Integrating Mission Timelines and Procedures to Enhance Situational Awareness in Human Spaceflight Operations

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ABSTRACT

Future human spaceflight missions to the Moon, Mars, and beyond will have significant transmission delays and reduced communications bandwidth compared to operations in Low Earth Orbit, requiring increased crew autonomy due to the limited availability of real-time support from Mission Control Center (MCC). In this paper, we argue for the development of technology to enhance situational awareness (SA) for a remote MCC and astronauts onboard the vehicle, describe a usability study conducted towards this aim, and identify key usability features for the design of future integrated timeline tools. By tightly integrating timelines and procedures, future crew systems can predict future constraint violations, suggest resolutions to these violations, and ultimately support more successful missions.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Visualization**; • **Information systems → Decision support systems**.

KEYWORDS

timeline, procedure execution, situational awareness, space exploration

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1 INTRODUCTION

Future human spaceflight missions are characterized as requiring increased crew autonomy due to communication delays and reduced support from Mission Control Center (MCC). While this level of crew autonomy is desirable, it produces new challenges as these shifting responsibilities will result in reduced situational awareness for both support personnel in MCC and crew members onboard. The distances involved with future missions will cause delayed communications, prevent MCC from following crews in real-time as they execute procedures, and reduce their ability to collaboratively resolve issues. Limited bandwidth will further reduce situational awareness, as MCC will no longer be able to downlink thousands of streams of sensor data and multiple high-definition video feeds from the vehicle. We envision a future where human spaceflight operations are better integrated, where crew timelines (collections of activities) and task procedures (collections of individual actions) are tightly coupled to support and assist astronauts. Such an integration would enable tools to have shared situation awareness of spaceflight activities.

Towards this aim, we conducted a remote usability study to evaluate a new software prototype being developed to assist with procedure execution. The purpose of the study was to investigate the utility of countermeasures designed to assist with procedure execution and determine how the various types of data generated during International Space Station (ISS) operations can be integrated into a mission timeline tool to improve overall situational awareness of mission personnel. Remote usability tests were completed with participants from the Human Computer Interaction Group at NASA Ames Research Center and those with experience in ISS operations as payload controllers to identify key usability issues with the interface and user experience. In this paper, we argue for the development of tools to enhance situational awareness for MCC and astronauts onboard, and we identify key usability features for the design of future integrated timeline tools.

2 TIMELINE AND PROCEDURE INTEGRATION

Enabling future crew autonomy — the ability for astronauts to execute tasks more independently from MCC — requires a substantial change in NASA's current concept of operations and must be supported with new technologies (e.g., advanced automated systems, improved just-in-time training). We propose that one way of improving on the state-of-the-art for crew autonomy is to better integrate two of the software systems that currently support task execution: timeline and procedures management. At the moment, timelines are pre-determined by a large team of Ops Planners, who coordinate with the rest of MCC to create a packed schedule for each of the seven crewmembers onboard the ISS. Each scheduled activity has one or more associated procedures that astronauts need to follow to complete each task. Astronauts onboard the ISS currently use Operations Planning Timeline Integration System (OPTIMIS) to view their timelines and International Procedures Viewer (IPV) to view their procedures [3, 7]. However, there is currently no relationship between these two fundamental software systems for task execution aside from including a link to procedures embedded in the scheduled activity description. In current operations the only

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exception to this are extravehicular activities (EVAs), which require months of dedicated planning and the addition of dozens of additional personnel in MCC during real-time execution. This current paradigm, while successful for ISS operations, is only possible when supported by near real-time communications and high bandwidth availability in Low Earth Orbit. Long duration exploration missions will benefit from neither of these capabilities, requiring a shift in architecture for how we support human spaceflight. A modern human-systems integration architecture (HSIA) should include a “one-stop shop” crew interface that reduces cognitive workload, facilitates operations, and ultimately enables crew autonomy [4, 8]. This system should be ubiquitous and accessible across the spacecraft, providing access to key aspects of the system, such as the vehicle status, training protocols, procedures, and mission timelines. Consistent designs across the system will enhance usability across the HSIA and can help to provide enhanced situational awareness to an increasingly remote MCC.

3 EXPLORATORY RESEARCH

A series of remote interviews were conducted as a means of considering new capabilities within timeline tools for enhancing situational awareness (SA) during task execution. The purpose of the interviews was to determine what kinds of information are most useful to track task execution progress and success to better determine ways to present this information. The utility of certain types of data, metrics, and task progress information were evaluated within a usability study which followed. The interviews were conducted with 1) researchers focusing on human capabilities for autonomous missions and 2) ISS operations personnel, and were aimed at identifying pain points in current work processes. We also asked participants about the potential benefits of incorporating multimodal interactions with timeline information and data relevant to procedure management.

Based on the interviews, the following objectives were identified as research questions for a usability study:

- Possible interface enhancements to enhance situational awareness for the crewmember rather than MCC personnel could include progress or task bar indicating task progress, augmented feedback for steps that are known to be “harder” to assist or enhance performance;
- Validating graphical elements for: warnings relevant to complete or incomplete task execution to enhance SA, or whether time on task information is beneficial to SA;
- Validating whether boolean data types (e.g., on/off) for sensors or other telemetry enhance situational awareness.

Based on the above objectives, we derived several concepts for how timeline and procedures might be more tightly integrated, that were later tested within a usability study. By following a procedures’ individual actions or steps, future systems could automatically status the activity as started/in progress/complete. Task execution time estimates could then be used to predict whether the activity is running early, on-time, or late. This alone would provide better shared situation awareness for both crew and MCC and would provide a low bandwidth way to continuously observe astronauts working in space. Many of the systems that astronauts work with are highly instrumented and produce a variety of data from sensors (e.g., power generation, system states, life support sensors). Visualization of this data, which is already being collected onboard the ISS, often allows procedural tracking at the step level, without requiring any extra work by the astronauts. Tightly integrating the data from these systems into a common interface and allowing the data to be visualized alongside the procedures and timelines would allow MCC to follow task execution without requiring high bandwidth video camera feeds. In addition to the two separate software systems currently used to track procedures and timelines, many activities require astronauts to work with yet another system to complete their tasks. An application that enables procedure execution workflows integrated with timeline tools may improve situational awareness and reduce cognitive load. Finally, most spaceflight procedures require the retrieval and/or stowage of tools and hardware from several locations across the spacecraft. This information could be transferred from the procedures and used as constraints in the activities, reducing disruptions among the crew when locations or tools are not available due to unforeseen conflicts.

4 USABILITY STUDY

To evaluate some of these ideas for procedure and timeline integration, we conducted a series of usability studies with space operations-naive participants, as well as individuals who have experience with ISS flight operations. The goal of the usability studies was to investigate different techniques for improving general situational awareness among flight controllers during spaceflight missions by providing enhanced electronic procedures and systems data alongside mission timelines

The timeline application used as the foundation for the usability studies was Playbook, a mission planning and execution software used on a variety of NASA analog missions as the primary mission planning tool [1, 2]. Playbook visualizes a crew’s activities, day by day, across an entire mission. Alongside these existing Playbook capabilities, we created a low-fidelity prototype of new features that allowed Playbook to integrate with external data systems and

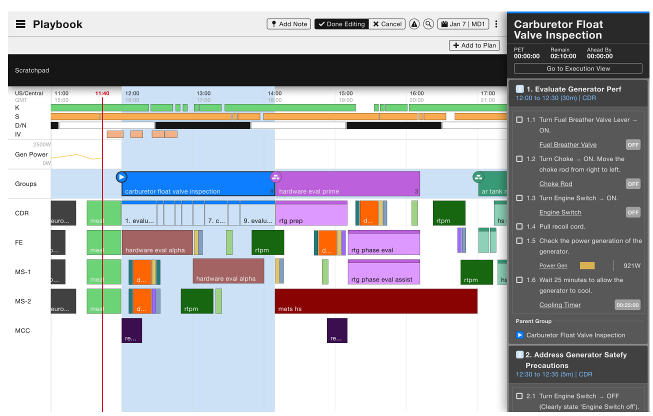

Figure 1: The user interface in our usability study provides immediate access to crew activities along with various systems data, such as signal acquisition, payload equipment on/off states, and equipment power output.

visualize that information in the user interface as well. The prototyped features included real-time graphs, numeric displays, imagery, progress meters, and status indicators (Figure 1).

In total, we had 9 participants in the usability study, including two pilot studies, conducted remotely. Sessions lasted approximately 45 minutes per participant and consisted of the participant taking a role as an MCC flight controller following the events of a task execution ("flight-follow"). The scenario prompt read to the user at the beginning of the usability session was:

> *Imagine you are an operations planner in the mission control center for ISS. You are on-console monitoring the overall mission timeline in Playbook as the crew conduct their science experiments. As an operations planner, your goal is to make sure that crew members stay on task and on schedule, and have resolutions prepared if there are ever deviations from the planned timeline. In the following scenario, you will be monitoring the crew member's progress as they start an experiment called "Carburetor Float Valve Inspection," which is related to maintenance on an on-board generator.*

As part of their roles as simulated flight controllers, participants were asked to complete a series of tasks of various complexity as instructed by the test conductor within a prototype of Playbook created in the design tool Figma (Figure 2). One instruction was given at a time over Microsoft Teams, and after the completion of each task, participants were asked several situational questions before moving onto the next.

The Playbook interface was augmented with features and data relevant to procedure documentation workflows. The Playbook interface was augmented with a vertical timeline configuration which guided participants through execution of the *"Carburetor Float Valve Inspection"* task; while integrating data on step and task completion, time on task, tools relevant for task completion, multimedia training documents relevant to task completion, and task accuracy. Participants were asked to identify how incomplete or delayed procedure execution activities might impact scheduling within the mission timeline.

Participants shared their screens so that we could see their interactions with the prototype. Interaction with the prototype was done through a "Wizard of Oz" methodology (Figure 3). Participants were also asked to speak aloud as they went about accomplishing the task. Think-aloud testing is a usability engineering method championed by Jakob Nielsen and is a direct observation method of user testing that asks users to report on their cognitive process as the demo occurs in real-time [5]. Users are asked to share thoughts with each interaction in the prototype as a means of assessing user focus, how the user brings prior knowledge to bear, and what the predominant usability issues may be based on the user's reasoning.

Usability issues have been categorized as either: a usability catastrophe, a major severity, or a minor severity. Severity ratings, according to Nielsen, are intended to reveal the most serious usability problems in advance of releasing a system to market [6]. The severity of a usability problem is a combination of the frequency with which the problem occurs, the impact of the problem (whether it might be easy or difficult for the users to overcome), and the persistence of the problem. In this context, a usability catastrophe

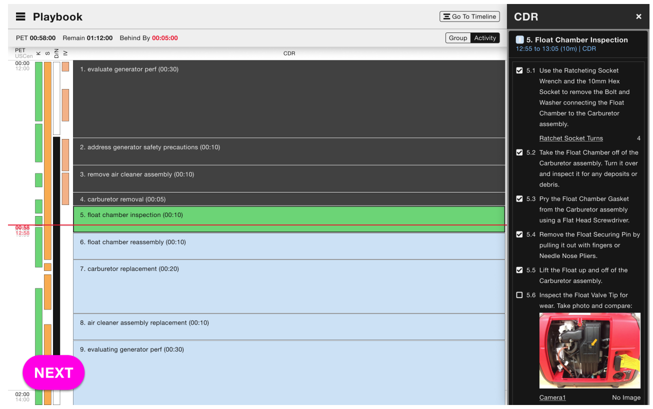

Figure 2: Participants were asked to identify sources of execution anomalies as part of the usability study. When crew is running behind, the estimated time remaining in the activity can be used to identify potential problems downstream in the schedule.

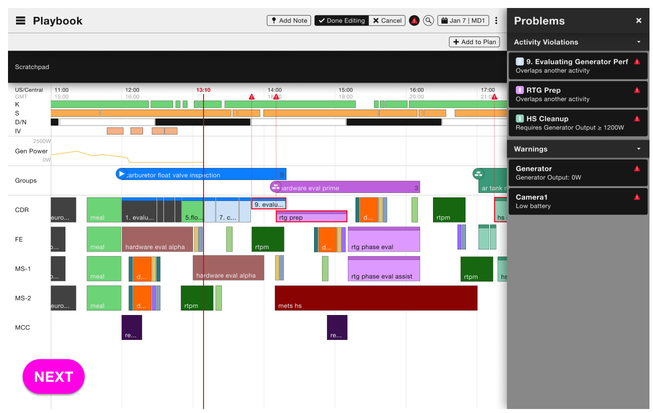

Figure 3: Progress into the simulated execution flight-follow task, as depicted in Playbook via Wizard of Oz. The view allows flight controllers to visualize the status of individual activities within the task execution schedule. Prototyped features add additional situational data for MCC support personnel to draw from to assess crew performance.

is classified as a problem imperative to fix, a major usability problem is important to fix and thus should be given high priority, a minor usability problem should be given low priority, and cosmetic problems need not be fixed unless all other higher priority usability issues are addressed [6].

From the usability studies, the following major or higher usability takeaways emerged:

- Verbiage and nomenclature — Terminology and verbiage is not universally understood. Without training, different users can interpret the same piece of text to mean significantly different things. Therefore, it is important that verbiage is clear and that the use of terminology across the tool remains consistent. For example, when referring to an equipment hatch, it is important to decide to use a definitive term, such as "closed," instead of a potentially ambiguous one, like "on."

- Visual scale and salience of information — Participants commented that the representation of systems and procedure data in the prototype could be improved. Multiple participants commented that the placement of relevant pieces of information in small sections of the user interface was problematic and made them difficult to find; while conversely, seemingly insignificant pieces of information were given much more interface real estate. Whether it be a timer, a graph, a status indicator, etc., the information that is most important to the current circumstance of the task execution should be the most easily accessible.
- Meaning of color — Like verbiage and nomenclature, without training, colors in the user interface can mean different things to different people, so communication through color must be clear. Typically, green is generally used in various software tools to indicate something positive, while red is used to indicate something that is negative. In the context of the usability study task to monitor an execution task, green can be used to communicate the desired state as it relates to the goal of the task, not for the state of the system on its own. For example, using the color green to indicate that the equipment hatch from above is "closed" is counterproductive if the intention of the task is for the equipment hatch to be "open."
- Expected state vs current state — What is the current state of the system, and what should the state of the system be? The integration of systems data within a timeline tool like Playbook needs to be shown not just as it is, but also as it needs to be. Because EVA activities often require the crew to perform an action until an expected state is achieved, that end state should be explicitly depicted in the user interface, so that users have a constant reference. The use of clear and concise verbiage and color, as mentioned earlier, is one method of conveying this information to the user.

Each of these four major usability takeaways introduce opportunities for future research and usability studies towards enhancing situational awareness. All of the participants noted that the additional information provided by the graph and the progress and status indicators was helpful to provide insight into task execution progress, but participants interpreted the new features in inconsistent ways. While the benefits of tying together timelines and procedures are clear, improper integration may instead lead to greater confusion by the crew or those monitoring remotely in MCC.

5 FUTURE WORK

The development of future crew systems and human systems integration architectures must focus on enabling crew autonomy in the absence of real-time mission support. These systems will provide enhanced situational awareness to both a remote MCC and to crew within the spacecraft and will help to reduce crew idle time. By providing tighter integration between timelines and procedures, future interfaces can support crew by suggesting dynamic, constraint-free plans that allow for successful missions in the presence of anomalies. Additional research in the development of multimodal countermeasures for enhanced crew autonomy will benefit from closer integration between tools for managing scheduling and timelines with data and workflows relevant to procedure execution. Applications for this research could include analog experiments where crewmembers are required to execute complex procedures over the course of the mission, yet nonetheless are given some flexibility with self-scheduling.

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