A Distributed Teaming Testbed for Human-Machine Collaboration in Futur-istic Space Missions

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Abstract

Future space missions present complex challenges for distributed human-machine teaming due to communication latency, operational uncertainty, and coordination demands across Earth, Moon, and Mars environments. We introduce a Distributed Teaming Testbed simulating multi-agent space missions involving astronauts, AI-enabled robotic agents, and ground control under variable communication conditions. The testbed facilitates experimentation with real-time perturbations and adaptive team behaviors in simulated space environments. Through layered dynamics and real-time analytics, we quantify team resilience using measures such as communication entropy, relaxation times, and influence metrics. Results indicate that resilient teams exhibit faster recovery from disruptions and more adaptive coordination, highlighting the role of human-AI trust calibration and autonomous agent integration. This platform serves as a scalable environment for studying cognitive, behavioral, and computational dimensions of distributed teaming. Future applications include predictive AI models for preemptive failure detection, adaptive autonomy, and resilience monitoring across space and terrestrial domains such as defense and disaster response.

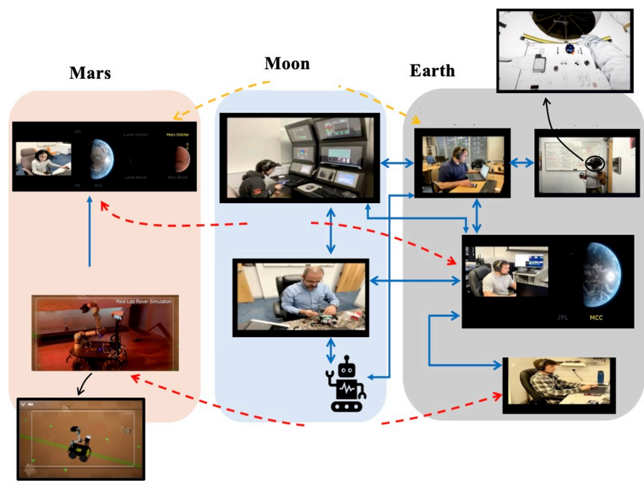

Figure 1: Representation of a distributed simulation of the Space Challenge, covering task environments on Earth, the Moon, and Mars (Zahmat Doost et al., 2024)

Introduction

Space missions present significant challenges in distributed human-machine teamwork, arising from communication constraints, system complexity, multi-agent coordination issues, and human-AI trust calibration. The extreme distances involved introduce latency in communication, making real-time decision-making difficult, while bandwidth limitations further restrict the exchange of crucial operational data (Yin et al., 2022). Additionally, interruptions, dropouts, and latencies in communication links create uncertainty, and the lack of a standardized vocabulary among astronauts, mission control, and robotic systems can lead to operational misunderstandings. Beyond communication, the integration of autonomous robotic agents poses challenges in trust calibration, as astronauts must rely on machine-generated decisions that may not always align with human intuition. Furthermore, the sheer complexity of space systems—with incremental technological development and cascading failures—makes it difficult to maintain stable mission execution. Addressing these challenges requires an adaptive, AI-assisted computational approach capable of detecting, predicting, and mitigating potential disruptions in space operations.

Background

To explore these challenges, we developed a Distributed Teaming Testbed, which simulates multi-agent space missions involving human astronauts, AI-driven robotic agents, and mission control teams spread across different space environments (ISS, Moon, and Mars; Figure 1). This testbed is designed to facilitate physical human-machine teaming in a ground-based environment, integrating robotic agents with varied functionalities such as search, retrieval, transport, and fine manipulation. This multi-environment testbed connects a ground-based lab and two distributed aerial labs via a communication system, allowing researchers to simulate controlled communication latencies—a critical factor in space operations.

We used this platform to explore resilient team performance in space-based human-machine teaming (HMT) and

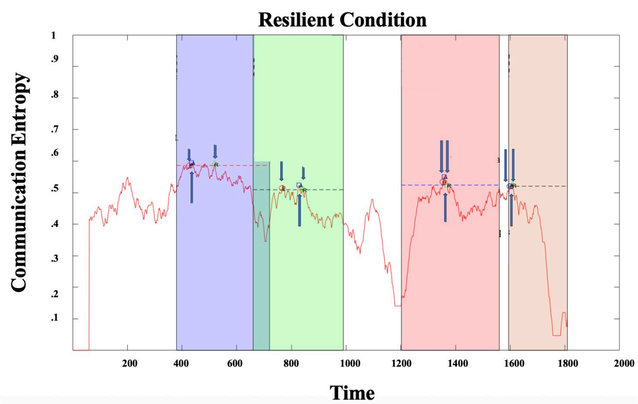

Figure 2: Communication entropy (reorganization) time series for non-resilient condition

developed a framework for quantifying and analyzing resilience using digital technologies (Cooke et al., 2013; Yin et al., 2025). The research is motivated by the high-risk and dynamic nature of space operations, which demand teams capable of adapting to unforeseen perturbations while maintaining peak performance under time pressure (Yin et al., 2022).

The study focuses on distributed space operations, where teams rely on both traditional communication networks and AI-driven robotic teammates, introducing complexity in coordination and decision-making. The simulation enables different types of scenario testing, including (1) nominal communications, a baseline scenario with routine operations and expected delays, and (2) resilience testing, a scenario where deliberate perturbations are introduced, requiring dynamic team adaptation. The testbed uses a layered dynamics approach to observe and measure team resilience using real-time analytics (Gorman et al., 2019). To analyze resilience during space-based perturbations, we examined relaxation times following disruptions (Gorman et al., 2025; Grimm et al., 2023), calculating average communication entropy (Shannon and Weaver, 1949; Gorman et al., 2019) to measure the variety in team responses across different scenarios, and comparing influence metrics (Communication Frequency and AMI) (Cover and Thomas, 2006; Gorman et al., 2020) to identify critical team members. We found that resilient teams exhibited shorter relaxation times and more effective adaptation to perturbations.

Future Works

Moving forward, this testbed provides a scalable research platform for further studies on human-AI teaming, space mission resilience, and autonomous decision-making in deep-space exploration. Future research could focus on enhancing AI-human collaboration through trust calibration models, refining adaptive learning techniques in AI-driven systems, and integrating real-time physiological and cognitive monitoring to assess astronaut workload and stress levels. A promising area of study would be developing predictive AI models capable of forecasting team performance breakdowns, allowing for preemptive intervention strategies before mission-critical failures occur. Further studies could also explore adaptive robotic autonomy, where robotic agents not only support astronauts but learn and evolve their decision-making processes over time through reinforcement learning and human feedback. This would allow robots to become reliable teammates also capable of independent problem-solving in extreme environments. Another important direction would be advancing multi-agent coordination strategies, where AI, human operators, and autonomous systems collaboratively optimize mission plans based on real-time constraints such as resource availability, energy consumption, and environmental hazards.

Beyond space exploration, the findings from this testbed have applications in defense, remote autonomous operations, and disaster response scenarios where distributed human-machine teams must coordinate in high-risk, high-uncertainty environments. Research could explore how AI-driven resilience monitoring and intervention strategies can support distributed military operations (e.g., Joint All-Domain Command and Control - JADC2), telemedicine for remote healthcare, and automated crisis response teams in large-scale disasters. As AI systems continue to evolve, the ability to detect, predict, and enhance team resilience using digital technologies will be critical for ensuring the safety, efficiency, and success of future autonomous and human-machine collaborative missions in space and beyond.

References

Cooke, N.J.; Gorman, J.C.; Myers, C.W.; and Duran, J.L. 2013. Interactive team cognition. *Cognitive Science* 37(2):255–285.

Cover, T.M.; and Thomas, J.A. 2006. *Elements of information theory (2nd ed.)*. Hoboken, NJ: John Wiley.

Gorman, J.C.; Demir, M.; Cooke, N.J.; and Grimm, D.A. 2019. Evaluating sociotechnical dynamics in a simulated remotely piloted aircraft system: A layered dynamics approach. *Ergonomics* 62(5):629–643.

Gorman, J.C.; Grimm, D.A.; Stevens, R.H.; Galloway, T.; Willemsen-Dunlap, A.M.; and Halpin, D.J. 2020. Measuring Real-Time Team Cognition During Team Training. *Human Factors* 62(5):825–860.

Gorman, J.C.; Grimm, D.A.; Robinson, F.E.; Winner, J.L.; Wiese, C.W.; and Roudebush, C. 2025. Dynamic Measures of Team Adaptation. *Human Factors*, 00187208251314262.

Grimm, D.A.; Gorman, J.C.; Cooke, N.J.; Demir, M.; and McNeese, N.J. 2023. Dynamical Measurement of Team Resilience. *Journal of Cognitive Engineering and Decision Making* 17(4):351–382.

Shannon, C.E.; and Weaver, W. 1949. A mathematical model of communication. Urbana, IL: University of Illinois Press, 11:11–20.

Yin, X.; Clark, J.; Johnson, C.J.; Grimm, D.A.; Zhou, S.; Wong, M.; Cauffman, S.; Demir, M.; Cooke, N.J.; and Gorman, J.C. 2022. Development of a Distributed Teaming Scenario for Future Space Operations. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 66(1):788–792.

Yin, X.; Grimm, D.A.; Zhou, S.; Pisors, J.; Teo, A.Z.Y.; Lijenstolpe, M.; and Gorman, J.C. 2025. Observing resilient performance in space-based teaming mission using digital technologies. *Applied Ergonomics*, 124:104409.

Zahmat Doost, E.; Yin, X.; Zhou, S.; Grimm, D.A.; Ljenstolpe, M.; Cooke, N.J.; and Gorman, J.C. 2024. Perturbation Detection in Space-based Human-Machine Teams (HMTs) in Different Layers. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 68(1):1712–1717. Sage CA: Los Angeles, CA: SAGE Publications.