular mastoid muscles. The electrodes are connected to high gain physiological amplifiers. The system allows recording of motor neuron pulse activity associated with contractions of the muscles involved in head tilt.

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[1] Some work in this area has been done with animals through selectively destroying the nerves and/or organs associated with one or more of the senses involved.

5. Ocular video. The center of the rotating dome has a hole through which a video camera may be focused to produce a close-up image of the subject's right eye. The subject wears a specially prepared soft contact lens with fiducial marks which allow measurement of ocular torsion. Putting a drop or two of distilled water into the eye, which makes the surface of the sclera sticky for a short time, prevents the normal "floating" motion of the lens.

6. Body sway video. A second video camera is located behind the subject to provide a record of body sway due to involuntary response to vection. Both cameras also provide time stamping to allow synchronization with the electronic data during analysis.

The Rotating Dome experiment has flown on three previous orbiting missions (SL-1, D-1, and SLS-1). It is controlled by an Experiment Control and Data System (ECDS) computer, a space rated Digital Equipment Corporation PDP-8. The ECDS has a very limited program which sets the rotation modes of the dome and turns on and off the dome motor at the appropriate times. It also converts the analog dome signals described above to digital form and presents the resulting data stream to a high rate multiplexor for real-time transmission to the ground. The also recorded for re-transmission in case initial transmission fails. The re-transmission process can be controlled from the ground and generally takes place during the astronauts' sleep periods. A small, battery powered, two channel oscilloscope is also available to the astronauts to see the analog signals at the ECDS inputs if necessary. It should be noted that the ECDS does *no* analysis of the experiment data, and the oscilloscope is not of the storage variety, so the astronauts can never see the overall results of even one complete trial using this equipment. They essentially have no feedback from the standard equipment about how well or poorly the experiment is being performed.

It cannot be overly emphasized that this experiment involves individual physiological responses. Very large variation in any population to identical stimuli requires each subject be viewed as a separate experiment. While comparisons between subjects may elicit interesting population-wide trends, the width of the distribution makes the validity of such conclusions highly suspect. Meaningful conclusions can only be made by comparison of observed differences of individual responses in- and outside of the effects of gravity. It is precisely this broad variation in individual response which makes the experiment difficult. While it may be interesting to pursue a repetition of part of the experiment to verify data from one subject under a given condition, it may be a waste of time to test any of the other subjects in the same manner. It is here scientific expertise becomes imperative.

[π] Hardware

The hardware architecture of [π] consists of two parts: a computer and an analog interface box.

"Off-the-shelf" equipment is employed in the system wherever possible. Constraints requiring modification or outright fabrication are, however, abundant. The entire system has to fit into half of one stowage drawer (approximately 33 x 29 x 13 cm). It has to be rapidly deployable and easily re-stowed in the zero-g environment. It cannot require more than 90 watts power. It must pass stringent safety, off-gassing, and conducted and radiated electromagnetic interference tests. Finally, any failure, due to hardware or software, must have no effect on the Rotating Dome experiment.

The computer is a flight-modified version of an Apple Macintosh PowerBook 170 laptop. Its memory is augmented to the maximum allowed, eight mega-bytes. The choice of Apple's PowerBook 170 was predicated on four years of software development on Apple computers together with the unit's small size, low mass, and low power requirements. We were fortunate because other experimenters were interested in using this computer in the manned space program. A small consortium was formed to share the cost to determine modifications required for limited flight qualification and have them implemented. The modifications to the Macs (one for flight, one flight backup, and one for testing by the development team) were done by a special laboratory at Johnson Space Center.

An on-going concern is the thermal energy produced by the machine. The laptop's 68030 microprocessor is a CMOS device. The more active the device (i.e., the less time the processor is idling), the more thermal energy it produces. Execution of [π] comes very close to utilizing every available cycle during both data acquisition and inter-trial analysis. Measurement of the temperature rise of the processor in the laboratory indicates the system will be functioning on orbit very close to the published maximum operating temperature. The problem of thermal balance is caused by the fact there is no convective cooling in the microgravity environment. We believe thermal overloading is a possible hardware failure mode for the system. Its use will be limited to a few hours on each of three days during the mission, so we believe the probability of failure is remote.

The Analog Interface Box (AIB) contains a power supply for the Macintosh, an eight channel high impedance analog to digital converter (A/D), a power supply for the A/D, and a Small Computer Systems Interface for communication with the computer (GW Instruments, Sommerville, Massachusetts). Power for the computer and A/D is drawn from Spacelab's standard 28 Volt DC bus via a tap in the rotating dome lighting circuit. The AIB's housing is a 7.8 pound machined solid aluminum box which acts as both electromagnetic shield and heat sink. New cabling was designed and fabricated to allow access to the analog data produced by the Dome.

[π] is considered a non-critical addition to the Rotating Dome experiment. This played a major role in reducing the cost and development time for the system. Standard (Class C) Spacelab hardware and software for experiment critical purposes is required to meet such rigorous fabrication and testing demands each piece must be individually produced. This increases the cost, even compared to modified off-the-shelf items, by at least an order of magnitude. [π] must interface with a critical experiment data path. However, by designing and fabricating just the interface to Class C standards and guaranteeing any failure on the [π] side of the interface will not cause interference to the host experiment, the rest of the computer system was accepted at Class D certification. While this still included a number of expensive hurdles which had to be jumped, the most severely demanding and expensive ones were eliminated.

[π] Software

NASA Life Sciences and Mission Management demanded [π] must not extend the time necessary to execute the Rotating Dome experiment. This single constraint drove many of the system design decisions. Operator inputs to the computer were kept to an absolute minimum and the system was designed to optimize the order of protocol steps to eliminate repeated operations wherever possible. If synchronization with the ECDS is lost or a dome malfunction of an unexpected nature occurs, the operator can enter a special oscilloscope mode. In this mode, [π] continuously displays data from all five channels without regard to dome rotation and without recording data. Should the [π] system itself be perceived to fail for any reason, the crew is instructed to power-down the computer and return it to its stowage drawer. This "Sword of Damocles" hanging over the experiment acted as a great incentive to quality assurance and verification of both hardware and software. In addition, astronaut comments and suggestions for changes and improvements were actively pursued and integrated into the system. The team spent a considerable portion of both time and monetary budgets on crew training and evaluation. In all, the software went through five releases before the final flight version was submitted.

The overall software architecture of [π] is best described as three major, independent but interacting modules.

First, a module written in the LabVIEW (National Instruments, Austin, Texas) language controls the A/D conversion and stores the resulting data in appropriate arrays. This module also does analysis of the numerical data to produce a small set of characteristic numbers or symbols describing the results of an experiment trial.

Second, a forward-chaining inference system written in CLIPS (NASA) uses the symbolic information provided by the first stage with a static rule base to infer decisions about the experiment. In particular, at the beginning of each experiment session the Rotating Dome system is subjected to a functional test sequence. Data from the functional test is used to determine the operational status of the dome and AIB hardware and to ascertain the "null" values for the various signals. The latter step is important because there are small, but important differences in the values of some of the components in the various versions of the dome hardware. We have no way of knowing ahead of time which instance of the dome hardware will actually be flown on the mission. Experiment-time determination of the "null" values for each of the signals allows the system to automatically compensate for these differences as well as any changes which might occur due to the equipment being stored for several months in the Spacelab module prior to launch.

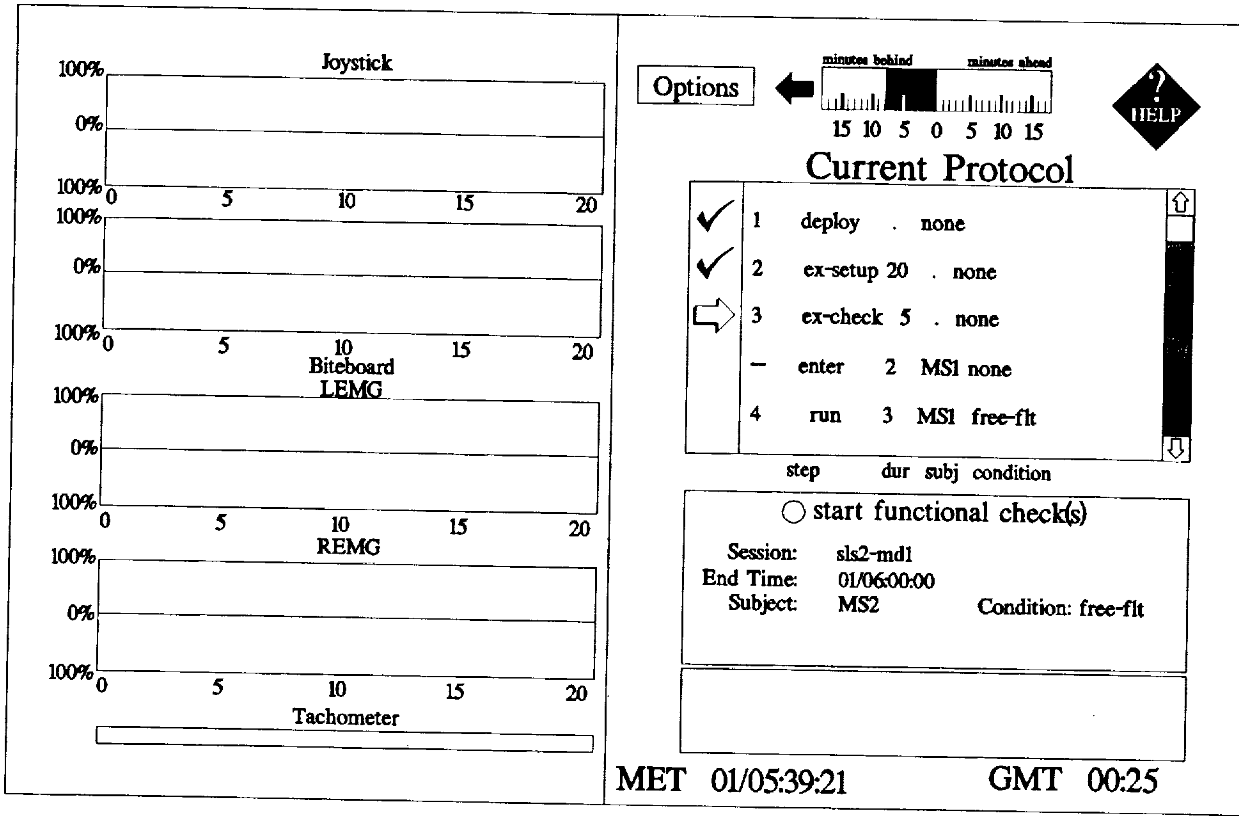

Figure 2

The third component of the system is the user interface, written in HyperCard (Claris Inc. and Apple Inc., both in Cupertino, California). The general interface (see Figure 2) consists of a vertically split screen, the left half of which is dedicated to graphic information while the right half contains active text and a graphic "delta clock". The delta clock shows the astronaut operators how well they are conforming with the experiment time-line. The active text consists of a scrolling script which reminds the operator of what steps have been completed and what remains to be done. Should the operator require more information concerning a step, clicking the mouse on the step text will produce a scrolling text box with detailed instructions for accomplishing the step.

Just before each dome data run, the operator "arms" [π] to look for initiation of dome rotation on the tachometer signal. Once rotation has been established data acquisition begins on all five channels at the rate of 225 samples per second. Should the tachometer signal be undetected for more than two seconds at the end of any trial, the run will be aborted by [π]. The usual cause for aborting a run is operator interruption by manually resetting the ECDS.

The data are shown in real-time on an oscilloscope-like display on the left side of the screen. At the beginning of each trial the data display from the previous trial is erased to be replaced by new data. Between trials the stored in separate files in unique directories (one for each run) and analysis is performed to be used to evaluate the run when all six trials are complete. While data acquisition is in progress all other activities are suspended. The delta clock shows a one dimensional horizontal bar graph indicating the number of minutes deviation from nominal progress. If the experiment protocol is on-time, the delta clock will be blank. Progress ahead of schedule is indicated by the bar growing to the right; if it falls behind the bar grows to the left. If the deviation is larger than eighteen minutes in either direction the bar cannot increase any further. Clicking the mouse on the delta clock causes the appearance of a dialog box informing the astronaut of the size of the deviation.

The system contains a very thorough trouble-shooting module. Failed functional checks can, with the operator's accord, lead directly to traversal of a malfunction tree. In the case a malfunction is beyond the astronaut's ability to repair, the system will attempt to continue the experiment without the affected signals. If the system cannot determine the cause of the malfunction from information it currently knows, it will ask the operator to perform pertinent test procedures. When a determination is made, a search for an appropriate repair procedure commences. Repair procedures are stored with the time necessary to perform them. The procedure execution time is compared with the delta clock to see if there is time available to do the repair. In addition, failures are scored by the severity of their impact on the data returned by the experiment. These two parameters allow the system to suggest carrying out the repair procedure or abandoning it to allow the experiment to continue in spite of the malfunction. The operator is given the opportunity to agree or overturn the suggested path. If the repair is undertaken, detailed directions are provided, including labeled exploded view drawings, tool locations, and step-by-step instructions. Unless the operator objects, at the end of any repair the affected signals are tested to recertify system status.

At any time when data acquisition is not active the operator can query [π] about alternative experiment protocols. [π] will generate two new protocols for any query. The "most desirable" protocol disregards all time constraints and attempts to optimize the scientific return based on all the observations so far collected for the entire mission. The "time optimized" protocol assumes the experiment will be required to terminate when specified by the mission time-line. It will try to optimize the scientific value of the data by omitting steps deemed less important. Determination of which steps to omit is based on the data collected during the mission. The astronaut may choose to execute either the "most desirable" or "time optimized" protocol or to stay with the current protocol.

[π] also possesses an efficient protocol editor which can be used to quickly create new experiment protocols or edit existing ones. The initial mission time-line and protocols were generated by the development team with reference to data published by NASA mission management. The likelihood that the time-line will change between stowage and launch is high, and the time-line is subject to change on-orbit. It is thus quite probable the astronauts will need to employ the editor and they have been trained to become very proficient with it. Any member of the crew can create a new, scientifically appropriate experiment protocol for the Rotating Dome experiment in less than two minutes. It is particularly hoped, should the mission be extended by one or more days, the availability of easily generated additional experiments may lead to greater scientific return from the experiment.

An important aspect of decisions concerning optimal scientific value is the "interestingness" of data generated by the subjects. This is certainly the most challenging and potentially rewarding issue in the whole program. Interestingness generally depends on what has been observed previously from a given subject. However, responses which are just "different" are not necessary interesting because there may be some obvious explanation for the difference. [π] is certainly not omniscient and much of what is obvious to the astronauts is not recognizable by the computer system. The best we can hope to do is flag what is believed may be interesting and allow the operator to agree with the observation, overturn it, comment about either action, or simply ignore the flag altogether.

A minimal text editor is provided to allow operators to log comments at any time when data acquisition is not in progress. Entries are automatically time stamped so they can be synchronized with experiment activities. It is not expected the astronauts will make much use of the text editor partly because it is somewhat difficult to type in zero-g: one tends to float away from the keyboard unless it is attached to one's body ([π] will be attached by velcro to a wall near the ECDS). In addition, the astronauts are provided with personal tape recorders on which they may voice comments. Unfortunately, the recordings are not time stamped and the tape recorders are often not operational. The crew is particularly aware of this problem and is willing to send their comments to us in real-time over shuttle voice communication when possible.

Conclusion

Our success getting [π] into space depended on a number of factors. The system is a *non-critical addition* to an already flight qualified experiment. Its size, mass, and power requirements are small. For a relatively small investment, it adds a number of valuable assets to the host experiment: a second data path to help guarantee capture of experiment critical data, the ability for the astronauts to see all the signals at once to monitor data quality, the capability to quickly assess changes in time-line to either take optimal advantage of extra time or to minimize the damage caused by losing time, a dynamic script to remind the astronauts of the protocol and their progress through it, and a powerful trouble-shooting and repair assistant. It is designed, like a good servant, to speak only when asked and to offer quiet but effective help whenever it can.

We conclude that as technology allows more experiments of greater complexity to be packed into Spacelab (or the Space Station) while crew size remains unchanged, the desirability and value of having [π]-like systems to assist in experiment monitoring and control will increase. Applications to earth-bound domains appear to be abundant and valuable. Generalizing the technology to a broader range of scientific domains and the creation of powerful software tools to allow relatively easy generation of these systems should be well worth the investment.

Acknowledgments

Irv Statler of NASA Ames Research Center Human Factors Branch provided invaluable interface design advice. Bill Mayer, Ed Boughan, Jim O'Connor, and Fred Miller, all of the MIT Center for Space Research, made significant contributions to the [π] hardware and cut through endless red tape for us. Bob Renshaw and others at Payload Systems, Inc., Cambridge, MA., fabricated the AIB and helped with astronaut training. Rob Dye, John Hanks, John Fowler, and Don Powers, all with National Instruments, Inc., Austin, TX., furnished in depth LabVIEW support and advice. Jeff Shapiro, of RECOM, Inc., Moffett Field, CA., did Macintosh toolbox level system programming. Glenn Weinreb and Ken Kolias of GW Instruments, Sommerville, MA., supplied hardware help and advice about their A/D converter. Dr. Thomas Mayer of Apple Computer, Inc., Cupertino, CA., offered invaluable information and advice about the hardware and design of the PowerBook 170. Judy Stephenson, Jessica Sekerka, Gloria Salinas, Stuart Johnston and Terence Adams, all with Martin Marrietta Services, Inc., Houston, TX., assisted us at Johnson Space Center. Steve Cox of NASA Kennedy Space Center made sure our work there went smoothly. We would like to thank Michelle Zavada of the MIT Aeronautics Department for proofreading this text.

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