Space Science Experimentation Automation and Support

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INTRODUCTION

This paper outlines recent work done at the NASA Ames Artificial Intelligence Research Laboratory on automation and support of science experiments on the US Space Shuttle in low earth orbit. Three approaches to increasing the science return of these experiments using emerging automation technologies are described: remote control (telescience), science advisors for astronaut operators, and fully autonomous experiments. The capabilities and limitations of these approaches are reviewed. Cost-effective automation often takes advantage of the presence of crew, regarding them as an essential component of the experiment system. Humans suffer from limitations as part of that system. However, humans have unsurpassed general purpose intelligence (common sense reasoning) and abilities as general purpose manipulators.

The US has had access to space for science experimentation for over three decades. Although the US has ventured as far as the surface of the moon with crewed vehicles, most work has been done in low earth orbit. Crewed mission series over the last two decades include Skylab, the Space Shuttle (with Spacelab and the aft flight deck lockers), and Shuttle/MIR, with Space Station Alpha anticipated by the next decade. Still, access to space for science experimentation has been sporadic. Putting people into space is a costly undertaking. Devising and building experiments suitable for use in flight is costly. Total mission payload mass and volume are carefully managed resources. Scarcer yet on Space Shuttle missions, is crew (experiment operator) time.

There are several aspects to the issue of limited crew time. First, missions have a fairly short duration. Second, the crew of a particular mission is usually identified only about a year prior to launch, leaving limited training time for a set of experiments often outside the range of expertise of a given crew member. Third, many of the Shuttle-hosted Spacelab missions are life-science investigations which often use crew as subjects. When experiment subjects, they are unavailable as experiment operators. Finally, space is a difficult working environment for humans. Crew typically suffer some disorientation in space, especially early in a mission. The disorientation limits the complexity of the tasks they can accomplish. This fourth issue is managed by scripting and rehearsing on-orbit activities. Deviations from the script are discouraged, and fixed experiment protocols are used. This major constraint severely limits the ability of an earth-bound scientist to change the course of an experiment even when the data and current situation clearly indicate that it would be scientifically more valuable to do so. Worse yet, it is sometimes the case that an experiment apparatus is damaged or is otherwise not producing valid data. The faults need to be identified and repaired. There is often an extended interval to identify, communicate, and execute needed on-orbit experiment apparatus repairs.

There are other significant features of the Spacelab task environment. One is that there can be several experiments being conducted concurrently, with different demands on uplink and downlink data transmission capability. In particular, video data may not be continuously available during an experiment session. Further, there is not continuous signal availability during the orbit of the Space Shuttle. "Loss of Signal" (LOS) occurs for perhaps 15% of a given orbit.

As a result, automation is viewed as a way of getting better return for the money invested in space science experimentation. We have identified three (and tested two) conceptual approaches to employing advanced automation techniques: (1) telescience, or remote operation of experiment using a command uplink, (2) laptop-based science advice for the astronaut experiment operator, and (3) a fully autonomous science experiment system. Each of these approaches is presented in turn.

TELESCIENCE

By "telescience" we mean that the space-based experiment is instrumented sufficiently well to permit a ground-based investigator understand the experiment's progress in "near real-time" and to directly control it using command uplink. The investigator may still depend on the crew to deploy and set-up the experiment apparatus. However, the investigator has direct control of experiment parameters and is controlling the execution of the experiment protocol. The key issue is real-time datalink access. If available, it is feasible to perform reactive scientific experimentation using this approach to automate certain types of investigations.

The telescience approach to automation was used to support the Superfluid Helium On-Orbit Transfer (SHOOT) experiment. This experiment investigated physical processes associated with superfluid helium flow in microgravity. For the STS-57-hosted experiment, a ground based Macintosh computer was used to control the conduct of the experiment. A Command and Monitoring System (CMS) was developed at the NASA Ames Artificial Intelligence Research Laboratory [1]. The CMS was used for all phases of the investigation's operation from hardware test and system integration, through launch pad servicing and telecontrol of the flight experiment during the mission, to post-flight data analysis. This paper highlights the CMS telecontrol of the flight experiment during the mission.

The CMS used a modern window-oriented point-and-click interface replacing the previously typical line-oriented keyboard interfaces. Key features of the system included a macro facility, flexible data displays, and scientific data analysis.

A set of low-level commands were devised to control the SHOOT experiment hardware. The commands control valves, voltages, and establish setpoints. This is not a useful level of abstraction for the experiment's investigator. The CMS macro facility was a pre-tested set of commands constructed from the experiment hardware's low-level command set. For example, the macro "transfer port-starboard for 10 minutes at 20 volts" would call the correct sequence of a dozen low-level commands to configure valves and set a helium pump's voltage level, timer, and relay. These macros facilitated rapid and accurate control of the experiment protocol during the flight. Macros were sent directly as immediate commands. They were also called up for display and modification before execution. Editing typically involved parameter (timing or voltage) adjustments to a pre-tested macro. The interactive displays were important in assisting users through the process, especially when the experiment was not behaving as anticipated.

The CMS also offered flexible data displays that could be manipulated by the operator, as opposed to previous "canned" displays offering only fixed views of the data on a display screen. Further, CMS offered the ability to dynamically change limits associated with telemetry out-of-limit checks. Some real-time scientific data analysis was performed in the CMS: a fluid-level adjustment calculation could be performed in real-time for the operator. This feature was crucial to the success of many on-orbit helium mass gauging operations, even though it had not often been required for pre-flight laboratory helium mass gaugings.

Further work needs to be done on displays of "aged" data. It is important to indicate both the importance of the data (nominal, borderline, out-of-limit) and its currency (recent, adequate, "stale").

SCIENCE ADVISORS

There is a wide assortment of experiments performed on many Spacelab missions. According to the Marshall Space Flight Center Payload Projects Office [2], there were 20 experiments performed during SLS-1 in June, 1991. There were 78 experiments performed during D-2 in April, 1993. This is a far greater number than a 4-person crew can master in the year between assignment to a mission and lift-off. Thus, with Mission Specialists working in Spacelab now, a generalist is performing a specialist's expert task. The expert is at a remote location (the ground), and is not in ready contact with the generalist during experiment execution. A possible solution is to make a science advisor available to the astronaut conducting the experiment in space. In this case, monitoring and analysis done by the ground-based investigator is replicated on a laptop computer connected to the experiment apparatus. The astronaut and the advisor work together to understand the progress of the experiment (Figure 1). These systems can empower the user by providing a readily accessible source of expert advice. This approach is not limited to space: it can be applied to any science or technical analysis task where an operator is gathering data and needs to make high-value decisions in real-time without ready access to the technical expert.

The Principal Investigator in a Box (PI-in-a-Box) system was used to support the Rotating Dome Experiment during the Spacelab Life Sciences Mission hosted by STS-58 [3]. It was developed at the NASA Ames Artificial Intelligence Research Laboratory and had direct access to all 5 of the experiment's analog data channels. The Macintosh PowerBook-based system provided support for the key activities of reactive experimental science: assuring sensor values are data, analyzing those data against the investigator's model of the phenomenon under study, and suggesting high-value departures from the pre-planned protocol in reaction to the results of the analysis. The astronaut is in overall control of the investigation, and can act with confidence using the advice of the surrogate scientist. In flight use, the system demonstrated superior data integrity assurance, data analysis, and model validation (Figure 1). The system also demonstrated graceful degradation when training recall problems were encountered. The ability to use "degraded operation" modes with simpler interfaces was cited by the astronauts as a key success of the system. The diagnosis and troubleshooting facility did not get exercised, as there were no equipment problems encountered with the experiment inflight. The protocol management facility was used with mixed success: some operators used it to modify protocols without incident while others had difficulty with the astronaut-computer interface.

A major issue that arose with the use of PI-in-a-Box was the willingness of the astronauts to operate as reactive scientists. The current culture surrounding Spacelab operations is tuned to set up the experiment and ensure data of reasonable quality is being archived on the ground for later detailed analysis. Thus, in many cases, neither the crew nor the investigators on the ground monitoring the progress of the experiment are reacting in real-time to change the preplanned, scripted course of the experiment. With both MIR and Space Station Alpha, this style will no longer be adequate. Presently, MIR is in contact with the ground for only about 50% of an orbit. This makes telescience-based control difficult. Furthermore, some experiments are sent up to a resident MIR crew that has had no training at all on them. Even if the communication connectivity is improved, there is a clear role for science advisor systems and fully automated experiment systems in this environment.

The PI-in-a-Box experience indicates that the astronaut-computer interface needs to be made as simple and "intuitive" as possible. Mastery of computer system skills in ground simulations does not guarantee successful recall in flight.

AUTONOMOUS EXPERIMENTS

As NASA moves to MIR and Space Station Missions, it seems likely that available air-to-ground bandwidth and crew time will be exhausted before other resources such as loftable mass and volume, and available power and thermal rejection capacity. In this case, experiments that can be fully automated can be run using "leftover" resources. NASA has flown "Get Away Special" containerized experiments in the past with mixed results. These experiments are preplanned and offer no opportunity for reaction to the data. The addition of intelligence would allow a much greater range of investigation by dynamically adjusting experiment coverage parameters based on intermediate results.

A semi-autonomous system, called AfDex, was developed at the NASA Ames Artificial Intelligence Research Laboratory for control of the SHOOT experiment (mentioned above) from the Shuttle aft flight deck. AfDex successfully executed several experiment steps autonomously: the system represents a good first step at fully autonomous experiment control. AfDex has helped to define the characteristics of experiments that would benefit from this approach. It appears that some of the plasma physics and materials science investigations performed on previous Spacelab missions could have been engineered for autonomous operation.

HYBRID APPROACHES

Integration of these three approaches may result in a system superior to one based on any single approach. In Space Life Sciences for example, routine maintenance of specimen viability is best achieved through autonomous control. However, astronaut intervention may be needed for detailed problem diagnosis or for complex visual evaluation of samples that have been treated with a fixing agent. Finally, control can be exerted with more powerful ground-based workstations in real-time at critical phases of the scientific evaluation. Ground-based workstations could also establish high-level experiment goals and timelines for experiment events occurring later in the mission. These goals and timelines could be uplinked to the on-board scientific advisor during periods of low air-ground channel usage (during crew sleep periods).

A hybrid advisory system proposed by one of the authors would monitor the experiment and mediate decisions made by the automated system, the astronaut, and ground personnel. At each choice point in the experiment, the system will communicate the need for a decision to (local and/or remote) human operators and in parallel, attempt to resolve the question autonomously. Unless human intervention cancels an on-board computation, the automated scientific advisor will notify the operator(s) of its conclusion. That conclusion is implemented after a time-out period dependent upon the criticality and time-sensitivity of the decision. This mechanism ensures that, when available, a human operator can question or override the automatic science advisor.

CONCLUSIONS

Presently, there are severe restrictions on the ability of crew to operate as reactive scientists in space laboratories. Advanced automation techniques have demonstrated a level of maturity that makes their inclusion in future science missions highly desirable. The approach selected for a given experiment depends on that experiment's characteristics, in particular the space laboratory resources needed to conduct the investigation and the opportunity offered by the investigator's model to conduct reactive science.

BIBLIOGRAPHY

[1] Shapiro, J. C.; and Villere, G. L., 1994. A Description of the SHOOT Command & Monitoring System. *Cryogenics* 34(5): 407-413.

[2] Torr, M. R., 1994. Scientific Achievements of 10 Years of Spacelab: An Overview of the Missions. In *Proceedings of the 32nd Aerospace Sciences Meeting & Exhibit*, AIAA 94-0340. Washington, DC: American Institute of Aeronautics and Astronautics.

[3] Frainier R. J.; Groleau, N.; Hazelton, L. R.; Colombano, S. P.; Compton, M. C.; Statler, I. C.; Szolovits, P.; and Young, L. R., 1994. PI-in-a-Box: a knowledge-based system for space science experimentation. *AI Magazine* 15(1):39-51.

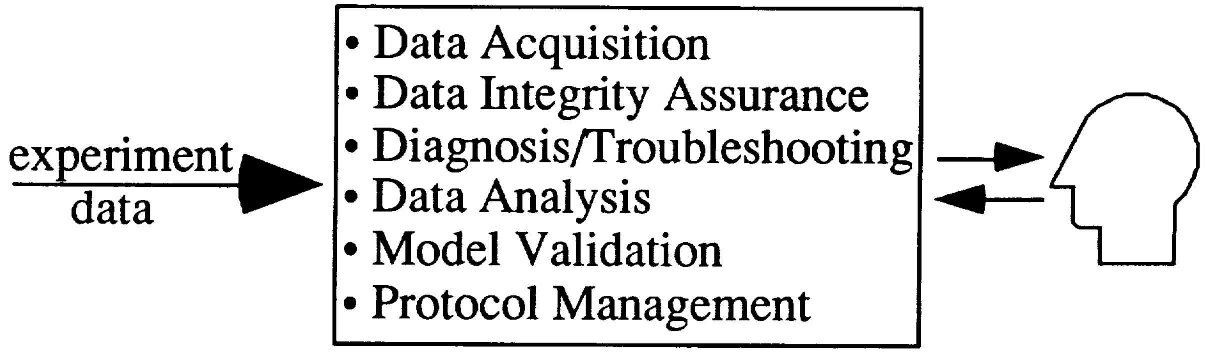

Figure 1. Advisor roles

SESSION SC

Spacecraft Control Systems

Spacecraft Control Systems