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COMPUTER SUPPORT FOR COOPERATIVE TASKS IN MISSION OPERATIONS CENTERS

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COMPUTER SUPPORT FOR COOPERATIVE TASKS IN MISSION OPERATIONS CENTERS

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ABSTRACT

Traditionally, spacecraft management has been performed by fixed teams of operators in Mission Operations Centers. The team cooperatively (1) ensures that payload(s) on spacecraft perform their work and (2) maintains the health and safety of the spacecraft through commanding and monitoring the spacecraft's subsystems. In the future, the task demands will increase and overload the operators. This paper describes the traditional spacecraft management environment and describes a new concept in which groupware will be used to create a Virtual Mission Operations Center. Groupware tools will be used to better utilize available resources through increased automation and dynamic sharing of personnel among missions.

KEYWORDS

Spacecraft Management, Distributed Operations, Real-Time Groupware Tools

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BACKGROUND

NASA's Goddard Space Flight Center (GSFC) is responsible for the ground control of near-earth scientific unmanned spacecraft. Each spacecraft (or series of spacecraft) has a unique mission. For example, EOS's (the Earth Observing System) objective is to measure various earth resources, while COBE (the Cosmic Background Explorer) detects microwave radiation from deep space. These spacecraft collect data for particular user communities. The users range from in-house NASA scientists to university researchers to commercial entities.

The job of the ground control center is to ensure that the instruments (e.g., the payloads) on a spacecraft capture and transmit the data specified by the user communities. These centers are called payload operations control centers (POCCs). In addition, the POCC personnel are responsible for maintaining the health and safety of the spacecraft and its payload. The center's relationships with the user communities and spacecraft are shown in Figure 1. Currently, each spacecraft has its own independent POCC, that is tailored and dedicated to supporting that mission.

A POCC will only have contact with a spacecraft for a limited period of time, called a "pass." This is because spacecraft can only transmit data when in contact with relay satellites or ground stations, both of which are shared resources. Typically a spacecraft sends telemetry data (electronically

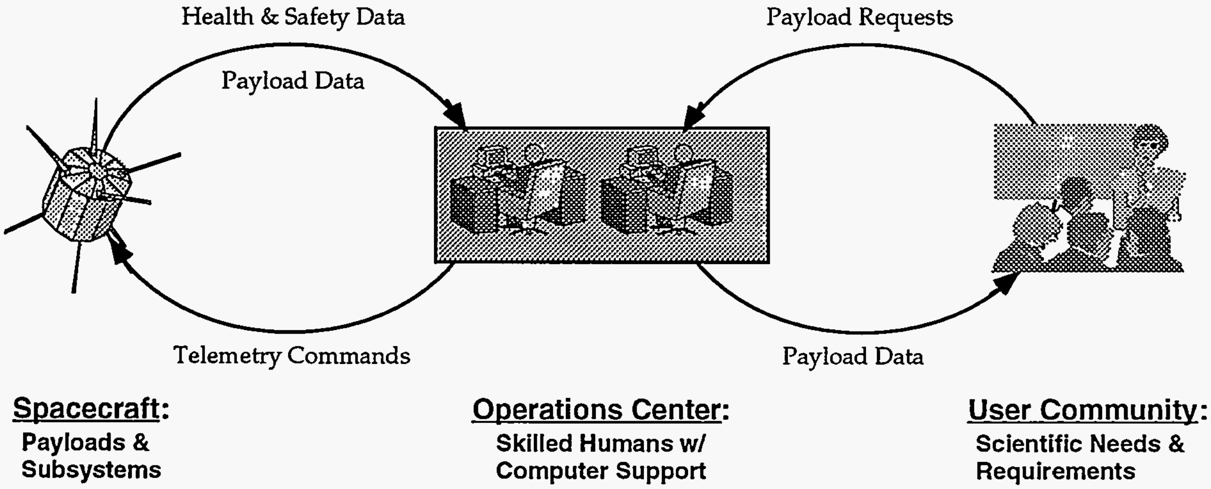

Figure 1: Overview of Mission Operations

transmitted data about the spacecraft) via either a relay satellite or special ground stations. The information is then passed to the POCC via a ground network. A typical pass may only last for 10 to 20 minutes, with a spacecraft making several passes during a 24-hour time period. The activities that occur during a pass are called real-time activities.

A control center is staffed by flight operations teams (FOTs) whose size is determined by the complexity of the spacecraft. Teams work in shifts so that all passes are supported. The FOT performs its command and control functions while in real-time contact with a spacecraft. Mission planning, scheduling, and bookkeeping activities occur in between passes. These activities are supported by subsystem specialists and engineers and are considered off-line activities.

The real-time operations team generally consists of some combination of the following positions [5]:

- Command controller -- responsible for configuring and monitoring the ground data network
- Spacecraft analyst -- performs analyses of spacecraft subsystem(s) to ensure health and safety
- Flight supervisor -- technical lead for team who performs or supervises both ground and spacecraft systems.

The number of people assigned to each position varies with the mission. For example, for SAMPEX (the Solar Anomalous and Magnetospheric Particle Explorer) spacecraft, the FOT consists of three pairs of spacecraft analysts and command controllers who monitor the health and safety of the spacecraft and configure the ground station [9]. The personnel are cross-trained in each position. However, the analyst is a more senior position, and tends to act as a supervisor and error checker, while the command controller performs most of the command and control activities. For a larger mission, like the Hubble Space Telescope, the real-time team consists of 4 controllers, 20 analysts, and 4 flight supervisors [5].

Each shift performs its work in the mission operations room (MOR). Traditionally, the room has been built specially for a spacecraft and dedicated to ensuring spacecraft's mission is accomplished. The MOR is staffed at all times, regardless of the activities being performed. A diagram of the primary work area of the SAMPEX MOR is shown in Figure 2. As shown in that figure, the two team members each monitor and perform work on two computers: a workstation (WS) and an X-terminal (XT), each with a 19" screen. Each team member also has a communications panel (Comm) for external communication (e.g., satellite ground station). A mission clock, located above the primary string, displays the current time and mission-specific time (i.e., time

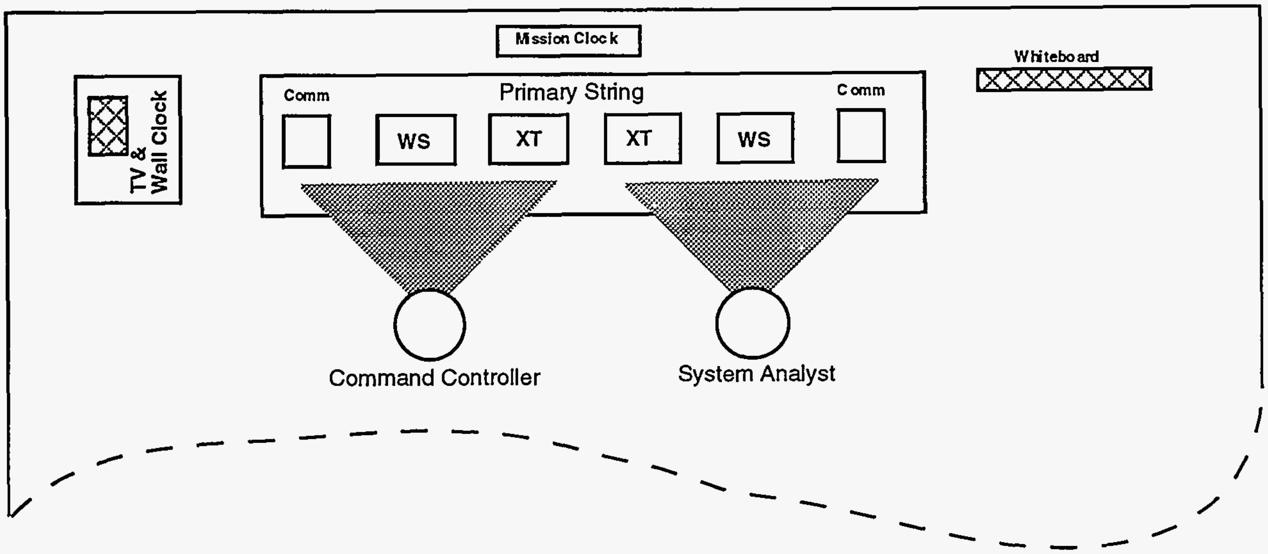

Figure 2. Primary work area of SAMPEX MOR.

until next pass). These devices make up the "primary string" where normal operations are conducted. Not shown in the figure are the backup string (used if there s a failure in the primary string), communications switch terminals, printers, processors, and storage areas.

MISSION OPERATIONS

The FOT's command and control tasks (real-time activities) can be divided into three phases: pre-pass, in which the team verifies the center's readiness to support the pass; pass, in which the team monitors the health of the spacecraft and controls operations (receiving, recording, and responding to telemetry data); and post-pass, in which the pass activities are reviewed, paperwork is filled out, and data are analyzed.

This paper focuses on the FOT's activities that occur during a pass. In particular it will focus on an important aspect of these operations called *fault management.* Fault management is the process of monitoring any faults or anomalies (irregular system behaviors) in a spacecraft's subsystem or payload. This paper will first provide a more detailed description of a team's fault management tasks, identify the problems with current practices, and discuss the cooperative work issues involved in fault management. The paper will then discuss a new operations concept that utilizes advanced automation and computer-supported cooperative work tools (groupware) and techniques to meet the challenges of future MOCs while adhering to the basic tenets of spacecraft control.

Fault Management

Fault management is a major task for the FOT that is not significantly automated and error prone. This section discusses the goals and activities involved in fault management and suggests some general causes for errors that occur. The goals of fault management are to (1) detect and compensate for anomalies, (2) identify the cause of anomalies when possible, (3) recover the faulty capabilities when possible, and (4) maintain safety and mission objectives based on the remaining functional capability when recovery is not possible [14].

When in real-time contact with the spacecraft, the operators actively monitor a large number of telemetry points in order to detect any faults. If faults go undetected, a spacecraft or one of its subsystems could be permanently damaged, resulting in lost data that are often irreplaceable or even the loss of the spacecraft. The monitoring of telemetry data is a very human-intensive process. Typically each operator monitors hundreds of parameters on multiple screens, looking for parameters that deviate from specified levels or go outside of tolerances. In general, the spacecraft telemetry data are presented in alphanumeric format at a component level. These low-level data are grouped together on a display "page" at a subsystem level (e.g., all the data related to a battery). A typical display page from a SAMPEX display is show in Figure 3.

must sometimes reference a large manual (often unique for each mission) for command syntax. Paper documents must also be consulted to determine past performance, contingency plans, operational procedures, and spacecraft constraints and restrictions. Operators can easily become overloaded in this environment. This can be confirmed by

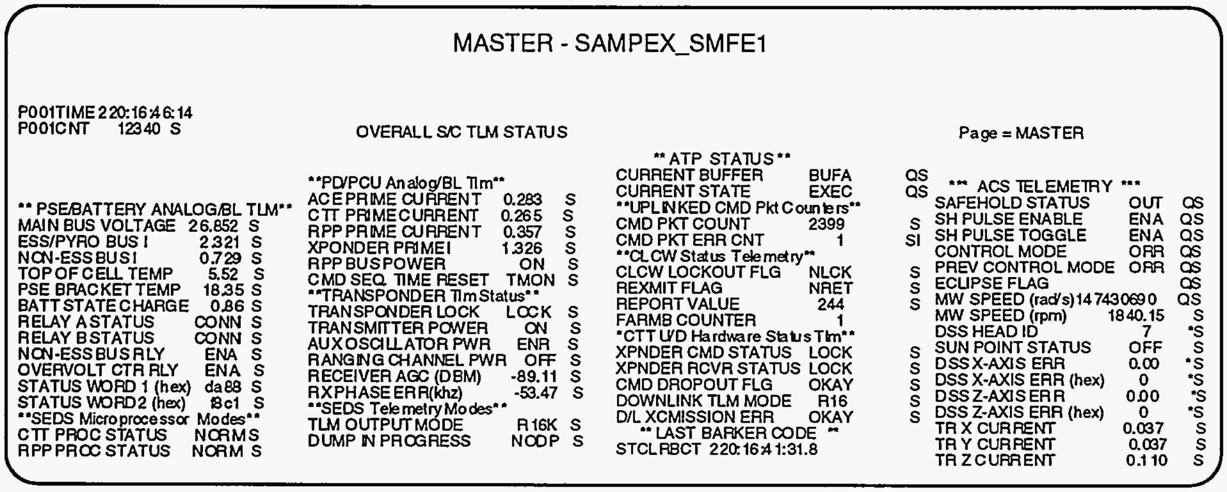

Figure 3. Typical SAMPEX Analyst Screen.

In many operations systems, very limited automated error-checking takes place only at the parameter level. The systems depend heavily on operators to detect and evaluate faults. Upon receipt of the data, the POCC's computers will compare the massive streams of parameters to predefined look-up tables. The data are then displayed to the operators. When values are out of tolerance, they are highlighted by color coding. For example, valid parameters may be displayed in green, out-of-bounds in yellow, and critical faults in red. The human must detect these faults from the other normal data and determine the meaning and impact. The human must integrate the individual alphanumeric values into a mental model of what is happening at the subsystem and system levels based on past performance knowledge, operational constraints, and operating procedures [5].

When sending commands to isolate and compensate for anomalies and to control the spacecraft, the operators must use a cryptic language called STOL. Little automation is available to assist operators. Because of the complexity of the language, the operators

that fact these activities account for the highest number of errors in spacecraft operations [5]. Such errors can be critical to the safety of the craft or affected subsystem.

Cooperative Work in Fault Management

The operators within a POCC and their support personnel work together as a team to achieve the common objective of maintaining the health and safety of a spacecraft in order to fulfill the needs of the spacecraft's user community. Because of the complexity of spacecraft operations, teams of specially trained individuals (i.e., command controllers and analysts) must work together to accomplish the large amounts of work required for a pass. For many complex command and control operations, goals cannot be reached without cooperative work [1, 2]. In such environments, the tasks are often too complex to be completed by individuals working in isolation and the cooperative work produces benefits that are greater than individual work.

In general, the FOT works semi-autonomously in the MOR, taking advantage of each member's specialized knowledge. Interestingly though, Jones and Goyle [9] found that for the SAMPEX POCC, the command and fault management activities require the highest level of team cooperation. This makes sense considering that these tasks were found to be among the least automated and most error-prone.

As Bently, et. al. [1] discovered in their ethnographic study of air traffic controllers in England, "What is important about the teamwork is not so much that the respective team members have individual tasks to perform, which they do, but that they are woven into a working division of labor.'" This can be seen in a description of how the SAMPEX FOT sends messages to its spacecraft [9]:

1. The spacecraft analyst reads the commands to the command controller.
2. The command controller types in the commands.
3. Both team members double-check the command syntax.
4. The command controller sends the commands, while the analyst watches.
5. Both members autonomously monitor to ensure the command is received properly.

From this description, the cooperative nature of the work can be easily identified. In this example activity, the central focus of the cooperative work is on a shared physical device (i.e., the computer screen into which the command is typed). This type of cooperative work has been called co-presence and is found in other command and control settings [12].

Other aspects of fault management also involve semi-autonomous activities. During normal operations, the team members at SAMPEX each monitor separate data on their own display screens. However, the spacecraft analyst (acting as a supervisor) will look at the controller's screens to observe those data. This is a manual way for the analyst to share the data that are primarily monitored by the controller.

However, the level of coordination and cooperation increases when a fault is detected. The operators must work together to diagnose the fault and recover from it. This includes the sharing of data, formulating plans, and implementing those plans, all in real time. Primarily, the FOT works together for the purpose of verification, using redundancy as a safety measure [10]. Once a failure is detected, most activities related to failure management are performed cooperatively. When anomalies occur, it is often necessary to involve domain experts to resolve the anomalies. Thus, engineers, mission specialists, and other support personnel will, at various times, be brought into this process. Depending on the severity of the fault, engineers and other support personnel will join the operators inside the MOR to perform their work. During and in between passes, other teams of support staff may be working together remotely to solve a problem. Likewise, when there is a critical maneuver or when the mission is in a more intense or hazardous phase (e.g., launch), specialist often will relocate to the MOR to lend support during passes.

This process becomes even more complex when an anomaly or fault cannot be resolved during a shift. In this situation, the staff that detected that fault must communicate the situation to the next FOT shift. This is typically done in two ways. The first method is through a bookkeeping process in which the fault in entered into anomaly reports, logbooks, and/or on a whiteboard located in the MOR. Critical information that needs to be passed to the next crew is written on this board. In this case, the information is passed asynchronously. The second method occurs synchronously. When the next crew arrives at the MOR, the relieved crew will discuss any information that they feel is important with the arriving crew. Thus, there is a significant amount of communication, coordination, and cooperation involved in fault management.

Additional cooperative tasks are carried out during each pass. For example, the telemetry data from the spacecraft are usually first received by some intermediate source (i.e., a relay satellite) and then sent via various network interfaces to the POCC's MOR. To ensure that these communication channels are configured and operating properly, the FOT must remotely communicate (via a voice line) with personnel at these other support locations.

These cooperative tasks can be effectively categorized using a time/space taxonomy (Table 1) [8]. That taxonomy divides cooperative work by location (whether the task interactions occur in the same or different places), and by time (whether the tasks are done at the same time, synchronously, or at different times, asynchronously). The above tasks are represented using this taxonomy in Table 1. Note that several of the activities occur in multiple cells of the matrix.

Fourth, the environment is inflexible. To perform any work that requires communication, including monitoring, with a spacecraft, the personnel must be within the MOR.

Unfortunately, the situation will only get worse. In the future, an increased number of smaller, yet more complex, spacecraft, will contain more sensors and subsystems that must be monitored [7]. If the current model is maintained, the already overloaded operators will easily become even more overwhelmed with all the additional data that must be monitored. With the current paradigm, the only solution to this problem would be to keep adding more operators and expanding the size of the control centers to support the additional people and equipment. However, there is movement towards building more autonomous spacecraft, using on-board processors, that will operate in more of a peer-to-peer relationship [7]. However, this too will require new, but different, demands on the human ground-based operators.

	Same Time	**Different Times**
Same Place	Synchronous face-to-face interaction: • FOT fault management • Spacecraft commanding • Bookkeeping	Asynchronous interaction: • Maintaining mission and fault status with logs and white board
Different Places	Synchronous distributed interaction: • Set-up and maintenance of network • Fault management when support personnel needed	Asynchronous distributed interaction: • Distributed fault management

Table 1. Time/Space Taxonomy of fault management and spacecraft control tasks

Problems and Challenges

This operations model has some significant drawbacks. First, each mission requires unique resources. Currently, each mission requires specially trained operators and dedicated facilities (i.e., physical room, computers, and communication equipment). Second, the FOT is at times overwhelmed by the sheer quantity of data that must be monitored in real-time during short-duration passes. Third, because the operators are performing the tedious task of monitoring these large quantities of data, they cannot perform more useful and intellectually stimulating work, such as trend analysis.

Not only will spacecraft become more complex, the length of missions will be extended to 10 to 15 years [5]. Significant crew turnover will doubtless occur during such a long period. Provisions must be made to train new team members and maintain mission knowledge. Also, computer technology (both hardware and software) will make tremendous advances over that time period. Unless there is a flexible way to introduce and upgrade the MOR equipment, systems will become outdated and unsupported, making maintenance a burden.

Because of budgetary constraints and increased automation, NASA plans to move away from the physically and functionally disparate control center concept to a unified mission operations center (MOC) concept in which all aspects of a mission will be located in one place. In this concept, fewer people will have to work together under tighter budget constraints. To further reduce operations costs, FOTs may be tasked to support multiple missions.

Also, operators are having to interact with more external groups. The MOC concept calls for the number of science users to be increasing. For example, scientists will be given more control access to experiments being conducted in space. Instead of scientists making requests for data that are then handed off to the FOT, the scientists remotely will be able to manipulate these experiments. These investigators will be distributed all over the world, using a wide variety of equipment.

DESIGNING FOR THE FUTURE

The MOC of the future will rely on many forms of advanced automation. However, any design for a MOC must adhere to three basic tenets of spacecraft control [16]: (1) humans must have the ability to control all reasonable processes and decisions, (2) humans must have access to all the available data, and (3) the system must be able to support the inclusion of personnel (e.g., specialists) as needed. Based upon these requirements and the new mission challenges described in the previous section, the design goals for future MOCs are listed below:

• *Seamless* -- allowing operators to easily access and display any level of mission data, from low-level component data to graphical representations of system-level states [15].

• *Extensible* -- allowing the number of operations personnel and computational resources to increase and decrease as needed.

• *Adaptable* -- providing the appropriate levels of expertise and layout based on operator preferences, mental models, and needs [13].

• *Integrated* -- combining the numerous new tools with existing capabilities, legacy applications, and system software into a common tool set with a consistent user interface design, in order to help facilitate user acceptance [11, 17].

• *Empowering* -- providing the FOT with the necessary applications and resources to perform useful tasks that help advance the mission work (i.e., putting the tools in the hands of the people who do the work) [6, 18].

• *Dynamically Heterarchical* -- supporting dynamic allocation of responsibilities, such that at any point in a mission, humans can take control of routinely automated tasks, assign tasks to be automatically controlled by the system, or reassign control and responsibility for tasks among the FOT.

The Virtual Mission Operations Center

At GSFC, these requirements are forming the basis for a new operations concept called the *Virtual Mission Operations Center* or *VMOC*. In the VMOC, spacecraft management would be conducted by dynamically configured teams who act as on-demand supervisors. The supervisory tasks would take advantage of increased automation that would allow for the implementation of the proactive management-by-exception paradigm [16]. This concept will be extended to distributed teams, where personnel are brought on to support missions from their remote locations using their own computers and equipment, without traveling to the physical MOC. A graphic representing the virtual operations concept is presented in Figure 4.

Thus, the center would be *virtual* in that its personnel and functions are dynamically

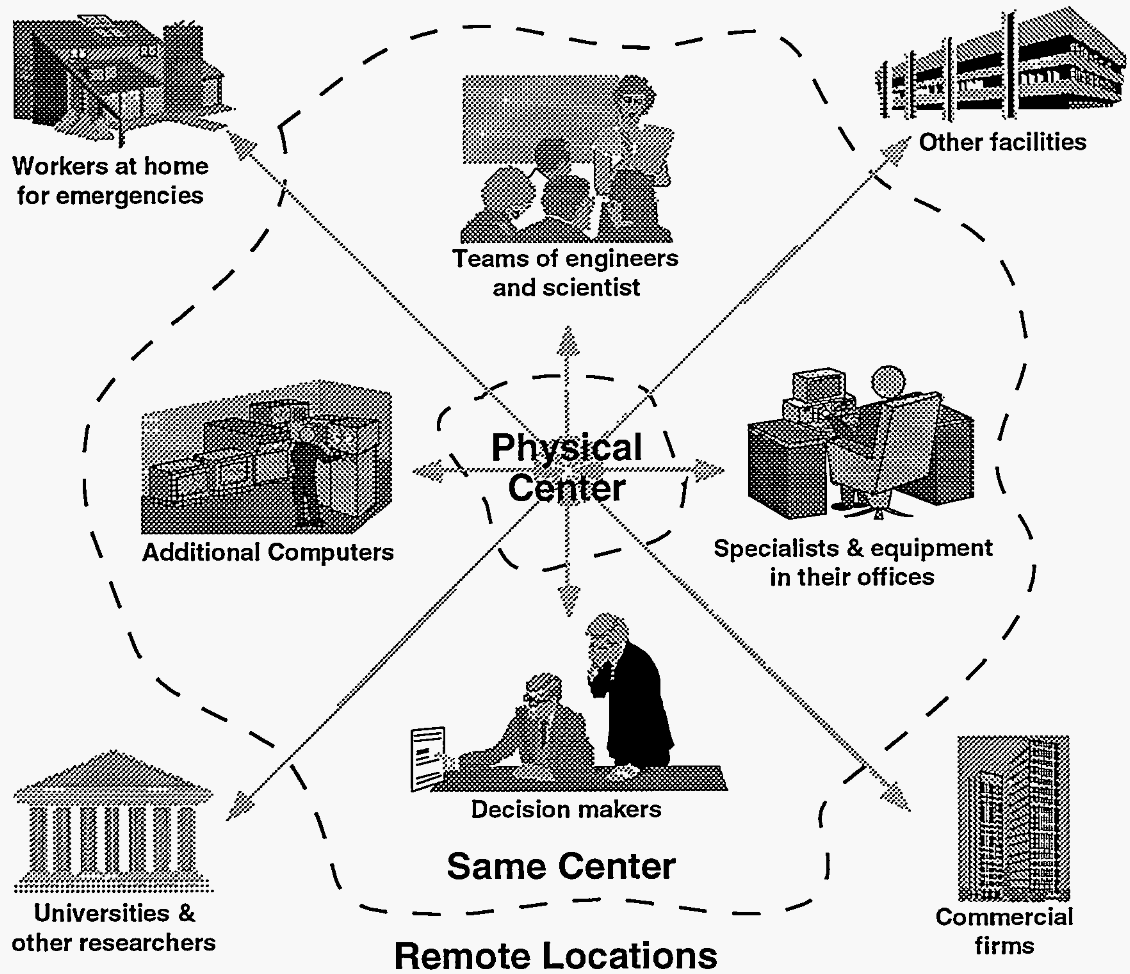

Figure 4: Virtual Operations Concept

distributed both spatially and temporally, allowing VMOC personnel to work together as members of the same team, whether they are working at the same time in the same room or distributed across the country with people participating at different times. In other words, the VMOC would exist as a dynamic, distributed collection of people and resources that can operate at any time in any place. Implementing this paradigm would also reduce costs because it would alleviate the need to have teams of operators watching data in around-the-clock shifts. For example, in the VMOC one or two team members could staff the MOR during daytime hours and could access specialists on an as-needed basis; or, during unmanned evening hours, team members could be automatically located and "paged" should there be a fault.

Potentially, VMOCs could even support multiple missions by using virtual teams [6]. In these virtual teams, people may simultaneously be members of more than one team by splitting their time among the missions and working together for only as long as it takes to complete a task. This method better utilizes the team members during large gaps between spacecraft passes.

CSCW in the VMOC

Because of the degree of collaborative effort involved in supporting spacecraft operations in the VMOC, computer-supported cooperative work (CSCW) tools and techniques will need to be incorporated and integrated into the infrastructure of the new design. Unfortunately, until now, the development of new computer tools has primarily focused on supporting individual members of the team. This is similar to the automation approach in the air traffic control systems [1]. Instead of relying on this old approach to automation, the new paradigm will focus on tools that support the group as a whole, as well as individuals, because the cooperative aspects of FOT activities are now recognized as critical to success and must be properly supported.

Moreover, the standard approach of implementing new technologies alone will not be able to solve all the challenges (e.g., supporting multiple missions, reducing the size of the teams, providing training) that will face future FOTs. New management paradigms and work processes will also need to be developed. Groupware will allow for the introduction of these new processes. The groupware will need to support both synchronous and asynchronous activities that occur physically inside the MOR and distributed remotely throughout the world. The groupware tools will need to support each of the following aspects of group work [3]: *communication* -- the ability to transmit information electronically, *cooperation* -- sharing of information to reach a common goal, and *coordination* -- support and management of group work tools. The ultimate goal of using groupware will be to provide the support needed to increase organizational flexibility and information flow. Some of the many potential uses of groupware are presented below.

• *Intelligent TeamBuilder* -- This application would be used by the FOT to locate appropriate personnel to support real-time mission needs. Using this tool, a member of the core FOT would be able to check the availability of a support specialist and the best means of contacting the person. For example, if a spacecraft's thermal subsystem should fail, the VMOC's systems analyst could use the TeamBuilder to get a listing of available personnel who could be brought on-line to address that anomaly. The TeamBuilder could display a list of all the available staff with thermal subsystem expertise, along with those people's resources (e.g., computer equipment and communications equipment), location (e.g., building, facility, home) and the means of contacting the people (e.g., fax, email, or phone). The availability of staff could be based on an agency-wide on-line scheduler that can be automatically accessed by the TeamBuilder.

• *Multi-User Hypertexts* -- Hypertexts would be created to allow team members to access mission-specific information and command syntax on-line so that the FOT members would not need to leave their workstations during a pass. The hypertexts would be multi-user so that core team members, as well as local and remote support personnel, could work cooperatively. For example, if a fault was related to a gyroscope, a systems analyst and gyroscope specialist (perhaps located at another center) could simultaneously view the documentation related to that subsystem and work together to diagnose the fault. That documentation could contain procedural text, schematic diagrams, and personal notes (user annotations) about experiences with various components.

• *Multi-media Screen Sharing and Email* -- A multi-media screen sharing tool would be a critical element in the VMOC. A tool is envisioned that will allow any member of the FOT to bring up an image or window that is displayed on any other member's screen. This will be true locally within the physical MOR as well as remotely for sharing information among distributed members of the support team. The screen sharing capability will be integrated with an email system that allows the group to actively comment on the shared image. This is similar to the Active Mail concept [4] in which a group of people can have an integrated interactive electronic conversation about a shared document. For example, this tool could be used in a situation in which an operator detects some anomalous information on her screen. She may not know the meaning or consequences of that data, so she contacts a specialist for advice (perhaps via the TeamBuilder tool). She sends the specialist a copy of her screen along with a message describing the problem. This avoids the problems involved with the specialist having to travel to the MOC to view the data or trying to understand the operator's oral descriptions of what's on the screen. The specialist could then look at the data or graphic and send a message back to the operator with advice. If it is a particularly complex problem, additional specialists could be brought into the conversation and sent copies of the screen in order to solve the problem cooperatively.

• *Intelligent Form Filler and Router* -- Typically, a FOT spends a significant amount of time performing bookkeeping tasks. For the most part, the FOT manually fill out various reports and forms including logbooks, anomaly reports, pass plans, and clock checks. Where possible, the intelligent form filler and router would automatically fill data into the appropriate forms based on data already in the systems or triggered by pre-defined events (e.g., a computer-detected anomaly). The software would also improve the efficiency of the workflow by automatically routing the forms and reports to the appropriate people. Should this mechanism prove effective, it could be expanded to include the automating of other processes, such as the automatic routing of data to the appropriate user communities.

• *Integrated Computer-Based Training (CBT)* -- In current MOCs, most of the training is on-the-job, with the trainee looking over the trainer's shoulder. Because of the advanced screen sharing and distributed control features built into the VMOC, a training capability could be built on top of those capabilities. For example, a new trainee could remotely monitor a live support mission via screen sharing without having to interfere with and distract the active operators. The training could begin with simulations of a support and then move to actually supporting a mission. As the trainee gains knowledge of the system, an analyst (the trainer) could assign and delegate increasingly more complex tasks to the trainee. At the same time, the trainer could monitor the trainee's work in real-time, offering recommendations and advice. In addition, other CBT features, such as individualized instruction, team-based training, and tutorials could be implemented to improve the training processes.

• *Team-Based Agents* -- One of the more critical new tools would be the use of on-line agents that could be taught to perform the parameter-level data monitoring activities. The goal of implementing agents is to shift the humans into more of a supervisory role instead of being full-time "data slaves." The agents would be incorporated as team members [14], monitoring the data and alerting the human team members of potential problems before they become faults. It should be noted that the agents would not be the critical decision-makers. Instead, the agents would be used to support and enhance the operators' expertise by automating routine duties and by translating the enormous amount of low-level data into higher-level information that is more readily usable by the operators. Such software has been classified as "cognitive tools" [19]. This preserves the basic tenet that humans can control all tasks while freeing the humans to perform more interesting and sophisticated fault management activities, such as trend analysis. If implemented properly, such a machine-supported role could detect anomalies before they become larger mission-critical problems; thus, allowing the team to work in a more proactive instead of reactive manner. This is known as the management-by-exception paradigm (for more details see [16]).

Advantages of the VMOC

The VMOC adheres to the tenets of spacecraft control; humans will control all reasonable processes and decision and have access to all available data, and the system will support additional persons as needed. In addition, the VMOC is seamless, integrated, and adaptable; the FOT will be able to access and display any level of information from a common tool set with a consistent user interface, based on operator preferences, mental models, and needs. The VMOC will empower the FOT to perform useful mission tasks, assign tasks to be automatically controlled, and take or reassign control as necessary.

Moving towards a VMOC environment has many advantages over the present MOCs. Most of the advantages stem from new organizational flexibility and increased information flow. With the proper tools, people will be able to work where they are normally located and have immediate access and getting experts involved on a shorter notice because they will not need to travel to the MOCs. Also, people will be able to respond *better*. When people are located in their own facilities or offices, they will have access to all of their own resources (i.e., hardware, software, manuals). This is also an opportunity to save costs because there will be less need for travel and to have additional dedicated equipment located in central places.

CONCLUSION

Currently, flight operations teams (FOTs) are working collaboratively around the clock to ensure that the spacecraft payloads capture and transmit the data specified by their user communities. During passes, the FOTs must monitor low-level telemetry data and send commands in a cognitively overwhelming environment. This situation will continue to worsen as spacecraft become more complex, mission lives are extended, external investigators gain more access to their experiments, and budgetary constraints reduce the size of the teams.

Designing the future generations of mission operation centers (MOCs) will require a thorough understanding of the group processes that are occurring in the current centers so that automation can be properly implemented. Automation must support the cooperative aspects of spacecraft operations. A new design concept called the Virtual Mission Operations Center (VMOC) is being designed to meet these new challenges. A critical aspect of the VMOC will be its implementation of groupware, along with the organization infrastructure to support it, to support and enhance the team aspects of mission operations. However, over the next 5 to 10 years, many technical, social, and organizational challenges must be overcome for the VMOC to be successful and to meet the needs of future generations of spacecraft users.

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