PROJECT NARRATIVE

SUPPORTING DISTRIBUTED HUMAN-ROBOT OPERATIONS THROUGH NOVEL INTERACTION ARCHITECTURES

Introduction

As robotic systems become increasingly prevalent in space operations, warranted attention is being called to the emerging area of human-robot interaction (HRI). HRI is broadly concerned with the interaction and teamwork of human and robot agents performing tasks such as the operation of a robotic arm to assist an astronaut during EVA or the telerobotic control of planetary rovers to perform scientific fieldwork (Marquez, 2017; Currie & Peacock, 2002; Fong et al., 2013). In the safety-critical domain of spaceflight, it is imperative that human operators adequately understand system states and capabilities while performing high risk robotic tasks such as construction, vehicle docking, and EVA. Software tools such as Interaction Architectures (IAs) may serve to mitigate risks and gaps associated with inadequate human-system design, promoting situational awareness and enabling resource and task allocation, managing control handoffs, and dialogue flow. IAs (nested within NASA TA 4.4.5) boast the potential to manage complexity inherent in space operations through the context appropriate dissemination of mission-relevant information across multiple agents and levels of abstraction.

The proposed work will include the development and testing of a prototype IA, aiming to deliver an integrative software framework supporting various forms of coordinative and collaborative behavior in distributed human-robot teams. A multi-phase research project will explore the development of novel IAs to support distributed human-robot operations and mitigate risks outlined in the NASA Human Research Roadmap (HSIA-701). The proposed work is envisioned over four years, divided into three phases to facilitate the delivery and testing of a novel IA prototype, as shown in Figure 1: [1] Data Collection, [2] Data Analysis, [3] Prototype Development and Testing.

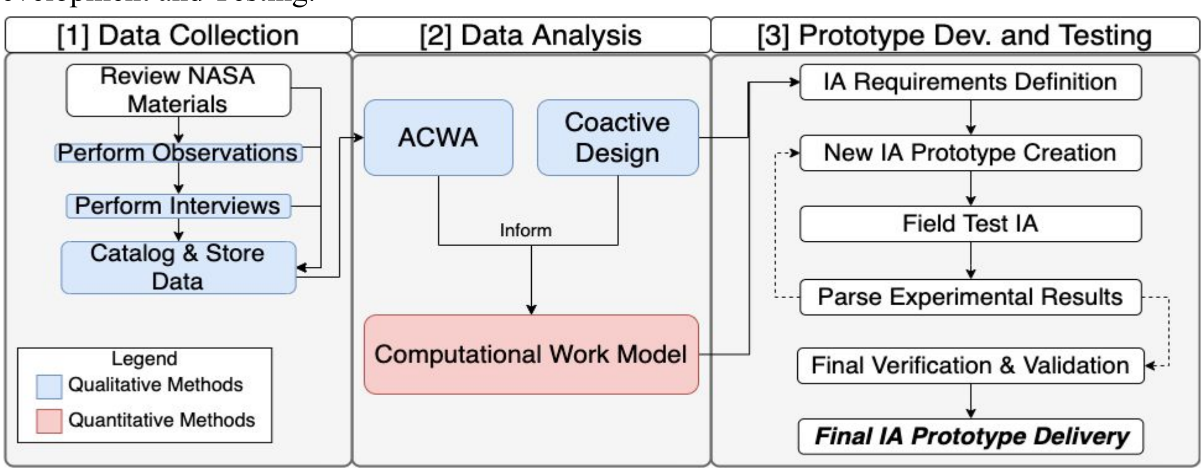

Figure 1. IA Project Phases

Expected Outcomes:

1. Documentation and map of work relationships associated with distributed human-robot teams performing space operations aboard the ISS.

2. A computational model of work capable of simulating and predicting system performance and interactions, allowing us to test the efficacy of various system architectures before implementing them.
3. A sophisticated IA prototype capable of facilitating resource and task allocation, trading and sharing of control, and dialogue management.

This proposed work will deliver a reusable software framework allowing distributed human operators to understand and navigate complex system states to desired outcomes. A computational model of work will support the discovery of novel interaction modes between agents, testing different frameworks for communication frequency, task allocation, and other relevant variables within work as discovered by analysis. These findings will drive the development of an IA prototype to undergo an iterative design and field testing cycle. Upon final delivery, NASA will acquire a 3rd Generation IA Prototype that supports distributed team problem-solving, communication within and across teams, and the effective allocation of resources. The project will also deliver an explicit documentation and analysis of robotic operation protocols and lessons learned from aboard the ISS. This information will prove valuable as the ISS begins the final chapter of its operational lifespan, driving the development of future human-robot system architectures for the Artemis program and Mars missions. The development and iterative testing of a novel IA Prototype will align perfectly with NASA's goals in this area, providing a repeatable and reusable framework for creating software that support distributed coordinative and collaborative teamwork in the complex world of space operations.

[1] Data Collection

Phase I will leverage knowledge elicitation methods drawn from cognitive systems engineering, ethnographic research, and HRI, aiming to capture the essence of the problem-solving environment that operators face (Woods & Roth, 1988; Cooke, 1994). An initial document search including a survey of relevant NASA handbooks, technical reports, and mission transcripts will be performed to gain background knowledge on human-robot operations aboard the ISS. After acquiring background and establishing a relationship with the visiting technologist, it is expected initial connections will be provided to begin performing direct observations and semi-structured interviews with relevant NASA personnel.

Targets for this effort include at least 40 hours of direct observation and 15 semi-structured interviews. Frequent travel to NASA facilities is envisioned as a major facet of this phase's success, supporting the orientation to the problem space and formation of important relationships with relevant personnel. NASA Johnson Space Center (JSC), the Jet Propulsion Laboratory (JPL), and Ames Research Center (ARC) appear to be salient candidates for work in HRI. JSC constitutes the majority of human spaceflight endeavors as well as oversight for the ISS. JPL and ARC will provide a glimpse into different expertise, more closely relating to the design of robotic capabilities for the ISS as well as planetary rovers such as Perseverance, Curiosity and the in-development VIPER rover. The visiting technologist's expertise could provide guidance to best support inter-center collaboration, leveraging specific focuses of each center as components of a well-rounded data collection. The perspective gained from these experiences will enable a more holistic and comprehensive understanding of the needs of human operators in the delivered IA prototype support decisions surrounding the later testing of the IA prototype. Existing NASA human-robot operational protocols for JSC, JPL, and ARC will be incredibly valuable to observe, and simulated operational environments for EVA and robotics testing (at JSC and JPL/ARC, respectively) may provide an avenue for efficient and low-overhead field testing in project phase [3]. Through observation and documentation of ongoing operations related to HRI, we can leverage existing NASA assets to collect ethnographic field data and elicit expert knowledge of the work domain to support later analysis and computational modeling.

[2] Data Analysis

Phase II will include the analysis of qualitative data using methods including (but not limited to) Applied Cognitive Work Analysis (Elm et al., 2003), an adaptation of mainstream systems engineering methodologies adept at engineering tools to support the cognitive work of practitioners in complex domains. ACWA is an end-to-end, repeatable methodology for the design of advanced software tools supporting human operators in complex environments, and is based on Vicente's (1999) Cognitive Work Analysis (CWA) framework. The methods of ACWA and CWA have been demonstrated as an effective approach to developing decision support tools for NASA, particularly for EVA operations (Miller, 2016; Miller, 2017). CWA is widely used in domains such as nuclear power, healthcare, and space shuttle mission control (Vicente et. al, 2004; Patterson et al., 1999; Roth, 2008). I believe that ACWA will work as a powerful analysis vehicle to organize qualitative data collected about the work domain.

A Functional Abstraction Network (FAN) will be created to highlight the processes and relationships underlying the human operator tasks. These mappings will help construct an understanding of the requirements of operator work at various levels, helping the explicit definition of what each operator needs to 1) understand the system in real time and 2) direct it to desired states. Information Relationship Requirements (IRRs) will serve as a qualitative tool to map the information necessary to perform cognitive work within the CWRs. These tools will help to explain the requirements of individual practitioners within the distributed system, such as understanding the specific information and cognitive tasks that support NASA personnel teleoperating a robotic arm on the ISS. By mapping the base information required for successful completion of a teleoperated mission task, this knowledge is recorded for later experimentation with our computational model of work. The FAN, with superimposed CWRs and IRRs, will graphically represent relationships such as information flow between operators as they complete tasks.

Another key aspect of the qualitative data collection is using Johnson's (2014) Interdependence Analysis. This method codifies interdependencies within work into a table format using an extension of traditional task analysis techniques (Annett, 2003). Methods drawn from Johnson (2014) will nicely complement the ACWA methodology, as the explicit identification of interdependencies associated with joint human-robot activity and their ramifications provides a perspective difficult to elucidate from the FAN. These tools combined will provide a thorough qualitative analysis illustrating how various agents and capabilities within the environment are connected, and will help identify the types of interactions that must be supported in the face of a dynamic and complex environment.

Though the FAN and Interdependence Analysis Table are strong tools to comprehend how work is performed, they do have limitations. The static and qualitative nature of the techniques makes them unable to predict human-robot team behavior over time, leading to their potential inability to predict adverse effects of a particular system architecture that emerge through interactions with other system components (IJtsma, 2019). This proposed work addresses these limitations through utilizing a computational work model enabling the prediction of emergent effects within work. This capability affords the prescient and informed development of space technologies; the ability to predict system behavior in response to simulated environmental variables makes a strong tool that can predict the weaknesses of proposed system architectures. Specific function allocations, inter-agent communication frequency during tasks, and various types of inter-agent control-handoffs can act as variables to run within the computational work model, allowing us to see the simulated results of an envisioned work system before allocating resources to build it out thoroughly. The work models will be developed in the simulation framework Work Models that Compute (WMC) (Pritchett et al., 2014), which has previously been successfully applied to analyze human-robot teams in space operations (IJtsma, 2019).
Though the use of computational work models, or WMC, may be an intensive process on the front end, it compensates through allowing the sophisticated simulation of the work domain with the ability to observe the effects of diverse environmental variables (IJtsma, 2017).

The results of the qualitative analysis will directly support the creation of the WMC, providing explicit mappings of the intricacies of work to be represented in computational form. Information requirements will be carefully considered as a feature of interest when considering the collaboration and coordination of distributed teams with information requirements and functional relationships spanning multiple levels of abstraction. Research expertise and laboratory capabilities at Ohio State University's Cognitive Systems Engineering Laboratory will be leveraged to create a realistic and powerful WMC software framework, enabling quantitative and dynamic measurements of team performance within distributed work systems (IJtsma, 2019; IJtsma, 2017; Pritchett et al., 2014). This tool will be created with the programming language C++, using the language’s object oriented nature to map the interactions of multi-agent systems by considering action sequences, task allocations, and resource constraints within work to quantify operational performance of human-robot teams. Such a robust and cutting edge approach to human-system design has major implications for the development of other new space technologies, including the design of robotic capabilities to assist in the contribution of a sustainable lunar base in the upcoming Artemis missions.

[3] Prototype Development and Testing

Phase III will include an iterative approach to design and test a novel IA. CWRs and IRRs, tested and verified with the computational work model, will elicit specific engineering and design requirements, acting as a natural extension of previously performed analyses. These requirements will define the needs the software tool must satisfy. Following satisfactory requirements, CWRs and IRRs will be codified through Presentation Design Concepts (PDCs), a technique from ACWA to translate requirements into display representations. The creation of several PDCs containing mission relevant parameters as determined by analysis will be the first step in the prototyping following the organization of requirements. to the development of several dashboards to monitor and allocate resources within the distributed work system (Elm et al, 2003).

A 1st Generation IA prototype will be developed from PDCs using Java or Rshiny, leveraging software development and data visualization capabilities held in the Cognitive Systems Engineering Laboratory at Ohio State to arrive at effective visual representations of complex phenomena that simplify the nature of work. Field testing will occur after the completion of the 1st Generation IA Prototype, aiming to gain valuable feedback and experimental results from embedding my software tool in an opportunistic knowledge capture environment, such as leveraging connections in the NASA-HRI sphere to run a simulation using the prototype. It's envisioned that these relationships will be fully formed by the end of the 2nd year of the NSTGRO work, allowing NASA assets to be leveraged in a low overhead fashion to support the evaluation of the novel IA prototypes in years 3-4. Envisioned field testing methods could include a simulation of a task requiring distributed HRI, with a flight controller using the prototype to perform tasks. Workload conditions presented during task attempts will be categorized using the NASA Task Load Index (TLX) to quantify the demands placed on operators and their subsequent performance. Control conditions for the experiment would include operation of the original software suite to perform the same task.

Following initial field testing, experimental data for the field test will be post-processed, driving a second iteration cycle in which the 2nd Generation IA Prototype will be developed, and subsequently field tested with the results post-processed. The development of the 2nd Generation IA will include a more refined approach considering feedback and results of the prior field test. Following the 2nd field test, results will be post-processed and added to a final verification and validation process to debug and edge-test the software system before delivery of the 3rd Gen IA Prototype, completing the NSTGRO proposed work as well as the fourth year of my Ph.D curriculum.

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NSTGRO SCHEDULE

Title: Supporting Distributed Human-Robot Operations Through Novel Interaction Architectures

Name: Jacob Keller

Milestones	Date
Begin M.S. Program	Aug-21
Begin NSTGRO 2021 Project	Aug-21
Begin Data Collection	Aug-21
Catalog and Store Data	Aug-2022
Applied Cognitive Work Analysis	Feb-2023
Interdependence Analysis	Feb-2023
Computational Work Model	Aug-2023
M.S. Thesis Completed	Aug-2023
M.S. Degree Earned	Aug-2023
IA Requirements Definition	Dec-2023
PhD General Exams	Feb-2024
IA Prototype Design (1st Gen)	May-2024
Field Testing of IA (1st Gen)	Jun-2024
Parse Experimental Results for Field Test (1st Gen)	Sep-2024
2nd Gen IA Prototype Design	Dec-2024
Field Testing of IA (2nd Gen)	Jan-2025
Parse Experimental Results for Field Test (2nd Gen)	May-2025
Final IA Verification and Validation	Aug-2025
Final IA Prototype Delivery (3rd Gen)	Dec-2025
Final NSTGRO Report	Feb-2026
PhD Thesis Defense	May-2026
PhD Completed	May-2026

Legend
Academic Milestone
Project Phase 1
Project Phase 2
Project Phase 3

Envisioned Course Curriculum

Envisioned Course Curriculum
Academic Year 1
ISE 5700 Introduction to Cognitive Systems Engineering (3)
ISE 5705 CSE Cooperative & Distributed Work - (3)
ANTHROP 8892.12 Applied Bayesian Statistics (3)
ANTHROP 8891.05 Ethnographic Methods & Research Design (3)
ANTHROP 5650 Research Design and Ethnographic Methods (3)
Computer Programming in C++ for Engineers and Scientists (3)
Academic Year 2
CSE 2021 Introduction to Modeling and Simulation (3)
STAT 6570 Applied Bayesian Analysis (3)
ME 3360 System Integration and Control (3)
CSE 5052 Survey of Artificial Intelligence for Non-Majors (3)
ME 7752 Mechanics and Control of Robots (3)
ISE 5720 Human Systems Integration (3)
Academic Year 3
DESIGN 5505 Information Design (3)
ISE 5710 Behind Human Error (3)
Anthro 8892.11 Statistics/Quantitative Methods (3)
ISE 5820 Systems Thinking & Engineering Design (3)
ISE 5770 CSE Design & Evaluation (3)
ISE 5194 Human-Centered Machine Learning (3)
Academic Year 4
ISE 5740 Human Centered Automation (3)
ME 5030 Intermediate Dynamics (3)
ECE 7858 Intelligent Control (3)
ISE 8999 Research in ISE for Dissertation (3)
NSTGRO Concludes
Autumn 2025 & Spring 2026:
ISE 8999 Research in ISE for Dissertation (3)
PhD Completed in Spring 2026