DEVELOPMENT OF A DISTRIBUTED TEAMING SCENARIO FOR FUTURE SPACE OPERATIONS

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The goal of the Space Challenge project is to identify the challenges faced by teams in space operations and then represent those challenges in a distributed human-machine teaming scenario that resembles typical space operations and to measure the coordination dynamics across the entire system. Currently, several challenges have been identified through semi-structured interviews with nine subject matter experts (SMEs) who were astronauts or those who have experienced or have been involved with interplanetary space exploration. We conducted a thematic analysis on the interviews through an iterative process. Challenges were categorized into four categories, including, communication, training, distributed teaming, and complexity. Based on the findings, challenges and key teamwork characteristics of space operations were integrated into the initial scenario development. In addition to the scenario, we plan to use dynamical system methods to analyze team activity in real time.

INTRODUCTION

Teaming in space presents unique challenges. For instance, the spatial and geographic distribution of teammates coupled with variable communication latency makes teamwork more difficult to coordinate. This is exacerbated by the complexity of operating in heterogeneous teams that include humans, robots, and artificial intelligence (AI) agents working as a multiteam system. As a result, the challenges related to teamwork in space operations must be identified and understood to ensure safe and effective space-based missions. This study aims to identify some of the unique challenges associated with Human-Machine Teaming (HMT) in space, to develop an ecologically valid testbed and associated measures to study these challenges, and to assess them in real time.

The Complexity of Space Missions

Several aspects of space operations are enabled by interactions between humans and machines, but present unique challenges. For instance, extravehicular activities (“spacewalking”) may be executed in two-person teams (EV Crew) who don spacesuits to execute activities outside of the international space station (ISS). The EV crew may use a Canadarm2 robotic arm to assist them in performing certain tasks such as moving supplies and equipment during station repair operations. In addition to the EV crew, there is typically an intra-vehicular (IV) crew member who coordinates with a ground control team and directs the EV crew. A second crew member inside the spacecraft or on the ground control team may operate the Canadarm2 in either a manual or semi-autonomous manner (Garcia, 2018).

For the US, a spacewalk is led by mission control at the Johnson Space Center (JSC), but also includes mission control centers worldwide. Ground control teams are made up of multiple sub teams of specialists in EVA, robotics, and maintenance that provide a wealth of expertise from which guidance can be provided to the crew in space. However, communication between the ground and space teams can be limited by satellite coverage and by the level of detail communicated to the spacewalkers. Furthermore, communication often passes through multiple levels. Communication from the ground during a spacewalk is typically coordinated by the JSC Flight Director and relayed through the Capsule Communicator (CAPCOM) to the IV crew member on the space station. The IV crew member then coordinates directly with the EV crew. Coordinating and prioritizing in this way helps maintain a focus on the details of the task that the EV crew is carrying out, but the many layers of communication can lead to difficulties.

Future technologies, such as automated refueling and repair operations, may reduce the need for astronauts to conduct spacewalks themselves, but present other challenges related to operating robotics and communicating between teams. For instance, teleoperation of robotic systems creates perceptual challenges that can be compounded by control delays and disruptions associated with operating in space (Sheridan, 2016).

Flexible Human-Machine Teaming

Spacewalks tend to be highly preplanned. However, interruptions during some tasks may be impossible to plan for and require flexibility within the unique constraints imposed by space operations. These tasks require re-specification of goals and approaches “on the fly”. For example, during the Apollo missions, one goal was to conduct geological research on the Moon (Hodges & Schmitt, 2011; Schmitt et al., 2011). Two-person teams of astronauts were augmented by a “backroom” of planetary scientists on Earth, with the objective to collect samples for laboratory analysis on Earth. The scientific community did not have a consensus about what sort of samples the astronauts would encounter on the moon, and thus re-planning continued as new observations were made. The research goals and operational strategies were continually evolving throughout each EVA, creating the need for increased coordination and potential errors. During the seventh crewed mission of the Apollo program (Loff, 2015), an archetypal example of flexibility and ingenuity was demonstrated when astronauts and ground control worked together to abort a moon landing and return to earth in response to a novel equipment failure.

The ability to adapt to changes is a hallmark of effective teams (Burke et al., 2006). However, a new era of planetary field research is now emerging (Hodges & Schmitt, 2011). Unlike the Apollo missions, future operations will likely rely heavily on on-site teams that also include robots operating alongside humans. Some robots will be teleoperated, with controls subject to a variety of latencies and bandwidth constraints (Lester & Thronson, 2011). However, others will be autonomous and capable of learning new procedures as the tasks evolve. Teaming with autonomous systems presents a new set of challenges that must be confronted (National Academies of Sciences, Engineering, and Medicine, 2021). Yet at the same time, AI agents may also be leveraged to help coordinate and optimize team activities. The complexity of the tasks, the need for close monitoring of operations, and the amount of information required for operations create a complex environment. If designed from a team-centric standpoint, the addition of AI monitoring and intervention systems could help identify and correct errors, team coordination problems, and missed procedural steps.

The Space Challenge Project

The purpose of the Space Challenge Project is to identify key challenges to distributed human-machine teamwork during space operations, develop a testbed to simulate those challenges for laboratory study, and to quantitatively sense and analyze disruptions to team coordination to inform AI-enabled team interventions. To that end, we conducted subject matter interviews and a literature review to develop an understanding of the current and potential challenges facing distributed human-machine teams in space. Findings from the literature review and interviews have been synthesized and are currently being used as inputs to scenario design within a distributed testbed that is undergoing testing and iterative development (Figure 1). This paper describes our preliminary findings from SME interviews and pilot studies and provides an overview of our unique data analysis approach.

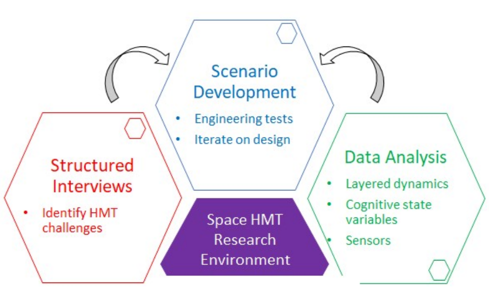

Figure 1. Overview of the Space Challenge Project

SUBJECT MATTER EXPERT INTERVIEWS

To supplement and validate the challenges that were identified in the literature review, semi-structured interviews were conducted with nine subject matter experts (SMEs). An advisory board helped to select individuals with experience in space operations. The backgrounds of the participants included former astronauts, astrogeologists, robotics engineers, and members of NASA mission control with extensive expertise. The SME profiles are summarized in Table 1.

Table 1. Subject Matter Expert Backgrounds and Experience

ID	Background	Space Experience	Robotics Experience
1	Astronaut	150+ days in space	Yes
2	Astronaut	50+ days in space	Yes
3	Astronaut	150+ days in space	Yes
4	Astrogeologist	No	Yes
5	Astrogeologist	No	Yes
6	Space robotics	No	Yes
7	Space robotics	No	Yes
8	Space robotics	No	Yes
9	Space robotics	No	Yes

We conducted a thematic analysis on the SME interview transcripts based on guidance provided by Williams and Moser (2019). First, open coding was conducted to identify broad themes. Next, broad themes were further refined and categorized into discrete codes representing themes and sub-themes organized into a codebook. Finally, line-by-line coding was conducted to identify the occurrence of codes. Iterative refinement of the thematic analysis is currently underway. Preliminary findings and associated quotes from the initial analysis are provided in Table 2. High level themes included *communication*, *training*, *distributed teaming*, and *complexity*. Two to five sub-themes were nested under each theme. For instance, *communication latency* was a sub-theme under the theme of *communication.*

Table 2. Preliminary Challenge Themes and Sub-Themes

Theme	Sub-themes	Examples quotes
Communication	*General communication challenges*	"I wouldn't call it 'overtraining', I would call it envisioning all the things that could go wrong and trying to think through what you might do in response."
	Common vocabulary: Lack of shared terminology and phraseology between individuals and subteams	"People were using…different random words. The people from Country Z would call it 'x', and it would get translated in English as 'y', and some other translating would translate 'x' as 'z'..."
	Communication latency: Communication latency resulting in lagged or asynchronous communications	"…it's [latency] is the biggest issue […] without efficient communication, things can go wrong."
	Communication bandwidth: Limited bandwidth resulting in slow transmission of information	"…bandwidth is a [concern] when sending certain data types with more frequency or higher priority."

Training	*General training* challenges	"… and then there were some people who had no training, and you couldn't teach them anything.'
	Lack of adequate cross-training: Inadequate time training on the roles of teammates leading to a lack of shared understanding of the work requirements	"Just use common sense and what a little bit of geology you've been able to learn so far, how would you interpret that…I will tell you that 99% of these planetary scientists knew nothing about field geology."
Distributed teaming	*General distributed teaming challenges*	"if you look at the sort of distributed team in here, … in time and space, you know there a lot of questions about how do you choose the right information, because obviously you can't transmit everything."
	Geographic distribution: Teammates are not in the same location	"…we had to do distributed geographic teamwork…"
	Multiple command centers: Multiple command centers to coordinate with or report to	"…when I speak down on the ground there's mission control from Houston but also [a different] mission control for the telescope so we're kind of keeping multiple audiences in mind."
Complexity	*General complexity*: The complexity of the socio-technical system (genera challenges)	"..that's a whole different level of complexity…"
	Multiple components: Numerous interacting components	"… these little systems all keeping track of their flow rate, their pressure, their 'this or that' right, we have independent sensors…"

SCENARIO DEVELOPMENT

One or more of the teaming challenges identified in our interviews will be the target of scenario development. In the past, we have developed several physical and virtual synthetic task environments for conducting team research (Cooke & Shope, 2004). This work leveraged an existing Remotely Piloted Aircraft System Synthetic Task Environment at Arizona State University (ASU) and replicated at Georgia Tech for conducting human-machine teaming studies for distributed teams. It also leveraged a recently developed testbed at ASU that allows for physical human-machine teaming in a ground-based environment with robots that have different functions (e.g., search, retrieve, transport, fine manipulation). The ground-based lab and two distributed aerial labs have been connected via the communication system, which also allows for the controlled manipulation of communication latencies. The lab also has biometric sensing equipment and full OptiTrack video recording capabilities, plus a radio communication system. Robots can be pre-programmed or operated via the Wizard of Oz technique (Cooke et al., 2020). Scenario design and implementation followed an interactive process of design, evaluation, and re-design to ensure that the challenges we have targeted exist in the testbed.

The scenario is crafted to reflect the nominal communications among a number of distributed entities that include NASA Mission Control Center (MCC), Jet Propulsion Laboratory (JPL), a lunar colony of a human (Bravo) and a robot (Alpha) who is not trustworthy, a lunar orbiter, the International Space Station (ISS) with two humans (Charlie, Delta), one on a spacewalk (Charlie), a Mars Rover, and a Mars Orbiter. The Mars Rover is played by a Husky robot and all other entities are played by human experimenters. Amidst the backdrop of nominal communications and activities, challenges or perturbations are interspersed. The nominal communications are described in turn in what follows and visualized in Figure 2.

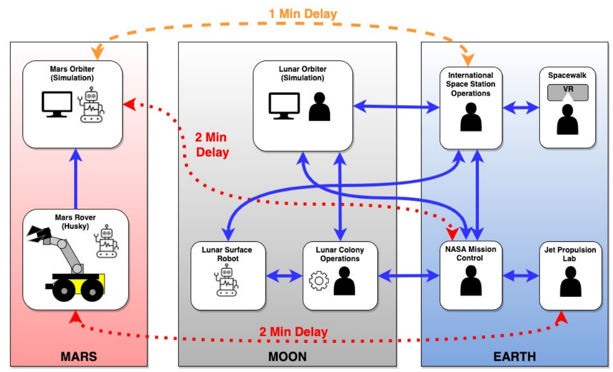

Figure 2. Diagram of Space Challenge distributed simulation spanning earth, moon, and mars task environments. Directional interaction channels for communication and control are indicated between components with arrows. Delays indicate time for 1-way communication.

Nominal Communications

NASA MCC. NASA MCC communicates any updates in tasking every three minutes with the ISS-Delta, who acknowledges. NASA MCC also communicates with Bravo, the human on the lunar colony. MCC reports new tasks to Bravo every 3 minutes, and Bravo reports any issues to MCC or reports A-OK. MCC provides the Mars orbiter with new tasking every two minutes, and the orbiter communicates its position to MCC; however, there is a 4-minute communication lag between these two entities.

International Space Station. In addition to the above communications with NASA MCC, the international space station (ISS) communicates with the lunar colony. Alpha, the lunar robot, communicates with ISS (Delta) about any discoveries, and ISS (Delta) provides scientific support and notes any new locations to explore every four minutes. The lunar orbiter also communicates positioning information to the ISS once a minute. The Mars orbiter also communicates positioning information to ISS-Delta once per minute. Further, during the spacewalk, Charlie, the walker, provides Delta with updates on status every 30 seconds.

Lunar Colony. In addition to the regular communications with NASA MCC and ISS, the lunar colony communicates internally and with the lunar orbiter. Alpha, the untrustworthy robot, is exploring and reporting positioning and new discoveries to Bravo who repeats back with Alpha confirming. The lunar orbiter also communicates positioning information to Bravo once a minute. All parties repeat back and confirm.

JPL. JPL is responsible for controlling the Mars Rover. In addition to its communications with MCC, JPL sends coordinates to the Rover and the positioning information is received each way with a 4-minute lag for movement and confirmation. In addition, the Rover sends its positioning information to the Mars orbiter every minute.

Challenges/Perturbations

There are a variety of challenges that are interspersed through nominal communications.

- Early on, ISS-Delta reports to Bravo that Alpha has communicated inaccurate information for the last three reports. Thus, Alpha is not to be trusted.
- The sudden need to replenish the earth's energy drives NASA MCC to task those on the lunar and Mars surfaces to quickly look for and collect samples of a substance called Enerphoto, known to be on the surfaces and a potential source of energy. The surface exploration must occur, followed by transportation of the Enerphoto by the orbiters to the ISS.
- An asteroid strike happens on the lunar surface and some equipment needs to be rebuilt by Bravo to preserve oxygen supply.
- The spacewalker comes untethered during the walk.

DYNAMICAL SYSTEMS METHODS

Layered Dynamics

To measure various levels of team activity in real-time, we adopted a layered dynamics approach (Gorman et al., 2019) to model simultaneous variation across numerous system states over time. This approach enables us to measure and make sense of variation in activity across the orbiters (vehicles), robots (rover), communication activity among team members, and variation in heart rate activity using interbeat intervals (IBI).

A key concept in using the layered dynamics approach is that of creating intersections. Intersections represent unique system states over time and can flexibly measure various types of socio-technical interactions across system sublayers. In this work, we use intersections to identify unique system states across orbiter (vehicle) activity, communication activity, and heart rate activity. Intersections are formed by representing each sublayer with a vector of binary numbers. Then, we can efficiently combine activity across sensors within a sublayer by horizontally concatenating the binary numbers to create a unique state across each sublayer. In general, we hypothesize that we will observe greater variety (entropy) of intersections during novel challenges (or perturbations) in which the behavioral variety of system states among the orbiter, communication, and physiological layers increases in response to such challenges.

Mars Orbiter. We used information entropy (Shannon, 1975) to measure the variety in orbiter and communication activity over time with a moving window. The use of the layered dynamics approach required that we define several inputs into the orbiter layer to quantify variety. Specifically, changes across the velocity, altitude, or bearing of the orbiter lead to an increase in the entropy (variety) of the orbiter state. The changes in these variables were represented using the intersections-based approach described earlier. Thus, changes in any one of these variables would increase entropy, but simultaneous adjustments across multiple values increase entropy to a greater extent. Using this approach, we have successfully detected a simulated loss of power and the landing of an orbiter on Mars.

Communication Dynamics. To coincide with these changing orbiter dynamics, we simulated the need to reroute communications across the network. These communication patterns also serve as inputs into the layered dynamics. The communications consisted of which teammate was speaking to whom at any second in the mission.

Like the orbiter, communication states were represented by numerical symbols in binary form. To enable the use of layered dynamics, we created intersections of communication states across team members. These intersections corresponded to unique system communication states at any one point in time as described earlier. Thus, when teammates were speaking in a highly patterned approach (see Nominal Communications), we would see low entropy and few novel intersections. However, communication pattern shifts are reflective of increased communication variety and novel intersections, both in terms of number and rate, resulting in high communication entropy at those times. This technique thus detects points during the mission, some of which coincided with increased orbiter entropy, in which team members needed to change their communication patterns suddenly, which may be indicative of the need for increased system orchestration.

As part of our communication dynamics analysis, we calculated how much each team member was speaking during the mission. This was simple communication frequency over time measure. However, we found more interesting results using average mutual information (AMI), which uses information theoretic concepts to quantify how much uncertainty about other team members' communication patterns as well as orbiter state is reduced by having knowledge of a particular team members' communication behavior. AMI allowed us to quantify the influence that any one teammate or subset of teammate communication inputs had on the system. In other words, we were able to detect differences in terms of how frequently team members spoke and the influence those communications had on the system.

Heart Rate Entropy. To apply the measure of entropy to the heart rate interbeat interval dataset to align these dynamics with the other system layers (orbiter; communications), we conducted phase space reconstruction on the heart rate data to find the number of active degrees of freedom (adf) of the interbeat time series. Upon identifying the number of adf, we calculated the moving window entropy on the binary time series that symbolically represented changes across these adf. Although we are in the preliminary stages of analyzing this heart rate data using this approach, we are expecting doing so will serve as a complement to the approaches described above for orbiter and communication state and can help detect instances of anomalous activity at a physiological level with unique intersections across all sensors pertaining to different system perturbations.

Multifractal Analysis

In this study, we plan to use another dynamical systems method called multifractal analysis. There is evidence that physiological signals generated by complex self-regulating systems may have a fractal structure. Fractal analyses are frequently employed in physiological signal processing to define the scale-invariant structure in electrocardiogram, electroencephalogram, mammography, and bone imaging (Lopes & Betrouni, 2009). For instance, the scale-invariant structures of interbeat interval (IBI) of ECG signals have differentiated between healthy and pathological conditions by using monofractal Detrended Fluctuation Analysis (DFA) and multifractal DFA (Ivanov et al., 1999; Wang et al., 2007).

Monofractal signals are homogeneous because they have the same scaling properties throughout the entire signal, and they are indexed by a single global Hurst exponent (H; Hurst, 1951). On the other hand, multifractal signals can be decomposed into many subsets characterized by different local Hs, which quantify the local singular behavior and relate to the local scaling of the time series. Thus, multifractal signals require many exponents to characterize their scaling properties fully (Ivanov et al., 1999) but capture heterogeneous fractal dynamics across varying timescales.

Each individual in a team is far more likely to exhibit different fractal patterns at different levels of analysis, from physiological to social, rather than a single pattern across all scales. More recently, it has been established that complex dynamical systems may instead result from a spectrum of processes with a range of different scaling parameters. Such systems with multiple scaling behaviors are called multifractal. Multifractal indices relax the assumption of self-similarity but also make it possible to detect scaling differences across scales of analysis. These can arise through several interacting processes, each with different self-similar behaviors acting in concert to produce the overall structure or a single process whose self-similar statistical properties change within the timeframe under analysis (Likens et al., 2014).

DISCUSSION

The goal of the Space Challenge project is to identify the challenges faced by teams in space operations and then represent those challenges in a distributed human-machine teaming scenario that resembles typical space operations and to measure these coordination dynamics across the entire system. Currently, the challenges have been identified through semi-structured interviews, which have then been implemented into a scenario.

The next steps of the project will involve collecting data on the complete scenario. Once a complete data set has been generated, our dynamical systems methods will be used to analyze communication patterns among teammates, vehicle states, and physiological changes before, during, and after perturbations to the respective tasks. The goal is to demonstrate that our methods can be used to detect the effects of perturbations on system coordination so that an agent may use these data to help orchestrate interaction in such a complex environment. The purpose of the scenario is to serve as a testbed that will allow for experimentation on how to identify and interpret system states resulting from the effects of perturbations that can occur during space operations and to ultimately improve teamwork between humans and robots in space operations.

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