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OPERATIONAL EFFICIENCY SUBPANEL
ADVANCE MISSION CONTROL

STATS White Paper

Operational Efficiency Subpanel
Advanced Mission Control

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Introduction

For purposes of this paper, the term "mission control" will be taken quite broadly to include both ground- and space-based operations as well as the information infrastructure necessary to support such operations. The paper will focus on three major technology areas related to advanced mission control. These are:

- **Intelligent Assistance for Ground-Based Mission Controllers and Space-Based Crew**: computational systems that increase human performance and reduce training time--this area will be referred to as IA for the remainder of the paper

- **Autonomous Onboard Monitoring, Control and FDIR**: computational systems that are independently able to montor, control, diagnose, and repair onboard systems when humans are unavailable or incapable of performing under the applicable realtime constraints--to be referred to as AOM

- **Dynamic Corporate Memory Acquired, Maintained, and Utilized During the Entire Vehicle Life-Cycle**: methods for acquiring, storing, preserving, and utilizing knowledge of many forms that is gained during design, construction, testing, and operations of a vehicle and provides an important basis for effective mission control--to be referred to as CM.

While only the first area falls within the traditional purview of mission control, all three contribute substantially to a truly efficient total system for operations of the Agency's next generations of space vehicles.

The paper will survey the current state-of-the-art both within NASA and externally for each of the three technology areas and will discuss major objectives from a user point-of-view for technology development. Ongoing NASA and other-governmental programs will be described (including approximate dates of readiness for operational Agency use) along with key contacts and facilities (both existing and planned). An analysis of major research issues and current "holes" in the program will be provided. Finally, the paper will present several recommendations for enhancing the technology development and insertion process to create advanced mission control environments.

Current State-of-the-Art

Within the IA area, NASA is considerably behind the industrial state-of-the-art. This is an area that has seen enormous advances both in hardware (moving from main frame driven alphanumeric displays to powerful individual workstation utilizing bit-mapped graphic displays) and software (with thousands of fielded knowledge-based systems and recent developments in hypercard and related technologies). While the Agency has several ongoing efforts to update information management for human mission controllers (some are described below), it still uses technology that has not advanced significantly since the 1960's in many cases. The contrast to industrial practice is seen best by comparison to off-the-shelf systems being produced by companies like Measurex to provide "mission control" to highly automated factories. The key point here is that, in this author's opinion, within the ground-based IA area there is little need for NASA to lead in developing new technology, but instead should concentrate on upgrading to the very best of current industrial standards.

For space-based systems there is little industrial or governmental precedent (mainly because we have only modest amounts of space-based "mission control" at the present). For crew on STS, complex procedure manuals and the radio link to help on the ground serve as their major information sources. Perhaps the best known work to improve the state-of-the-art here is the Pilot's Associate Project sponsored by DARPA and the Air Force. Several projects to build intelligent assistants for crew are described below; NASA should clearly lead in this area, particularly as it moves to human exploration missions where the link to the ground is far more tenuous than it is today.

Within the AOM area, both NASA and outside industry rely mainly on conventional algorithmic methods for monitoring and control with few, if any, operationally fielded autonomous systems capable of complex diagnosis and repair (even if solely by reconfiguration). The "conventional" systems can be quite complex (e.g. the systems that control STS ascent), but are poor at reacting to unpredicted events outside of a narrow mission envelope. Considerable basic research has been accomplished over the last ten to fifteen years to improve this situation. The growth of work in "model-based reasoning" within the artificial intelligence field is an attempt to expand from experience-based heuristic methods (commonly known as expert systems) to systems that are capable of reasoning from first principles of science and engineering to accomplish control and diagnosis in real time. NASA is currently among the leaders in work in this field (see below) and should continue its efforts with increased emphasis on technology insertion projects as the basic work matures.

The CM area is viewed by many in the computer science community as one of the next great challenges to the field. The goal here is to expand upon current data base and knowledge base technology to allow for the automatic creation of information systems several orders of magnitude beyond those in current use. A current example of a NASA information system is the Space Station Freedom Technical and Management Information System (TMIS). Ideally TMIS would encapsulate all of the design, construction, testing, and operations knowledge (both formal and anecdotal) from dozens of contractors and thousands of engineers in a form that is maintainable and useable (both by humans and by automated systems) for the thirty-plus year life span of SSF. Practically TMIS will be a massive document indexing and retrieval system utilizing mainly current data base technology. This does represent the state-of-the-art in the field. Efforts (some described below) are underway to improve those conditions, but NASA, because of its nearly uniquely complex and long-lasting information requirements, is in the ideal position to lead new initiatives to improve the state-of-the-art in this area.

Objectives

Each of the three technology areas has several objectives that relate to improving mission control environments within NASA. For the **IA** area the major objectives are:

- **Reduced manpower needs**: current STS operations require over 400 support personnel in the FCR and back rooms. Round-the-clock SSF operations over thirty-plus years will impose a manpower problem (and therefore a cost problem) of massive proportions unless technological improvements make a substantial contribution. The objective here is to automate as many of the back room functions as possible as those personnel serve mainly in information gathering roles for FCR officers who make critical decisions.

- **Reduced training time**: current systems require two years or more of extensive training to turn a novice controller into an expert. Much of that time is needed to explain abstruse displays and terminology to engineers already versed in actual vehicle structure and functions. Systems that can deal with trained engineers in closer to the normal language of engineering (schematic diagrams, technical English, etc.) already show strong potential for major reduction of the training period.

- **Improved critical decision-making**: current systems present too much information at a single cognitive level during periods of critical, time-limited, decision-making. Intelligent assistants that can highlight and focus attention will provide substantial improvement in human performance (in essence this is the major theme of the DARPA/Air Force Pilot's Associate Project--allow the crew to focus on the crisis at hand).

For the **AOM** area the major objectives are:

- **Free crew to conduct mission tasks**: if automated systems can be built to monitor and control routine onboard subsystem operations (e.g. power, thermal, communications) and to find and in some cases even correct failures, then crew can be freed to conduct the real business of reactive space science and exploration. This will greatly enhance the effective return of major Agency missions. As an interesting note, an informal, but substantial survey of crew done for the SSF Level I Study on Advanced Automation showed that crew were overwhelmingly in favor of automated systems that would allow them to become productive scientists and engineers rather than "on-off switch flippers" for Space Station Freedom missions.

- **Provide realtime capabilities beyond human performance levels:** for many subsystems, humans simply cannot react fast enough for major classes of control and fault-correction situations. Any enhanced capabilities beyond those currently available from algorithmic control will contribute substantially to crew safety and mission performance.

- **Enhanced mission safety by discovery of incipient failures:** humans are notoriously poor at tracking thousands of engineering parameters over dozens or hundreds of days. Some onboard problems occur with little warning, but, in theory, many could be found in the anomaly, as opposed to failure, stage by diligent, autonomous analysis of all telemetry data, carefully looking for trends that may lead to failure.

For the CM area the major objectives are:

- **Capture, represent, and maintain knowledge throughout design, construction, test, and operations:** ideally a corporate memory system would acquire knowledge routinely throughout a vehicle's entire life cycle. It is important to note that the oft-repeated Agency goal of "Design Knowledge Capture" tends to obscure the fact that design knowledge is only part of the information that can lead to efficient operations since enormous amounts of practical information are gained later in the life cycle, and that knowledge capture is only part of making information useful (after all, the tens of thousands of pages of engineering documents "capture" knowledge, they just do not make it practically available to problem-solvers).

- **Automatically provide focused problem-solving capability:** a long-term objective is to provide the ability to automatically "compile" specific problem-solving systems from a generic corporate memory. This would allow the same information to be used effectively in several different problem-solving contexts, e.g. diagnosis and re-design without the current process of expensive "hand-crafting" of knowledge-based systems. While it is unlikely that this objective will be met within the short-term, basic research results sponsored by NASA have already shown the concept to be viable.

Ongoing Activities

Three NASA programs are conducting research and development activities in the technology areas described above. In OAST, the CSTI Artificial Intelligence Program (run by Code RC, the Information Sciences and Human Factors Division) is responsible for basic scientific research, applied engineering development, and significant amounts of applications prototyping in all three areas. In fact, the **IA**, **AOM**, and **CM** areas make up about 75% of the entire Program, and much of the remaining portions of the Program deal with engineering telemetry analysis, of clear peripheral relevance to the three areas discussed here. Basic research in planning, scheduling, knowledge acquisition, cooperating intelligent systems, machine learning, and large-scale knowledge base technology is conducted at ARC and its associated grantees and contractors, and at JPL. Engineering development of tools for scheduling, modeling and simulation of complex Agency devices, integration of symbolic and numeric control methods, and man-machine interaction is conducted at ARC, JPL, JSC, and MSFC. Prototype and fielded applications for existing mission control environments (e.g. MCC at JSC, Firing Room at KSC, POCC at MSFC, and Planetary mission controls at JPL) and planned future environments (e.g. SSCC and major onboard subsystems for SSF) are being built at all NASA Centers except LaRC and SSC. Total spending in these areas in FY 1990 will be approximately $10.5M.

Code MD runs the Advanced Operations Program which supports studies and protoype applications construction at JSC and KSC. The JSC work includes advanced graphics, simulation tools, and command processing languages for MCC, intelligent computer assisted training (ICAT), and autonomous methods for such applications as ascent guidance and onboard system management. The KSC work includes automated planning and scheduling tools, launch decision support systems, ICAT, operations analysis, and natural language interfaces. Total spending in these areas in FY 1990 will be approximately $4.5M.

Code MA (formerly Code ST, the SSF Strategic Plans and Programs Office) runs the SSF Advanced Development Program. About 75% of that program is relevant to the topics of this paper, including work in Flight Systems Automation; Ground Operations Automation; Space Station Information Systems; and Advanced Automation Software, Hardware, and Human Factors. Projects are underway at all NASA Centers except SSC, covering prototyping of applications of advanced technology to all major onboard subsystems (individual subsystems like power and thermal as well as subsystem coordination through OMS), ground-based systems like SSCC, and support systems like TMIS. Total spending in these areas in FY 1990 will be approximately $8M.

All three programs described above are frequent collaborators, co-funding certain activities and developing joint plans for technology transfer. One example of inter-program cooperation is the Real Time Data Systems (RTDS) series of expert systems applied to MCC at JSC. Early funding was provided to the Principal Investigator, John Muratore of JSC, by the OAST Artificial Intelligence Program. He developed the INCO Expert System through prototyping, flight testing, and routine use for STS missions. Expansion of the concept to other consoles was funded jointly by OAST and Code MD. Code MA has added funding to apply the technology to the development of a Space Station Control Center (SSCC).

External to NASA, the governmental program of greatest relevance is that run by the Information Sciences Technology Office (ISTO) at DARPA. ISTO has funded basic research and military applications of **IA**, **AOM**, and **CM** since the late 1960's through a core technology program and the Strategic Computing Program. Of particular relevance to this paper is the Pilot's Associate element of Strategic Computing. Total spending of work related to this paper in FY 1990 is $30M. Through personal contacts and a MOU between DARPA/ISTO and ARC there is frequent co-funding and joint technology planning between ISTO and both the OAST Artificial Intelligence Program and Code MA's Advanced Development Program.

Key Contacts and Facilities

OAST AI Program	Mel Montemerlo	HQ-RC
	Peter Friedland	ARC-RIA
MD Advanced Operations Program	Chuck Holliman	HQ-MD
MA Advanced Development Program	Gregg Swietek	HQ-MA
ARC	Peter Friedland	ARC-RIA
	Monte Zweben	ARC-RIA
GSFC	Walt Truszkowski	GSFC-522.3
JPL	David Atkinson	JPL-366
	Richard Doyle	JPL-366
JSC	John Muratore	JSC-DF
	Troy Heindel	JSC-DC341
	Kathy Healey	JSC-EF5
	Bob Savely	JSC-FM721
KSC	Astrid Heard	KSC-PT-AST
LeRC	Karl Faymon	LeRC-5400
MSFC	Tom Dollman	MSFC-EB44
DARPA/ISTO	Steve Cross	DARPA/ISTO

Most of the work discussed in this paper takes place in existing Agency research and development facilities and is tested in existing (and planned future) operations facilities. A 1990 CofF has recently been approved to start construction of the Automation Sciences Research Facility at ARC which will contain office and laboratory space dedicated to advanced automation for all Agency missions. The most important resources are dedicated groups of scientists and engineers at a majority of Agency Centers, including world-class artificial intelligence research laboratories at ARC and JPL, and experienced artificial intelligence applications groups at GSFC, JSC, KSC, LeRC, and MSFC.

Major Issues and Needs

Several technical issues seem particularly important for improving operational efficiency of future mission control environments at NASA:

- **The correct mix of humans and machines for decision support:** taking into account costs, reliability, and capabilities

- **Integration of Artificial Intelligence and advanced interaction concepts (Hypermedia, Data Gloves, etc.):** mixing AI concepts that allow intelligent assistance with recently developed information presentation and manipulation methods

- **Hardware and software environments for realtime behavior:** developing computing environments that will allow effective use of advanced automation methods under the rigors of realtime Agency settings, both ground-based and onboard

- **Data storage and realtime access for very large-scale corporate memory systems:** supporting technology for information storage and management systems several orders-of-magnitude larger than those in common use today

- **Knowledge acqusition and maintenance during long-term missions:** how to make the corporate memory of a major Agency system (e.g. STS or SSF) a living entity that is continually updated and improved during a multi-decade lifetime.

It is the author's belief that the existing programs at NASA, primarily in OAST and Code M as described above, are well-positioned to meet current and future Space Transportation Systems needs in the areas of advanced mission control discussed in this paper. Either directly as civil servants or support service contractors at Agency Centers, or indirectly as grantees or contractors to those Centers, NASA has perhaps the best human resources in the nation in the three areas of **IA**, **AOM**, and **CM**. However several non-technical issues, relating to funding, organizational structures, and the current NASA culture (or at least how the culture is perceived) may seriously impact the progress of work in the area. Among those issues are:

- **How seriously does the Agency really take issues of life-cycle efficiency:** in the initial planning of major long-term missions (e.g. SSF) there is much talk of the need to consider life-cycle costs for maintenance, modification, and utilization. When the inevitable budget cuts arise, all funds which are not seen as essential for initial mission deployment are put in grave jeopardy.

- **Why is design discrete from operations:** current NASA organizational structures seem to segment system designers from actual and potential system users. A classic example is the Hubble Space Telescope. MSFC is responsible for getting it built, while GSFC is responsible for running it when it is built. This has led to rivalries as well as duplication of effort in designing automated operations systems for HST

- **Why is evolution discrete from operations:** current NASA organizational structures seem to segment those responsible for current systems operations from those responsible for the "next generation" of those operations. The JSC Mission Control Center is one such example where separate directorates are in charge of ongoing operations and design of the next operations environment. This, too, has led to rivalries and duplications of effort.

- **Does the current system of exhaustive verification and validation really lead to safer, more reliable mission control environments:** on the face of it it seems as though the more testing the better in potentially life and mission critical settings. However, in information critical environments (which all missions controls certainly are) it may be better to have more information sooner, even if some of it is clearly marked "incompletely verified" as long as human decision-makers are part of the control loop. Current structures impose huge time and cost burdens on making simple changes (perhaps based on results from prior missions) to mission control environments. Is that always right?

- **Is the current balance of research, development, and applications correct:** the current NASA environment seems to place enormous priority on those efforts which can show direct payback to ongoing missions in the very short term (at most a year or two). Our culture is to demand a precise schedule of "deliverables" for such work. For example, it is relatively easy to "sell" expert systems for ground-based information analysis and system diagnosis because the technology is "off-the-shelf" and construction of such systems can meet the same set of schedules expected for any software product. However, it is far more difficult to fund or provide precise schedules for longer-term topics that promise even greater impact on future mission controls; most of the work in the AOM and CM areas described in this report falls into that category. We tend to assume "somebody else" will do the fundamental work necessary to create new off-the-shelf technologies the way DARPA did for expert systems over the past twenty years. Is this the best strategy for an Agency whose devices and missions are among the most complex ever designed by humans?

None of the above issues are simple ones. In all cases the "correct" solution is most likely somewhere in the middle of two extremes. However, it is this author's perception that the current Agency culture is too close to one of the extremes and some changes may be in order. The final section of this document will make some recommendations.

Recommendations

The following recommendations are those of the author alone, although they do attempt to encapsulate many discussions before, during, and after the STATS meeting, particularly with John Muratore, Ray Hartenstein and Michael See of JSC, Tom Davis and Astrid Heard of KSC, Ann Blackburn of Mitre, and Ellen Ochoa and Monte Zweben of ARC. Recommendations will be given in three classes: technical, fiscal, and organizational.

Technical:

1. Continue the blend of technical topics being supported by the OAST, Code MA, and Code MD programs. Particularly encourage those that span several disciplines (e.g. artificial intelligence and human factors).

2. Begin a substantial Agency program (most likely in OAST) in the software engineering of large-scale, realtime systems that encompass both traditional and advanced automation methods.

3. Use the existing RTDS work at JSC to do a careful study to attempt to quantify increase in safety, reduction in manpower, and reduction and training time that will result from judicious use of automation in mission control environments. Almost all current work in this area is speculative, and an empirical study on the operational MCC systems would help in future decision-making.

4. Use SSF TMIS as a case study of CM systems for major Agency missions. Determine what capabilities will actually be provided and which would have been available with a 5-10 year research program prior to TMIS initiation.

Fiscal:

1. Ensure stable multi-year funding for scientific and engineering research and applications prototyping for the areas discussed in this paper. The funding should be at a fixed, small percent of operational funds (perhaps 5%), but should not be subject to elimination or serious reduction except on technical grounds of quality of work. There is no other way to ensure that life-cycle issues are not the first to be lost under inevitable short-term cost-cutting pressures.

2. Include careful analyses of life-cycle costs in all contractual selections of major space transportation subsystems. If the mission is designed to last 30 years, then selection should be made on total 30-year cost, not on initial cost of flight.

Organizational:

1. Do a better job of providing user partnership in design decisions. Whenever possible include users as part of design teams, SEB's, and the like in more than just a token fashion. Prototype major systems quickly and get user feedback from the prototypes instead of relying solely on lengthy, but often irrelevant, requirements documents.

2. Do a better job of connecting operational and "future-planning" organizations. Ideally, the latter should be part of the former, not a separate, often rival, organization. Personnel should flow freely between the two. The same comments about prototyping vs. requirements documents as discussed above apply.

3. Respect short, medium and long-term efforts equally within the NASA organizational culture. If a careful analysis of current missions and technology reveals a "hole" (such as the CM area) that will take many years of research to fill, then commit to supporting internal organizations for that necessary time. Recognize that different schedules and performance metrics apply to each class of activity.

4. Analyze and consider early testing, in operational environments, of prototype information management systems before exhaustive verification and validation. Consider safety and reliability of such systems in a larger context than simply ensuring against any possible harmful effects of that system. Particularly consider manual, semi-automatic (with human intermediaries), and fully automatic methods for providing incremental improvement in system operations during and between individual missions.