Facilitating Crew-Computer Collaboration During Mixed-Initiative Space Mission Planning

Advanced software interface features address challenges of autonomous crew self-scheduling

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As NASA looks toward longer duration missions, there will inevitably be a stronger emphasis on crew autonomy, particularly in the domains of mission planning. Ensuring that astronauts, while subject to lengthy periods of communication delay with Earth-based mission support personnel, are able to independently adapt their schedules to rapidly changing environments is a critical aspect of deep-space exploration. This task will likely require the assistance of computer support systems, as the task of mission planning is complex and currently requires dedicated console operators. A mixed-initiative approach can help alleviate some of the more workload-heavy aspects of planning by offloading the intricate task of constraint management to a computer, while still allowing the crew member to maintain overall control of the plan. Playbook is a mission planning, scheduling, and execution tool that has been developed specifically to support this type of mixed-initiative scheduling. This paper examines: 1) the operational evidence of the challenges and viability of autonomous crew planning, and 2) the novel scheduling capabilities in Playbook that are meant to address those findings.

CCS CONCEPTS • Human-centered computing → Human computer interaction (HCI) → Interactive systems and tools

Additional Keywords and Phrases: Mixed-initiative planning, spaceflight software, user interfaces, crew autonomy

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1 INTRODUCTION

With NASA turning its sights towards deep-space human missions, the roles of ground-based mission support and in-space crew members within the larger contexts of these missions will need to be reexamined, especially given the increasing communication delays experienced between the two teams as crews venture further from Earth.

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A major aspect of this role shift will be within the domain of mission scheduling. Space mission scheduling is a complicated task—one that is complex enough that current space missions require dedicated support personnel within Mission Control Center. Current space mission timelines are a sophisticated web of activities, resources, preferences, and the constraints amongst all of these components. In today's missions, timeline planners try to account for possible anomalies ahead of time, while off-nominal situations encountered during mission execution can usually be resolved through real-time communication between crew and ground support.

However, the inherently less-defined nature of deep-space exploration missions, combined with decreased access to immediate guidance from mission control, will require future deep-space exploration crews to have the ability to autonomously adapt their schedules to rapidly changing and unpredictable environmental conditions [5]. While manually creating timelines provides benefits to planning (e.g. integrated personal preferences and a familiarity with an upcoming day's activities), it requires a lot of effort for inexperienced planners [1, 8]. In a high-stakes spaceflight environment, relying solely on manual planning risks increasing the likelihood of human errors and compromising mission success.

On the other end of the spectrum is fully automated scheduling, which could involve astronauts simply clicking a button to direct an algorithm to create a feasible schedule based on predefined activity constraints and requirements [2]. However, this obscures preferences, which vary from person to person and are prone to changing over the course of a mission. Crew members may feel as if they are blindly following a schedule with no insight into why activities are ordered a certain way. Additionally, automated schedules would not take real-time changes to constraints or resources into account.

Therefore, it is essential to strike a balance between manual and automated scheduling: a mixed-initiative approach. Mixed-initiative planning involves collaboration between a human scheduler and a supportive computer system [3]. In the context of mission planning, such a system will need to use automation and user interface features to facilitate the planning process by assisting in decision-making and relieving workload.

Designing, evaluating, and deploying computer aids is critical to streamlining astronaut scheduling during long duration space missions. Such aids should enhance performance while keeping users in control of the system so that they can better integrate their preferences, anticipate the sequencing of upcoming timelines, and collaborate with other crew members. The remainder of this paper examines one such computer aid—Playbook, a mission planning and execution tool which has been under development for over a decade [9]. We specifically address operational evidence that demonstrates the challenges and viability of autonomous crew planning.

2 OPERATIONAL OBSERVATIONS AND INFERENCES

Through many years of analog mission and spaceflight deployments, Playbook's development team has observed the challenges that are associated with shifting mission planning responsibilities to crew members (e.g. "self-scheduling") and have tailored Playbook's scheduling capabilities to encompass a future where mixed-initiative scheduling is the default method of planning while in-mission.

The team has studied a variety of users conduct self-scheduling with Playbook across several different types of environments: Earth-based analogs missions, aboard the International Space Station (ISS), and controlled lab experiments. Analog mission crews have completed self-scheduling in both NASA Extreme Environment Mission Operations (NEEMO) [8] and Human Exploration Research Analog (HERA) [4], while one crew member aboard ISS has completed self-scheduling so far.

When self-scheduling was evaluated in spaceflight operations aboard ISS, there were some surprising lessons learned. While it was demonstrated that crew self-scheduling with Playbook was achievable in a real spaceflight environment, the tool's scheduling features at the time were not sufficient for the complex constraints and requirements involved in ISS mission planning [7]. Specifically, the crew member attempted to resolve a complicated series of constraint violations within a mission day but was unable to. Ultimately, the crew member cited a lack of understanding of the rationale behind the series of constraints as a contributing factor for her inability to resolve the scheduling conflict. At the time, Playbook did not explicitly convey the constraint details to the user. This observation led to a controlled-lab experiment where the Playbook development team examined the individual effects of different types of constraints [6, 13]. The results of this study suggested that constraints and violations needed to be clearly identified and explained for the user, especially to assist them in de-conflicting schedules. It also showed that users prefer a sense of understanding and salience over a mission plan and cannot rely solely on completely abstracted affordances to plan successfully.

When deployed in analog missions, Playbook successfully enabled users with minimal training to complete the complex mission scheduling tasks required by those missions. For example, crews in NEEMO handled numerous constraints when scheduling extravehicular activities, maintaining autonomy and flexibility while still communicating with Mission Control [8]. Analog crews were able to successfully rely on Playbook's user interface to schedule executable plans that were free of constraint violations. It is important to note that the Playbook development team constantly improves on the tool as it receives feedback. The versions of Playbook deployed on analog missions at this point had already incorporated improvements that resulted from the ISS feedback earlier on.

From the human preferences perspective, the team has observed a full spectrum of scheduling preferences from analog astronauts in both NEEMO and HERA. Some analog astronauts prefer not to self-schedule, while others prefer to self-schedule on a daily basis. Some analog astronauts have also expressed their desire to create their own activities within mission timelines in order to protect their time from other mission activities. We have seen that many analog astronauts adjust their timelines in real-time to reflect when activities were actually completed. Finally, some have anecdotally indicated that self-scheduling is empowering and enables them to introduce crew preferences into the timeline.

3 ENABLING MIXED-INITIATIVE SCHEDULING

As a software tool, Playbook has a feature set that concentrates on modeling hard requirements and then empowering users to plan within those requirements. One of the primary components of Playbook's scheduling aids is a series of visual affordances across the user interface that explicitly call out constraint violations that occur in the plan. Rather than requiring the user to mentally maintain the catalog of plan constraints, the tool calculates and presents this critical information directly. In the timeline, these affordances appear as red violation indicators at the start times of violated activities, on the activities themselves, in the information panel called the Streamview on the right side of the interface, and within a tray dedicated to summarizing violations within the plan. The presence of these violation indicators immediately signifies to users that the plan is not viable (Figure 1).

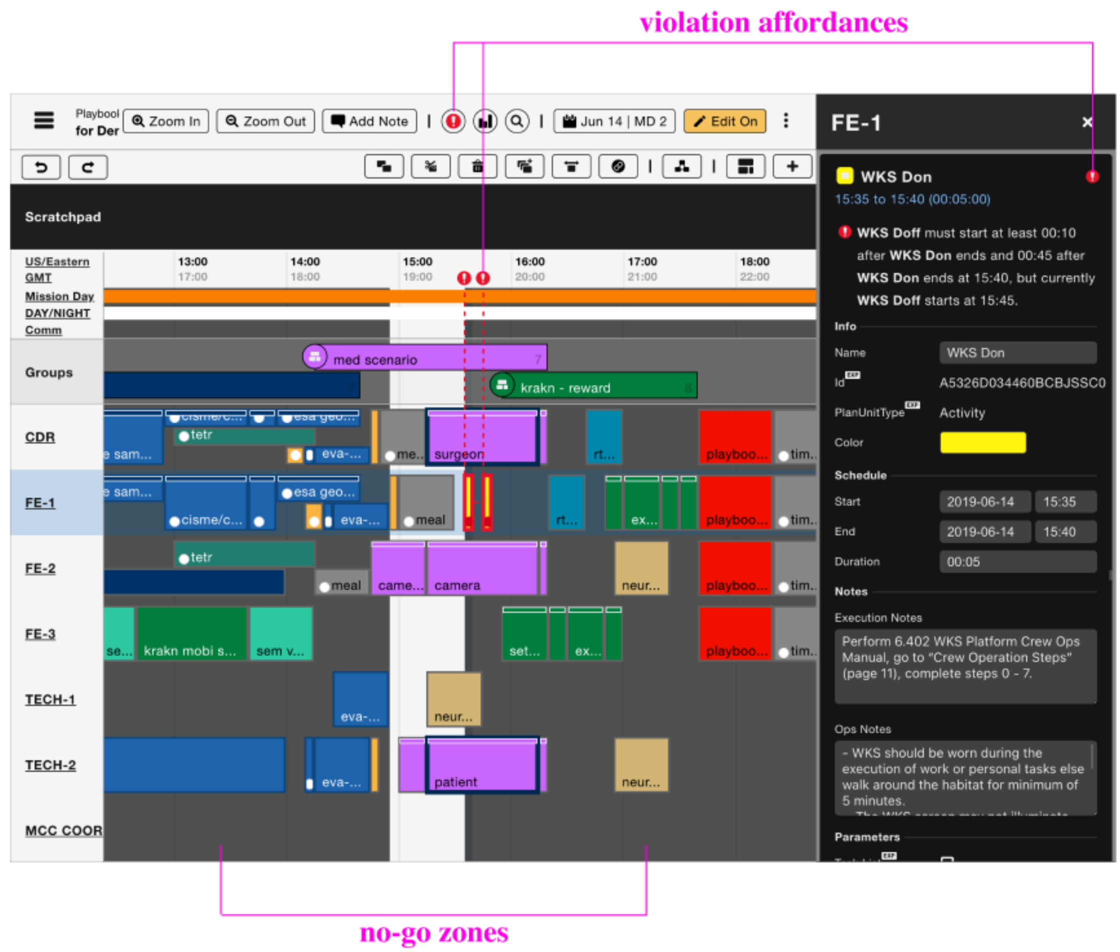

Figure 1: Red violation icons across the user interface call out constraint violations within the mission plan, while dark gray "no-go zones" present a simplified visualization of complex constraints. Constraint violation descriptions are also present to keep the user aware and informed about the plan status.

When a constraint violation is perceived, the next action by a planner is typically to understand and resolve that violation. Playbook describes each constraint and violation in simple language to facilitate salience and action among users. Along with this, Playbook has a feature called "no-go zones," which are abstracted representations of an activity's cumulative constraints. They appear as dark gray overlays on the Timeline and are a key component of Playbook's ability to guide users towards constraint violation avoidance and resolution. When an activity is scheduled into an area where it overlaps a no-go zone, it will be in violation of at least one of its constraints, and violation affordances will appear (Figure 1).

Because Playbook has a model of the constraints on activities, it can suggest and execute scheduling resolutions (if possible) when a constraint violation does occur. Appearing in the "violations tray," suggested fixes must be triggered by the user, and will move the necessary activities to viable locations along the Timeline (Figure 2). This feature simplifies the violation resolution process by immediately presenting the user with a viable solution at the click of a button.

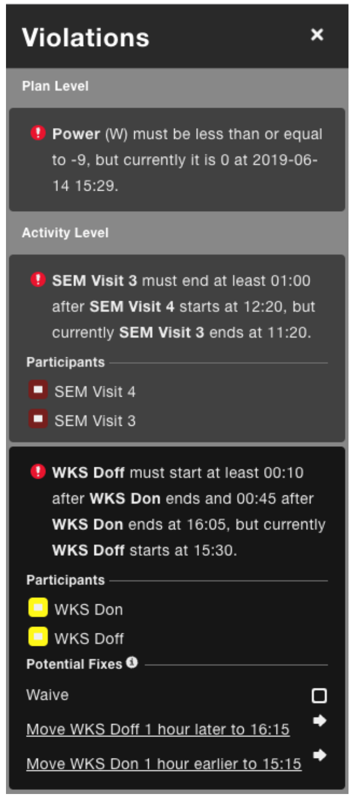

Figure 2: When possible, Playbook suggests options for fixing constraint violations.

Likewise, the constraint models that exist in Playbook allow users to act on multiple constrained activities at once. As activities within the plan are constrained against time and amongst each other, a temporal constraint network (TCN) develops. As the number of constraints in a plan increases, the constraints within the plan become exponentially more difficult to manage. Playbook's network move feature can consider the entirety of a single activity's TCN and allows the user to move that activity within the full bounds of its TCN constraints without creating any unary or binary constraint violations (Figure 3).

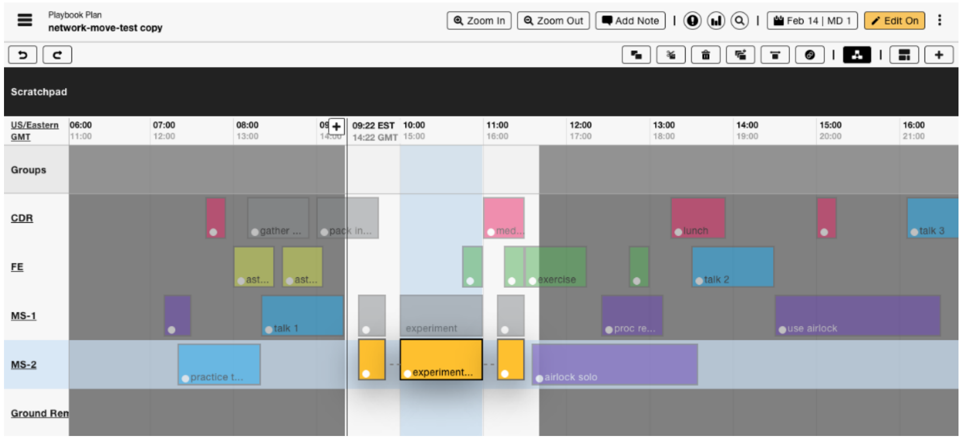

Figure 3: Rather than moving one activity at a time, Playbook's network move feature allows all activities within a temporal constraint network (TCN) to move at once, preventing the creation of constraint violations.

Altogether, these features share a common theme in that they simplify the multifaceted constraint relationships between the different components within a mission plan, making them digestible and actionable for users who may not have intricate knowledge of those details. We hypothesize that this decreases cognitive workload and ultimately allows the planner to focus more on the qualitative aspects of scheduling. A key thing to note among all these features: it is ultimately up to the user to make the final scheduling decision, which helps the user maintain a positive sense of control over the overall mission schedule.

4 FUTURE WORK

Currently, our team is evaluating the effectiveness of these mixed-initiative Playbook features in isolated lab settings and high-fidelity HERA analog missions. We are validating these aids by collecting performance data (e.g. time on task, violations created) [6], qualitative and quantitative usability data [12], human-system trust scores [11], and workload scores. If we observe improvements in these measures, it will indicate that the aids in our interface facilitate the use of Playbook by planners and enable crew autonomy effectively.

We are also conducting psychometric analyses on a novel questionnaire that is designed to capture subjective attitudes toward self-scheduled plans [10]. This will help us understand how computer-supported mixed-initiative scheduling increases plan quality from the human user's perspective.

Finally, because integrated preferences are a vital component of a good schedule, we are studying how crews use allocated time to discuss preferences in HERA's current and upcoming campaigns. We are leveraging audio data from these meetings to study how crews cooperate to build a strong plan, and to inform the experimental design of future analog missions to better capture the role of preferences in mixed-initiative scheduling.

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