

Envisioning an Analog Work Domain Across Deep-Ocean Exploration and Human-Robot Spaceflight Exploration

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What if one existing work domain could be leveraged to inform an instantiation of a second type of work domain? This is the question that informed a three year NASA-funded study, SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog), on the use of ocean science and exploration via telepresence as an analog for future human-robot spaceflight. SUBSEA included two field programs performed in 2018 and 2019. Each was comprised of a multidisciplinary team of natural scientists studying deep-sea venting sites in tandem with a team of social scientists conducting work ethnography to understand the existing ocean exploration domain. This paper presents results from the 2018 field program which includes analyses that were required to generate specific “flight-like” conditions for the 2019 field program.

INTRODUCTION

In 2017, researchers from space and ocean communities began working together on studies of geological, biological and chemical phenomena at deep-sea venting sites while also participating as subjects of social science research on conducting ocean science and exploration via telepresence. The Systematic Underwater Biogeochemical Science and Exploration Analog (SUBSEA) program provided science operations and ethnography researchers the opportunity to examine the question, “Can the existing work domain of ocean science research using telepresence be used as an analog for informing future human-robot spaceflight low-latency telepresence (LLT) operations?”

The SUBSEA program included two ocean research cruises. The first of which was a twenty-day field program (Aug-Sept 2018) to the Lō`ihi Seamount, located off the coast of Hawai`i’s Big Island. A second cruise was performed on a sixteen-day field program (May-June 2019) in Gorda Ridge off the coast of Oregon. The 2018 cruise was studied to determine what conditions could be imposed for a 2019 cruise, which would run in accordance with analog research conditions for future human-robot spaceflight. This paper presents the results from the 2018 research cruise that informed the specific flight-like conditions that were implemented for the 2019 research cruise.

ACROSS DEEP SPACE AND DEEP OCEAN

A connection must first be made between the space flight and ocean exploration work domains. NASA is developing a long-term strategy for achieving extended human presence in deep-space. This includes mission destinations such as cis-lunar space, the Moon, Near Earth Objects, the moons and the surface of Mars. A universal component of these envisioned future missions is the utilization of LLT operations. This involves unavoidable communication and data transmission latencies ranging from minutes to tens of minutes one-way light time (i.e. approx. 8-44 mins return) between crew (humans and robots) in deep-space locally controlling robotic assets and Earth-bound experts.

The impact of these communication delays combined with the potential system demands of LLT operations are a subject of NASA interest. On recent NASA Mars missions, scientists working with remote robots have had from one to several days to deliberate between sending and receiving data between Earth and Mars. Within future human-scale mission LLT operations, it is anticipated that decision-making timeframes will be significantly more compressed in order to affect actions by Earth-bound support to take advantage of having crew locally conduct LLT operations.

Examinations to date within the human spaceflight domain offer hypothetical applications of telepresence capability (Lester et al., 2017; Schmidt et al., 2012). Within the specific domain of scientific spaceflight telepresence, NASA Goddard’s former chief scientist James Garvin has stated, “There is a profound lack of real experience with low latency telepresence here on Earth, in geological field situations, with which to understand how to utilize the obvious benefits of this approach on the Moon, Mars, asteroids, or beyond... This experience gap limits our understanding of how to develop the engineering and technology capabilities required for using low latency telepresence in deep space field science (David, 2012, p. 44).” Therefore, the inclusion of telepresence capabilities in future human spaceflight missions remain speculative at best. Because human LLT operations are not common within the current spaceflight domain, these LLT hypotheses make them susceptible to the *underspecification*, *ungrounded*, and *overconfidence* properties of the envisioned world problem (Woods and Dekker, 2000).

This study of an existing telepresence capability in an existing domain provides a meaningful pathway, from a sociotechnical systems standpoint (Bijker et al., 1987), to informing future human-robot LLT spaceflight missions. Understanding work context plays a central role to unpacking the behaviors that shape domain operations in complex sociotechnical systems (Militello et al., 2018), demonstrated in over 30 years of work domain investigations in aviation, military, and nuclear

operations (Hutchins, 1995; Hutchins and Klausen, 1996; Mumaw et al., 2000; Stanton and Bessell, 2014).

“Telepresence” as employed in ocean science and exploration is a sociotechnical system comprised of satellite and communication networks, distributed work practices, and human-technology relationships (Mirmalek, 2014). Pioneering the use of telepresence in deep-ocean research, Robert D. Ballard first began using video cameras, streaming video in real-time to the ship, mounted on a remotely-operated-vehicle for exploration that led to the recovery of the RMS Titanic in 1985 (Ballard, 2008). By its development in 2005, it was able to support a 10-day expedition led by Dr. Deborah Kelley and scientists located in Seattle, Washington. They worked in near real-time (less than 2 seconds latency) in the Atlantic Ocean to study hydrothermal vents (Kelley, 2005). While the components of telepresence in ocean exploration trace back over a hundred years, the particular configuration in the 21st century and application is still relatively new (Mirmalek, 2014).

SOCIOTECHNICAL CONSIDERATIONS

Human factors research emphasizes sociotechnical systems (Waterson, et al., 2015), context (Woods, 2003; Ulrich et al., 2015) and communication (Keyton and Beck, 2010) in understanding the intersection of people, technology and work. Similar research resides within fields such as anthropology (Hutchins and Klausen, 1996; Jordan, 1996; Traweek, 1988) and cognitive systems engineering (Elm et al., 2008). A single disciplinary approach has yet to yield a robust account or guide to developing complex systems as work domains are constituted of multiple primary agents (e.g., humans, technology, geographic location) and interactive relationships. And while interdisciplinary research requires more time commitment, data collection and analysis are more robust (Efstathiou and Mirmalek, 2014).

For SUBSEA, we brought together approaches and perspectives from the cognitive sciences (Miller) and anthropology, communication, and science technology studies (Mirmalek). In addition to these core competencies, prior relevant work experiences in space and ocean domains informed scoping, data collection, study condition management (e.g., subjects, infrastructure, multi-institutional workflow) and analysis for the SUBSEA project. Dr. Mirmalek’s ethnographic study of human-technology relationships began almost twenty years earlier in the airline work domain (Wales et al., 2002) and includes NASA’s Mars Exploration Rovers mission (Mirmalek, in press), ocean science and exploration with robots (Bell et al., 2015; Mirmalek, 2014, 2018), and human spaceflight analog research through the BASALT program (Mirmalek, 2017; Sehlke et al., 2019). Dr. Miller has over five years of NASA human spaceflight and operations analog research experience (Miller et al., 2017; Miller and Feigh, 2019; Marquez et al., 2019). The SUBSEA Principle Investigator, Dr. Lim, brought over twenty years of experience managing science and operations analog research for space exploration (Lim et al., 2011, 2019a).

Research advancing work domains falls under the sociotechnical challenges of the envisioned world problem (Woods and Dekker, 2000) the activity of imagining, determining and articulating characteristics of a future work domain. These characteristics include technologies, personnel roles, human-technology relationships, institutional practices, and socio-economic relationships. The envisioned world problem, traditionally, has focused on translating an existing system to a possible future of itself (Miller et al., 2017; Murphy et al., 2017). Examples of constructing future versions of an existing domain include nuclear power plant operations (Ulrich et al., 2018; Woods and Hollnagel, 1987), and healthcare development (Hettinger et al., 2017). We pose: what if one existing work domain could be leveraged to inform an instantiation of a second type of work domain?

SHAPING THE PROBLEM SPACE

Fashioning an analog spaceflight work domain within the ocean exploration work domain requires a definition of what it means for these two specific domains to be ‘analogous.’ The SUBSEA program neither created an actual future spaceflight work domain, nor attempted to presuppose and impose the components of a hypothetical future spaceflight domain in the ocean domain. This study approached the examination of what it means for ocean science and exploration to be an analogous work domain for human-robotic planetary exploration. For NASA spaceflight mission research, “analog” is widely used to describe environments on Earth that are similar to (analogous) planetary sites, e.g. gravity, scientific features.

SUBSEA’s approach involved shaping a representative spaceflight analog within the deep-sea work domain by imposing *necessary* (conditions that must be present for an event to occur) and *sufficient* (conditions that will produce the desired event) conditions garnered from an unaltered ocean expedition via telepresence. During Cruise A (2018), SUBSEA’s first field program, the ocean exploration domain was studied to understand if the domain in question could be extended to a spaceflight analog to assess what might be *feasible* for implementation of future spaceflight domain features. Cruise B (2019), SUBSEA’s second field program, was performed as a test of whether the derived spaceflight conditions successfully created a version of a spaceflight analog setting. Figure 1 shows the visual relationships between the two domains: spaceflight (A) and ocean exploration via telepresence (B).

From an envisioning standpoint, it is not apparent how to implement analog spaceflight features within the ocean context, even though the two domains might appear analogous. Collecting data (in our case qualitative) on sets of work practices constituting the work domain is a critical first step towards understanding what opportunities exist for alteration/extension from one work domain to another. In this study, Cruise A focused on examining whether or not the E/V *Nautilus* telepresence architecture and work (science activities) could be leveraged to develop a spaceflight analog. This effort aligns with “discovering or identifying the processes that drive

performance and adaptation” to understand “what may be the effective stimuli that control behavior out of the infinite possible ways one could represent the stimulus [analog spaceflight] world (Woods 2003, p.43).”

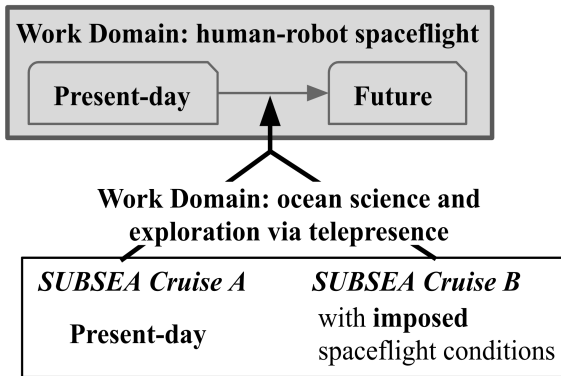


Figure 1. SUBSEA program in relation to generating spaceflight LLT analog environments.

Between Cruise A and B (8 months) we analyzed Cruise A data to determine and implement some NASA “flight-like” conditions for Cruise B. Flight-like is defined as the operational parameters to produce current and expected conditions of future deep-space missions. These are drawn from the catalogue of NASA ‘Flight-Rules’ (Keyser, 1974) and NASA missions (e.g., Apollo and MER). The remainder of this paper discusses the results of Cruise A and details the shifts prepared for Cruise B.

**NASA SUBSEA CRUISE A
EXAMINING THE EXISTING OCEAN DOMAIN**

For SUBSEA Cruise A, scientists studied seafloor fluid venting in Earth’s deep ocean as it may relate to environments on other ocean worlds in the outer solar system that could host similar chemosynthetic ecosystems (Hendrix et al., 2018). A series of 10 dives over 16 days at sea, shown in Table 1, was performed at the Lō`ihi Seamount, located off the coast of Hawai`i’s Big Island at more than 1 km beneath the ocean surface. This location was chosen because it hosts a distinct class of low-temperature (<100°C) and shallow depth (hence, low pressure) fluid flow that might provide a particularly relevant scientific analog for seafloor hydrothermal conditions (T = 50–200°C; P = 10–50 MPa) inferred for Enceladus, one of the 10 highest priority known ocean world candidates (Lim et al., 2019b).

Table 1. Highlighting the unpredictable conditions in an extreme environment, row 1 and 2 show the Cruise A planned dive count and actual dive count.

Planned	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Actual			1	2			3	4	5	6			7	8	9	10

The SUBSEA team consisted of distributed natural and social science teams located on board the E/V *Nautilus*, operated by the Ocean Exploration Trust (OET) (Figure 2) and on shore at the Inner Space Center (ISC) at the University of Rhode Island (Figure 3). The team on board the E/V *Nautilus* consisted of science instrument and ROV specialists, data managers,

SUBSEA scientists, and ship crew, all of whom worked in various workspaces including a control van, multiple laboratories (wet and dry), and on deck. Social science team member Mirmalek, and PI Lim, also worked onboard.



Figure 2. A partial view of the control van workspace on board the E/V *Nautilus*.

The team located in the ISC included SUBSEA scientists from the fields of microbiology, geochemistry, and geology who provided real-time input to the execution of each ROV dive. Personnel from SUBSEA’s technology team, the ISC, and OET were also present. Social science team member Miller worked at the ISC.



Figure 3. Within the ISC, SUBSEA scientists view the deep sea floor above their workstations.

The social science data collection activities during Cruise A consisted of a variety of data products across the two work sites, see Table 2. OET and ISC’s existing telepresence architecture provided the network connections (audio, video, text, telemetry) between the tethered ROV and E/V *Nautilus* with the ISC via satellite link, which facilitated recording. In addition, simultaneous in-situ observations of both the ISC and E/V *Nautilus* workspaces were made throughout dive operations, which included notes, image photography, daily surveys, and interviews.

Table 2. Research data collected from Cruise A.

Data Type	Description
In-situ observations : ISC and E/V <i>Nautilus</i>	120 and 220 hours of observations (recorded via fieldnotes)
Images of ISC and E/V <i>Nautilus</i>	O(1500) images taken of both work locations
Digital text client transcripts (SciChat)	120+ hours of time-stamped text communication
Teleconference audio recorded of teams	9 hours of teleconference audio
Daily communication modalities form	200+ responses
Dive robot video recording	1 TB+ of footage
Dive audio communication recorded	120+ hours of audio track
Interviews	15+ individual interviews

SETTING THE STAGE FOR SUBSEA CRUISE B AS AN ANALOG SPACEFLIGHT DOMAIN

To address the research question of whether the E/V *Nautilus* telepresence architecture could be leveraged, for the generation of a spaceflight LLT analog (Cruise B), the short answer is yes, but not necessarily in the form of what was originally proposed. At the onset of the SUBSEA project, the intent of Cruise B was to implement a communication latency, between ship and shore teams, close to the upper limit experienced between Mars-Earth (e.g., 15 minutes one way latency) within the existing E/V *Nautilus* telepresence architecture. After Cruise A, based on assessments from various subteams, we found the technical implementation of this latency condition was not feasible, for Cruise B. Given this evaluation, the social science team developed a set of “flight-like” conditions, described below, both necessary (work modes modulating latency) and sufficient (communication tools and shifted work roles). These conditions were then vetted for feasibility within the existing sociotechnical system and for being robust to the inherent variability of dive opportunities that exist at sea (Table 1). These conditions were buttressed by the addition of communication technologies and the reallocation of some team roles, that elevated and formalized what we found on Cruise A.

For Cruise B, we had the science team utilize a timeline for the planned dives that was separated into two distinct work modes, Mode 1 (M1) and Mode 2 (M2). Forty percent of the dives were allocated to M1; sixty percent of the dives were allocated to M2. During M1, scientists on shore did not have the ability to participate in real-time over audio channels (or written, via OET Science Chat) with dive operations conducted on the ship. Instead, they relied on specific communication technologies (SUBSEA Dive Plan authored by shore, and Dive Recovery and Data Report authors by ship) for sending and receiving content, between the ISC and personnel on the E/V *Nautilus*. These two

products were reflectively developed based on Cruise A work practices and SUBSEA M2 goals (Schön 1984).

During Cruise B M1, SUBSEA science team produced a daily SUBSEA Dive Plan for each dive and sent it to the ship; Once the dive was completed, the ship team produced a daily SUBSEA “Dive Recovery and Data Report” sent to shore. This communication cadence intentionally produced a temporal separation between requesting action (i.e., dive objective) and receiving confirmation of completion of action (i.e., dive objective). This was the intentional production of communication latency on the cycle of 24-hr exchanges between the two work groups. During M2, scientists on shore gained the ability to direct dive operations in real-time over audio and text channels in addition to the communication technologies described above. M2 communication cadence included a combination of temporal separation (as defined in M1 with the communication technologies) and real-time discussion throughout dive operations.

During Cruise B, personnel roles were modified to remove all lead scientists from the E/V *Nautilus* and co-located at the ISC. This shift separated all lead scientists from ship-side science work. Additionally, we added a mapping and navigation specialist to work with the SUBSEA science team at the ISC to support the science team’s incongruous practices for mapping and navigation activities. NASA technology team supported the use of a data management tool, Exploration Ground Data System (xGDS), also located in the ISC.

Continued research aims to collect and examine data on workflow (e.g., coordinated activities of work schedules, information flow, software support, knowledge production, distributed decision-making, and remote communication) during Cruise B work modes. These data will, in part, be used as a comparative to data collected during the first field program. We project these analyses will inform the intersection of socio-technical systems concepts and the importance of context and future work domain development.

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