Data Integration and Knowledge Coordination for Planetary Exploration Traverses

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Abstract. In order to implement an ambulatory physiological monitor in a free-range environment, a number of human performance sensing, human-computer interaction, data visualization, and wireless transmission technologies must be effectively and unobtrusively integrated. The Zephyr BioHarness™ is being integrated into NASA's Biologic Analog Science Associated with Lava Terrains (BASALT) Mars simulation in order to monitor and transmit crewmember health and activity information during "extravehicular activity" (EVA) sample collection tasks. The structure of the simulation and the different types of data and knowledge coordination are described. The importance of physiological monitoring in extreme environments, the selection of the BioHarness™ for use in the project, the process of integrating the monitor into the simulation, and the anticipated results from the analysis of the gathered data are also discussed.

Keywords: Physiological monitoring · Extravehicular activity · Human performance · Extreme environments · Distributed task coordination

1 Introduction

Ambulatory physiological monitoring has been shown to be effective in experiments in a variety of fields. However, nearly all of these experiments have taken place in controlled, enclosed environments, such as a hospital [1], or research laboratory [2–4]. With the desire of the space community to send humans to Mars and conduct necessary extravehicular activity (EVA), it is necessary to move ambulatory physiological monitors out of the lab and into free-range, extreme environments to collect data in situ and to transmit that data to a secondary location to allow for real-time monitoring.

In an attempt to fill this gap in research, a commercially available physiological monitor was selected and integrated into NASA's Biologic Analog Science Associated with Lava Terrains (BASALT) Mars simulation. The BASALT simulation was designed to test concepts of operations and sample collection protocols for human planetary exploration, while performing actual geological and geobiological science in

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scientifically interesting terrestrial settings. The lava terrains involved in the BASALT study include geologically recent (< 2000 years) and currently active lava flows in Idaho and Hawai'i, respectively.

The architecture as well as the data and knowledge coordination demands of the BASALT simulation are described below. The importance of physiological monitoring in extreme environments, such as the Martian climate and long duration spaceflight, is also discussed. Different physiological monitors were examined for integration into the BASALT simulation before the Zephyr BioHarness™ was eventually chosen; that process and the steps taken to integrate the selected monitor into the simulation are described in Sects. 4.1 and 4.2. Finally, the anticipated analyses to be performed on the collected data and the implementation of the results of those analyses are discussed.

2 BASALT

2.1 BASALT Architecture

BASALT is a NASA-organized research study simulating mission coordination and science achievement within the communication limitations caused by transmission lags of 5–20 min between Earth and Mars. The first BASALT deployment is scheduled for June 18th–30th, 2016 on the Eastern Snake River Plain (ESRP) in Idaho. This site was investigated as an analog to lava plains on Mars. A second BASALT deployment is planned during autumn 2016 on the Big Island of Hawai'i near Kilauea volcano. Crew information coordination and knowledge sharing in both Idaho and Hawai'i deployments are structured similarly, as shown in Fig. 1. An extravehicular (EV) crew left the simulated Mars habitat to perform scientific experiments and collect biological and geological samples on the lava flows. An intra vehicular (IV) crew remained in the

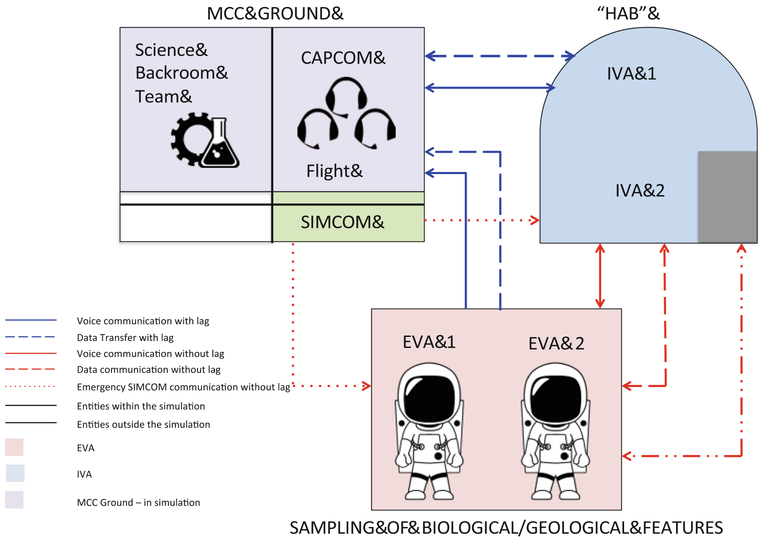

Fig. 1. BASALT simulation architecture

habitat to coordinate with the EV crew, monitor their progress, and to communicate with the Mission Control Center (MCC) stationed in a different location.

MCC consists of the capsule communicator (CAPCOM) and the flight controller, as well as the simulation communicator (SIMCOM), who monitors the simulation in real-time to ensure crew health and safety. The science backroom team is composed of individuals who have some scientific interest in the simulation, whether in its use as a Mars analog, or in the geological or biological samples taken from the site.

EV and IV crews can communicate with each other in real-time. Communication channels between the IV crew and the MCC, with the exception of the SIMCOM, are lagged 5–20 min to simulate real communication from Mars to Earth. MCC can also receive EV crew communication transmissions but their ability to respond to those communications was limited to sending messages through the IV crew; this was done in order to minimize distractions to the EV crew in the field.

2.2 Varieties of Data and Knowledge Coordination Demands

In order to fully capture the range of scientific mission achievement and knowledge coordination demands associated with the BASALT mission, comprehensive concepts of operations must be developed that enable and support a wide variety of data exchange and information alignment capabilities. The widely multidisciplinary nature of the BASALT research teams means that no two researchers will be necessarily focused on the same sources of engineering status, science achievement, or technology performance data flows. Nonetheless, the BASALT Simulation Architecture must be able to support this variety of flows, and remain robust to experimentally induced lags in data availability, as well as unintentional dropouts in communications.

The physiological monitoring of EV crew must be considered one of these data flows; however, such data does not map directly to a geologist’s interest in infrared spectral analysis data of a basaltic structure, or proper GPS-based location tagging and annotation of the origin of a particular physical sample. However, all of these may be considered “mission data” or sources of “knowledge development” or “achievement”. Further, data streams may be prioritized on the basis of bandwidth requirements or net benefit/cost ratios of scientific value to cost of bandwidth used. (For this reason, in constrained bandwidth scenarios, EV and IV crews may find it preferable to exchange high-resolution still photos with MCC, rather than continuous motion video.)

In addition to the technology requirements associated with constructing and maintaining the BASALT Architecture, members of the BASALT team have also found it important to distinguish various forms of science achievement, engineering status, human performance, and mission-related analog operational experience data or knowledge development. In order to help facilitate this distinction, the second author developed the following set of identifiers based on prior BASALT preparation meetings and initial deployment in Idaho in August, 2015. Rather than focusing on technical aspects of bandwidth or communication protocol requirements, the following identifier list addresses differences in the types of scientific and mission activities served:

- **Sample Artifact Direct (SAD):** physical artifacts collected for later transport and processing (e.g., rock piece or powdered material in sample bag);
- **Processed Artifact into Data (PAID)**: use of instruments to conduct on-site analysis of artifact characteristics for immediate transmission via communication architecture (e.g., diffraction or infrared spectra);
- **Context-Relevant Instrument Measurements and Elaborations (CRIME):** instrument data important in defining or describing location, elevation, or composition of physical location (e.g., LIDAR or GPS instrument, visuals from aerial vehicles);
- **Activity, Communication, and Execution as Data (ACED):** human performance and mission task completion used for studies of time- and location-based crew capability and task activity (e.g., voice communication, physiological monitoring);
- **Artifacts for Later Processing Offline (ALPO):** a subset of SAD objects must be sent for further processing (e.g., thin sections of rocks for crystallography) long after the analog deployment is completed;
- **Experiential Learning and Knowledge (ELK):** a variety of lessons learned, updates to task protocols, or changes in understanding of scientific domains based on field experience (e.g., considerations of new lava types or different communication protocols after a week of field deployment).

Full details of the mapping of BASALT Architectures to data flow types is beyond the scope of this paper. However, future studies of human-computer interaction and distributed knowledge coordination for similar mission designs will require conceptual and operational (if not technological) sensitivity and differentiation of the benefits and costs of obtaining different types of information resources in a constrained planetary science mission configuration. For the purposes of this paper, the remaining discussion will focus on the BioHarness physiological monitoring as a form of ACED data; further work will emphasize analyzing BioHarness and terrain information (integrating ACED and CRIME data sources) for further insights into proper crew scheduling and health monitoring strategies (creating new ELK mission operations baselines).

3 Physiological Monitoring in Extreme Environments

EVA offers a level of operational flexibility that will be paramount during long duration space flights and planetary exploration [5]. However, space and non-Earth planetary environments are arguably the most extreme environments humans have ever ventured to explore. Mars in particular combines the challenges of working in a very cold environment as well as in space.

Due to its thin atmosphere, Mars does not retain heat in the same way Earth does and therefore can reach temperatures as cold as −125°C near the poles in winter [6]. It is for this reason that arctic environments on Earth are often used as analogs for Mars. In an environment that can reach such low temperatures, there is a high dependence on technical systems to keep astronauts warm, especially when they are required to perform EVA. It is also important to note as the temperature of the body decreases, there is an increase in human metabolic rate in order to keep warm [7].

Along with its frigid temperatures, Mars offers other challenges specific to planetary exploration. The reduced gravity on Mars presents significant challenges. Studies of human locomotion hypothesize that energy expenditure increases in lower gravity environments due to the increased amount of effort required to self-stabilize and the decrease in traction with the reduced gravitational force. Large, cumbersome space suits also reduce mobility [8, 9]. The reduced gravitational force on Mars will also deteriorate weight-bearing bones and muscles, and cause pressure changes within the cardiovascular system, which could significantly impair an astronaut's ability to perform EVA. In addition to this, psychological parameters such as isolation, confinement, dependence on technical systems, and the high risk of the environment could present themselves physiologically and affect EVA efficiency [7, 10, 11].

Though data on the effects of long term spaceflight has increased since the establishment of the International Space Station (ISS), there will still be many unknowns and risks when it comes time to send the first manned crew to Mars or the Moon for a long-duration mission [7]. It is for this reason that remote and real-time physiological monitoring will be such a critical capability during these missions. Even early American and Soviet space programs recognized the importance of being able to physiologically monitor the first astronauts and cosmonauts that were sent into space [8–10]; it allows identification of anomalies and early reactions to potentially dangerous situations, which is invaluable in such an extreme environment [15, 16].

In order to overcome the lack of knowledge surrounding long term spaceflight and planetary explorations, simulations such as BASALT are used in order to attempt to fill some of the gaps in research. While it is not possible to simulate reduced gravity or cold climates during this simulation, Idaho and Hawai'i offer their own extreme environmental factors. The black lava flow at the Craters of the Moon National Monument & Preserve can reach temperatures of 77°C in the summer due to solar radiation [17] and Hawai'i is a tropical climate with high levels of humidity at sea level, but mountain sites may be more desert-like at altitude, with high solar incidence. More specifically, the active fumaroles in the BASALT target site can release toxic gases at any time. Both of these environments could cause EVA crewmembers problems with core body temperature cooling. In this situation physiological monitoring is also critical to ensure crew health and safety as the EVA crew may not recognize when they are overheating or dehydrated [7, 18].

4 The Zephyr BioHarness™

4.1 Selection

Unlike the early Russian and American space programs, computing power and mass is no longer a restricting factor in determining which physiological parameters can be monitored in space [12, 13]. There are many commercially available, wearable technologies that monitor a variety of physiological parameters and transmit the data in real-time.

When considering which physiological monitor to implement into the BASALT simulation, multiple wearable technologies were evaluated. Due to the variety of parameters that it can measure, the reliability with which it measures those parameters, and the unobtrusive placement of the device, the Zephyr BioHarness™ was chosen (Fig. 2).

Fig. 2. The Zephyr BioHarness™ worn around chest [19]

The BioHarness™ is worn on a strap around the wearer's chest, as shown above, and is able to measure heart rate, respiration rate, posture, activity levels, and estimated core temperature, among others [19]. This is a larger variety of physiological parameters than many other available monitors, which will give a more accurate indication as to the exertion of the EV crew. Also, the placement of this device is not only unobtrusive, but it also allows for more accurate measurements of vital signs than a wrist wearable technology. A monitor worn on the wrist would make accurate body posture and acceleration measurements impossible, due to the hands-on tasks crewmembers perform during EVA. The BioHarness™ also comes with its own live-monitoring and post-activity analysis software, which reduced the amount of work required to implement the device into BASALT.

The BioHarness™ has been used in a variety of laboratory studies including experiments simulating spaceflight [15], healthcare experiments [1, 2, 20], and sports settings [3, 4]. These experiments have shown the BH to be an accurate and reliable method to measure physiological parameters however they have all taken place in laboratory settings. There was no available literature on its use in extreme environments or in simulations such as BASALT.

4.2 Integration in BASALT

The BioHarness™ is worn by both EVA crewmembers while they complete the scheduled EVA tasks. When it is worn, the device automatically logs the wearer's physiological data internally for future download and analysis.

The IV crew and SIMCOM are responsible for monitoring the EVA crew's physiological parameters in real-time in order to ensure their health and safety at all times during an EVA. The data is also transmitted to the MCC with a time delay for observational purposes.

A key challenge of the BASALT mission architecture is the requirement to transmit real-time data to the IV crew, SIMCOM, and MCC. While the BioHarness™ transmits data over a Bluetooth or IEEE 802.15.4 connection, this only supports short range remote monitoring. Because of the challenging environment at the BASALT field sites, the IV crew, SIMCOM, and MCC can be located several miles away from EV crewmembers. Instead, the data will be locally linked to a Bluetooth relay device at the field site (Zephyr Echo Gateway). Then, the USB output from the gateway will be converted to an Ethernet data stream to be transmitted over BASALT's wireless Local Area Network (LAN) to IV and SIMCOM. This LAN provides a backbone for all communication (voice, video, data) between EV crewmembers, IV, and MCC. At the IV or MCC sites, the data stream can be received from the network and monitored with the standard software provided with the BioHarness^{TM}.

5 Anticipated Use of Physiological Data

The sampling rate of the BioHarness^{TM} provides large amounts of data to analyze, enabling a variety of different human performance aspects to examine.

First, the physiological data will be paired with EVA tasks to ensure that crewmembers did not need to overstress in order to keep to the scheduled timeline. This could eventually lead to the creation of guidelines for task scheduling. There are currently few standards applied to EVA scheduling, although studies suggest that the order in which tasks are arranged can have some effect on human performance. For example, performing repetitive tasks can be fatiguing and the longer an EV crew needs to be performing a task increases the risk of error, which could lead to injuries [9, 21]. This demonstrates the need for efficient scheduling of EVA tasks.

Gaining a base understanding of the workload requirements of different EVA tasks could also help allocate the appropriate amount of resources for each task [9] and could optimize crewmember performance by keeping individuals within defined performance parameters that ensure they are not expending too much energy [22]. Ultimately, strategic task scheduling and performance optimization will increase the robustness of planetary exploration missions.

Comparing the frequency and duration of communication transmissions against the measured physiological parameters could also ensure that communication was not compromised during particularly strenuous tasks. As a critical aspect of EVA, if a certain sequence of tasks causes a critical reduction in EV crewmember communication then that sequence of tasks will need to be reevaluated.

6 Conclusion

Physiological monitoring in an environment as extreme as Mars is critical for crew survival. Even in an analog (but scientifically valid for other purposes) field deployment environment, there are considerable needs for ongoing health monitoring of field crew/scientists during deployments at the science site. However there have been few implementations of ambulatory physiological monitors outside of controlled environments capable of providing reasonable or real-time performance data in such a challenging, "free-range" setting. The implementation of the Zephyr BioHarness^{TM} into

NASA's BASALT Mars simulation demonstrates the possibility of integrating a commercially available monitor into an extreme environment. One of the largest challenges of this implementation is getting the real-time data to transmit over the simulation's internal network.

It is anticipated that the analysis of the collected data will lead to EVA task scheduling guidelines that will ensure EV crewmembers do not need to overstress to keep to task timelines and that communication is not compromised during strenuous tasks.

References

1. Claudio, D., Velazquez, M.A., Bravo-Llerena, W., Okudan, G.E., Freivalds, A.: Perceived usefulness and ease of use of wearable sensor-based systems in emergency departments. IIE Trans. Occup. Ergon. Hum. Factors **3**, 177–187 (2015)
2. Stenerson, M., Cameron, F., Payne, S.R., Payne, S.L., Ly, T.T., Wilson, D.M., Buckingham, B.A.: The impact of accelerometer use in exercise-associated hypoglycemia prevention in type 1 diabetes. J. Diab. Sci. Technol. **9**, 80–85 (2015)
3. Kim, J.-H., Roberge, R., Powell, J.B., Shafer, A.B., Williams, W.J.: Measurement accuracy of heart rate and respiratory rate during graded exercise and sustained exercise in the heat using the Zephyr BioHarness$^{\text{TM}}$. Int. J. Sports Med. **34**, 497–501 (2013)
4. Hailstone, J., Kilding, A.E.: Reliability and validity of the Zephyr$^{\text{TM}}$ BioHarness$^{\text{TM}}$ to measure respiratory responses to exercise. Meas. Phys. Educ. Exerc. Sci. **15**, 293–300 (2011)
5. Newman, D., Barratt, M.: Life support and performance issues for extravehicular activity (EVA). In: Fundamentals of Space Life Science. (1997)
6. Sharp, T.: What is the Temperature of Mars? (2012). http://www.space.com/16907-what-is-the-temperature-of-mars.html
7. Gunga, H.-C.: Human Physiology in Extreme Environments. Elsevier, Burlington (2015)
8. Chappell, S.P., Klaus, D.M.: Enhanced simulation of partial gravity for extravehicular activity. Hum. Perform. Extrem. Environ. 10 (2013)
9. Chappell, S.P., Norcross, J.R., Abercromby, A.F.J., Gernhardt, M.L.: Evidence Report: Risk of injury and compromised performance due to EVA operations, Houston (2015)
10. Bishop, S.L.: Evaluating teams in extreme environments: from issues to answers. Aviat. Sp. Environ. Med. **75**, 14–21 (2004)
11. Le Pape, M.A.: Human-computer interaction in extreme environments: interaction effects between field dependency-independency and altered ± Gz accelerations on end-user performance. University of Hawai'i (2009)
12. Karandeyev, K.B.: Biological measurements in space (1965)
13. Holt, T.W., Lamonte, R.J.: Monitoring and recording of physiological data of the manned space flight program. In: IEEE Trans. Aerosp., pp. 341–344 (1965)
14. Fei, D.-Y., Zhao, X., Boanca, C., Hughes, E., Bai, O., Merrell, R., Rafiq, A.: A biomedical sensor system for real-time monitoring of astronauts' physiological parameters during extra-vehicular activities. Comput. Biol. Med. **40**, 635–642 (2010)
15. Rai, B., Kaur, J.: Human factor studies on a mars analogue during crew 100B international lunar exploration working group EuroMoonMars crew: proposed new approaches for future human space and interplanetary missions. N. Am. J. Med. Sci. **4**, 548–557 (2012)

16. Cermack, M.: Health and safety monitoring in extreme environments. J. Ocean Technol. **7**(3), 28–38 (2012)
17. Craters of the Moon - Weather. National Park Service (2016). http://www.nps.gov/crmo/learn/nature/weather.htm
18. Peacock, C.A., Glickman, E.L., Sanders, G.J., Pollock, B.S., Burns, K.J., Kakos, L., Gunstad, J.: Assessing a monitoring scale of physiological health and risk assessment among those exposed to heated environments: a brief report. Hum. Perform. Extrem. Environ. 12 (2015)
19. Zephyr Technology Corp.: Zephyr BioHarness 3 User Guide (2015)
20. Rodes, C.E., Chillrud, S.N., Haskell, W.L., Intille, S.S., Albinali, F., Rosenberger, M.E.: Predicting adult pulmonary ventilation volume and wearing compliance by on-board accelerometry during personal level exposure assessments. Atmos. Environ. **57**, 126–137 (2012)
21. Whitmore, M., McQuilkin, M.L., Woolford, B.J.: Habitability and performance issues for long duration space flights. Hum. Perform. Extrem. Environ. **3**, 64–74 (1998)
22. Cermack, M.: Monitoring and telemedicine support in remote environments and in human space flight. Br. J. Anaesth. **97**, 107–114 (2006)