

## SUBMISSION TYPE

Abstract

## AUTHORS

Laura Bauer (Michigan State Univ.), Dorothy Carter (Michigan State Univ.), Lauren Landon  
(KBR)

## TITLE

Leading Autonomous Component Teams in Multiteam Systems: Insights from NASA

## ABSTRACT

Multiteam systems (MTS) often appear in high-stakes environments like in the military and in space exploration. Although MTS research often assumes the leadership team has full authority over component teams, extreme contexts, such as a mission to Mars, challenge that assumption and highlight a need for dynamic allocation of authority among teams. We conducted 31 interviews with NASA subject matter experts who are preparing for future missions. Themes extracted from these SME interviews suggested key recommendations for supporting MTS coordination as component teams become more autonomous.

## WORD COUNT

(2993)

## **Leading Autonomous Component Teams in Multiteam Systems: Insights from NASA**

Multiteam systems (MTSs) are an aggregation of two or more interdependent component teams with different functions, skills, and expertise that allow them to tackle large, complex problems (Mathieu et al., 2001). Due to their increased size and flexibility compared to standalone teams, MTSs often appear in dynamic high-stakes environments, including military contexts (Hærem et al., 2022), medical contexts (Zaccaro et al., 2012), disaster responses (Fodor & Flestea, 2016), and space exploration (Pendergraft et al., 2019). In many of these contexts—including the military and spaceflight environments—one or more “leadership” teams are often located at a “headquarters” to help manage and support the actions of the component teams operating in the field. For example, in current spaceflight missions in low-Earth orbit to the International Space Station (ISS), the spaceflight crew relies heavily on the decision-making and guidance of Mission Control situated back on Earth (Mesmer-Magnus et al., 2016).

However, for many real-world multiteam systems operating in dynamic environments, it is not always possible for component teams to rely on real-time leadership teams for guidance and direction. Communication might be disrupted or delayed, and component teams may have to operate unassisted, often under extremely dangerous conditions. This is epitomized by depictions of future long-duration spaceflight exploration missions, like a mission to Mars. During a Mars mission, the spaceflight crew must coordinate with Mission Control across vast temporal and geographical distances. Indeed, the anticipated communication delays of these future missions will require the spaceflight crew to operate without immediate input from ground teams, forcing them to be more self-sufficient as they travel further away from Earth (Palinkas & Suedfeld, 2021).

Despite this reality, the extant literature on MTS coordination provides little guidance for supporting system functioning when leadership teams lack full and/or immediate decision-making authority “over” the component teams. In fact, empirical studies of MTSs often implicitly assume that leadership teams can have constant, real-time communication to coordinate with the component teams. This lack of research attention to the challenges of leading MTSs without full leadership control is an important limitation of current literature, given the prevalence and importance of such challenges.

To build an initial evidence base for how to support multiteam functioning when leadership teams lack full leadership control, we conducted a series of interviews with 31 subject matter experts (SMEs) who are current or former members of NASA’s Mission Control Center (MCC). These SMEs not only possess real-world experience working within complex and extreme multiteam systems, they are capable of articulating how current spaceflight operations must adapt to meet the challenges of future missions, including the need for greater crew autonomy during a mission to Mars. Our interviews probed SME’s responses to two key questions:

1. What are the new challenges of MTS coordination associated with a long-duration, long-distance spaceflight mission to Mars?
2. What are your recommended solutions for mitigating these challenges?

Our findings point to important practical recommendations for adapting MTSs to dynamic and extreme environments that produce varying levels of component team autonomy. Therefore, we advance research on MTS functioning and the practice of MTS coordination when leadership teams do not have direct control over their component teams.

## Methods

### Sample

To understand and identify adaptation processes within MTSs in high-risk environments, we conducted a series of 31 interviews with SMEs who were current or former members of NASA's MCC. All SMEs had extensive experience working within high-risk MTSs and a comprehensive understanding of spaceflight coordination. SMEs held diverse roles in various departments, including flight controllers, flight directors, and capsule communicators. SMEs were contacted through a NASA point of contact. Interviews were conducted virtually using Microsoft Teams.

### Procedure

At the beginning of each interview, the lead researcher introduced other research team members and indicated that the interview would be transcribed. Additionally, the researcher provided a brief overview of the research project, explaining that the focus was on understanding how coordination within MTSs would need to adapt for longer-duration spaceflight missions and exploring potential barriers and solutions for mission success.

The interviews were semi-structured and lasted approximately 60 minutes. Guidelines for conducting qualitative semi-structured interviews were followed based on best practices identified in literature (e.g., Roulston, 2010; Smith, 1995; Willig, 2013). Following introductions, participants were asked to recall a critical incident involving the coordination of multiple teams to solve an off-nominal problem within the spaceflight MTS. Depending on the nature of the incident, the researcher would then ask relevant probing questions to clarify details. Subsequently, the interviewee was prompted to consider how the coordinative abilities of the MTS—as identified in the critical incident—might need to adapt for future long-duration, long-

distance missions. Finally, participants were invited to recommend solutions to overcome any coordinative barriers.

### **Interview Analysis and Theme Extraction**

Interview analysis and coding progressed in three phases. First, a team of two researchers extracted and compiled all quotes from the 31 interviews relevant to this study's two research questions. Quotes were then categorized as relevant to understanding (1) the MTS coordination challenges of future missions or (2) recommendations for mitigating those challenges. Then a separate team of three researchers reviewed each quote and identified an initial set of themes for the core challenges and recommendations. The team met to discuss these initial themes and iteratively agreed on the core themes for each question. Finally, these themes were given to an independent SME who further evaluated and refined the extracted themes. This inductive approach for identifying themes is a common method in the study of MTSs (e.g., DeChurch et al., 2011; McIntosh et al., 2016) and is consistent with best practices for conducting thematic analysis (e.g., Braun & Clarke, 2006; King, 2004).

## **Results and Discussion**

### **Key Challenges of Future Spaceflight Missions**

Results of our SME interviews highlight key themes regarding the major MTS challenges involved in a mission to Mars, summarized in Table 1. The first challenge is the increased communication delay between the spaceflight crew and the Mission Control teams, with one SME stating:

*The lunar delay is maybe a nuisance, but then the Martian delay is significant.*

Communication delays between teams in high-risk environments can negatively impact team performance (Parisi et al., 2023) and are associated with increased stress and frustration (Kintz et al., 2016). Indeed, our SMEs have stated that this communication may impact team coordination, cognitive load, and planning capabilities. For instance, one SME noted:

*You have to be more organized in what you transmit in each moment knowing that you're not going to have the iterative back and forth... knowing that it might be 40 minutes before you get your response... you're not going to be able to tackle five things all at once. So how do you decide, "We're going to send [the crew] this transmission because it's more important, and then we'll get to this one next, but we don't want to overload them."*

Indeed, the increased communication delay was the most notable challenge that SMEs identified for future spaceflight missions, as it subsequently impacted the coordinative possibilities between the spaceflight crew and ground teams.

The second theme that emerged was the reduced availability of telemetry and technological capabilities, a partial byproduct of communication delays. Not only will there be a lag in information sharing between the spaceflight and ground teams, the ever-increasing distance will also limit technological capabilities and the availability of real-time telemetry. Even a trip to the Moon will result in decreased information quality. One participant neatly summarized this problem:

*It's all bandwidth... If you go to the Moon, 300,000 something miles away, you're moving much faster, your vehicles are much smaller, and they're generating much less power... and so now our antennas are way smaller, and the amount of data that can be beamed from a [small capsule] orbiting the Moon is significantly less than what [a larger vehicle*

*in low-Earth orbit] can do. So definitely we see that in the video that we can see the quality is much less and the amount is much less.*

With this decrease in data quality and content, the ground teams will have to rely more on the spaceflight crew aboard the vehicle for information, thus leading into the next challenge.

A third challenge identified was the need for an increase in the spaceflight crew's autonomy. Many, if not all, of the SMEs agreed that the increased communication delays in future long-distance, long-duration missions will necessitate the spaceflight crew becoming more autonomous from Mission Control. One participant discussed how Mission Control currently operates with the spaceflight crew and how this process may be disrupted in future missions:

*We say, "Here's what we're thinking, what are you guys seeing up there? What do you think? What's your endpoint?" And then we come up with a joint decision. We can do that because it's real-time communication. So with the delay, I'm a little worried about how we adapt that process to be not just Mission Control [providing the forward plan]. You lose that extra insight from the crew who's in the vehicle or in the habitat. They know what it looks and smells and feels like, and they may have data you don't have.*

This challenge is the crux of the issue and the paper's main focus, as leadership teams must learn how to adapt their authoritative capabilities and redistribute some control to other teams who will have more direct access to pertinent data. However, this disbursed decision-making will not only exist within the spaceflight MTS, it will also be found in outside forces.

Thus, the fourth challenge that emerged regarded the complications that arise from international and inter-organizational partnerships. For instance, one participant highlighted the limitations of working on a complex project across multiple agencies:

*We're restricted a little bit by just the way the [agency] and then the way the government works ... and then just the very diverse blending of teams and their perspectives. Our government, even inside our government, but also other governments and other space agencies across the world. And then you add the commercial elements in there, everyone has their own perspectives.*

Finally, the last theme associated with challenges for future MTS missions was about the difficulties of planning when too many factors are unknown. One participant illustrated this point by highlighting the complications around trying to prepare for different scenarios:

*There is no automated response that cannot outsmart a human being in every scenario because the automated responses are built around failures we expect. And what we have learned from [spaceflight experience] ... is when the real vehicle breaks, it will look nothing like what we thought, no matter how many smart heads we had.*

Thus, these five challenges were prevalent topics among our SMEs, and potential mitigative strategies for addressing them were also discussed.

### **SME Recommended Solutions for Addressing Challenges of Future Spaceflight Missions**

Table 2 summarizes the key themes extracted related to different recommendations that SMEs provided for adapting the spaceflight MTS for future missions. Overall, five core recommendations emerged. The first recommendation was a solution to mitigate the impact of communication delay by increasing the system automation of the vehicle. Roughly half of our SMEs believed that the complications arising from these long-distance, long-duration missions will require more automated systems onboard for the spaceflight crew to take some cognitive burden off of the crewmembers, as they will not be able to be trained experts on everything and

the missions are long. Instead, the focus should be on understanding the software itself. For example, one participant stated:

*You've got that 20-minute delay between taking in the data, talking about it, and making a decision. You're adding, essentially, 20 plus minutes to everything you do, so software absolutely has to take care of your problems. So you turn into more understanding of the software, understanding what the software does, how it's working.*

Whether it be leveraging AI to conduct anomaly reporting, automate routine tasks, program a repository, or code a contingency program onboard, many SMEs included different ways automation may help in future missions.

Another recommendation from SMEs specifically targeted to combat the communication delay challenge is advising that communication should be packaged clearly and concisely. This is also a common recommendation in the spaceflight communication literature for future spaceflight missions (e.g., Dove-Steinkamp & Henning, 2012; Marquez et al., 2019; Mosier & Fischer, 2023). For instance, many SMEs mentioned that communications should be packaged in digestible formats, with one participant imagining a scenario where the crew has to take action while they wait for input from the ground teams during the delay:

*The crew, 22 minutes away, is going to have to have a lot more autonomy to be able to handle things themselves because of that time delay. If [a system failure] were to happen, most likely the crew would have just secured the system, probably shut it down, reconfigured off of that leg of redundancy ... and then we'd be putting the recovery plan together ... instead of doing it ourselves, most likely, we're putting that whole package together and just shipping it off to them and saying, "Okay, you go do this and tell us*

*how it you know, tell us how it turns out.” There would not be as much of a real-time rush.*

However, both of these recommendations still require the spaceflight crew to rely on the ground teams. Although roughly half of our participants cited these types of recommendations, the other half took more crew-centered approaches as the crew gains more autonomy throughout these missions.

One such recommendation was shifting the leadership model of Mission Control to provide the spaceflight crew with more autonomy. One participant noted that both the crew and the vehicle will be more autonomous from ground input:

*That's why crew autonomy in a Mars mission is that much more important, and it's going to actually be a whole different operation architecture that will have to be developed in the autonomy of the spacecraft itself to be able to do things, or at least additional information that the crews can have to be able to make these decisions. That, in my mind, is the biggest thing that will change when we start going out to Mars is tremendous amount of autonomy that the crew has, or that the vehicle has, without ground input, because it may be too late if you don't have that autonomy to respond to something.*

This recommendation focuses on imparting more control over to the spaceflight crew to make decisions. However, this increase in autonomy must be established with a solid relationship of trust between the spaceflight crew and ground teams.

Thus, the fourth recommendation proposed by SMEs focused on building up the relationship between the spaceflight crew and Mission Control teams, which has also been shown to impact MTS performance positively in the literature (Pendergraft et al., 2019). Many

SMEs highlighted the increased importance of building up trust pre-launch before these future missions:

*I think best practices are developing that trusting relationship, that trust. I think it's critical to have not only trust integrity, like, "Hey, you're a good person, you can be trusted," but also that you get results, that you are capable and are effective at what you do. So I think that trusting relationship, whether it's individuals or whether it's offices or providers, I think the most valuable investment is to build those trusting relationships.*

Finally, the last recommendation was to increase pre-mission training for both the Mission Control teams and the spaceflight crew, cited by nearly half of our SMEs. Increasing training is also shown in the MTS literature to have a beneficial effect on performance (Dempsey & Barshi, 2020) and is a focus in the spaceflight teams literature (Landon et al., 2018). This recommendation usually, but not always, directly countered increasing system automation, as many believed that automating these systems can be very difficult and will not be failproof; therefore, the spaceflight crew should receive more authoritative power to make up for this fact. For example, one participant noted:

*We've had experiences in the past where, when updating that software, the [update] inadvertently created a bug that caused a problem... even with our testing protocols that we go through and the years it takes to verify the software, we still miss stuff. And that's the sort of thing that makes me worried about over reliance on automation versus relying on the human in the vehicle to make decisions for what's best for their survival.*

Overall, SME recommendations on system automation and crew training signify that the leadership team must balance incorporating programmed autonomous operations with human decision-making, whether it be by the crew or Mission Control. This suggests a need for the MTS

to have more discussions about where and when to strike that balance. A universal solution may not be suitable, but instead, there is a need for conversations about when system automation is suitable versus when crew training is preferable or when optimizing both is advantageous.

### **Conclusion**

Current research on MTSs assumes that the leadership team always has real-time, direct control over its component teams, but this is not always the case. Future spaceflight missions epitomize this, as the long-distance and long-duration nature of the missions means the leadership team will have less real-time capabilities to directly oversee the spaceflight team, resulting in the need for increased crew autonomy. Therefore, the present study investigated the challenges these MTSs will face during these missions and the potential solutions can be leveraged to counteract these challenges. Our findings lay the groundwork for future work to explore how leadership teams can lead subordinate teams across large temporal and geographic distances. This study contributes to the growing literature on real-world MTS functioning and offers practical insights into how multiteam systems can adapt to future missions.

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## Tables and Figures

**Table 1**

*Challenges of Future Spaceflight Missions Identified by SMEs*

<b>Theme</b>	<b>Example Quotes</b>
Increased Communication Delay	<i>"Usually figuring out beforehand what all possible ramifications of failures are so that you can handle it in real time is what the flight controllers are there for, if you add a 22 minute delay on that's going to be a problem."</i>
Reduced Telemetry and Technological Capabilities	<i>"We're constrained on data and this is something that I've been guessing will still apply to astronauts who are on Mars... we can't just dump down as much as we can."</i>
Increased Crew Autonomy	<i>"I think a lot of a lot of folks around here are still struggling with giving up some of the control that we've traditionally had in low Earth orbit and allowing the crews, or even the vehicles themselves, to do more."</i>
International and Interorganizational Partnerships	<i>"What scares me about the future missions are the interfaces with all of the different countries and providers... what do you tell the crew? What authority do you give them over ESA's module and JAXA's rover and NASA's people?"</i>
Too Many Unknowns	<i>"That is unfortunately the problem is it might be kind of a failure of imagination... you don't think about how many different things can go wrong because there's so many of them, it's just not possible."</i>

**Table 2**

*Recommendations for Addressing Future Spaceflight Mission Challenges Identified by SMEs*

<b>Theme</b>	<b>Example Quotes</b>
Increase System Automation	<i>"The first thing you want to do is maybe consider putting more automation onboard the spacecraft to handle whatever contingency scenarios we come up with that requires a response quicker than what we can get communication with the FCC said an hour or two."</i>
Adjusting Communication Protocols	<i>"With longer comm delay you have to be more organized in what you transmit in each moment... you have to package things, knowing that it might be 40 minutes before you get your response."</i>
Changing Leadership Mindsets	<i>"That is the biggest thing that will change when we start going out to Mars is the tremendous amount of autonomy that the crew has or that the vehicle has without ground input, because it may be too late if you don't have that autonomy to respond to something."</i>
Forming Trusting Relationships	<i>"When we go to Mars, that crew member and that leader of the ground team better have spent time together and established that trust because when things go wrong, and they will, you're going to need that."</i>
Adjust Component Team Selection and Training	<i>"There are going to be problems from time to time that we did not foresee that automation will not be able to respond to, so what do you do? Well that gets back to crew training. You have to train the crew."</i>

**Figure 1.**  
*Recommendations Plotted on an Authoritative Continuum*

