Planetary and Space Science 58 (2010) 706–716

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Performance evaluation of underwater platforms in the context of space exploration

A.L. Forrest [a,*], B.E. Laval [a], D.S.S. Lim [b], D.R. Williams [c], A.C. Trembanis [d], M.M. Marinova [e], R. Shepard [f], A.L. Brady [g], G.F. Slater [g], M.L. Gernhardt [h], C.P. McKay [b]

[a] *University of British Columbia, Department of Civil Engineering, 6250 Applied Science Lane, Room 2010, Vancouver, BC, Canada V6T 1Z4*
[b] *NASA Ames Research Centre, Space Science & Astrobiology Division, Building 245, Mail Stop 245-3 Room 283, Moffett Field, CA 94035-1000, USA*
[c] *McMaster Center for Medical Robotics, McMaster University, St. Joseph's Healthcare, Hamilton, 50 Charlton Avenue East, Hamilton, ON, Canada L8N 4A6*
[d] *Department of Geological Sciences, College of Marine and Earth Studies, University of Delaware, 109 Penny Hall, Newark, DE 19716, USA*
[e] *Division of Geological and Planetary Sciences, California Institute of Technology, MC 150-21, Pasadena, CA 91125, USA*
[f] *Department of Geology, University of California, One Shields Avenue Davis, CA 95616, USA*
[g] *School of Geography and Earth Sciences, McMaster University, 1280 Main Street West, Hamilton, ON, Canada L8S 4K1*
[h] *NASA Lyndon B. Johnson Space Center, 1601 NASA Parkway, Houston, TX 77058, USA*

ARTICLE INFO

Article history:
Received 18 February 2009
Received in revised form
28 July 2009
Accepted 17 August 2009
Available online 31 August 2009

Keywords:
Autonomous underwater vehicle
Human–robotic interface
Performance metrics
Exploration metrics
Remotely operated vehicle
DeepWorker

ABSTRACT

Robotic platforms are essential for future human planetary and lunar exploration as they can operate in more extreme environments with a greater endurance than human explorers. In this era of space exploration, a terrestrial analog that can be used for development of the coordination between manned and robotic vehicles will optimize the scientific return of future missions while concurrently minimizing the downtime of both human explorers and robotic platforms. This work presents the use of underwater exploratory robots – autonomous underwater vehicles (AUV), remotely operated vehicles (ROV), and manned submersibles – as analogues for mixed human–robot exploration of space. Subaqueous settings present diverse challenges for navigation, operation and recovery that require the development of an exploration model of a similar complexity as required for space exploration. To capitalize on the strengths of both robotic and human explorers this work presents lessons learnt with respect to the fields of human–robotic interface (HRI) and operator training. These are then used in the development of mission evaluation tools: (1) a task efficiency index (TEI), (2) performance metrics, and (3) exploration metrics. Although these independent evaluations were useful for specific missions, further refinement will be required to fully evaluate the strengths and capabilities of multiple platforms in a human–robotic exploration campaign in order to take advantage of unforeseen science opportunities in remote settings.

Published by Elsevier Ltd.

1. Introduction

An integral part of establishing a human presence across the solar system is the development coordinated human–robot exploration:

> A partnership between humans and robots is essential to the success of such ventures. Robotic spacecraft are our scouts and proxies, venturing first into hostile environments to gather critical intelligence that makes human exploration feasible.—*The Global Exploration Strategy: The Framework for Coordination* (2008)

Human and robotic space exploration programs have traditionally been independent; however, the complexity of future human missions will require an unprecedented use of automation and robotics (Mishkin et al., 2006). Technology specialist divisions of space agencies have traditionally conducted robotic development; a paradigm shift must occur to couple engineering and science lessons in mission design to ensure mission success. This needs to be done to maximize the scientific return of a mission by capitalizing on the strengths and abilities of each survey platform (autonomous, remotely operated, and manned). Robotic exploration is driven by balancing the collection of scientific data in remote, and often extreme, environments while concurrently developing robotic innovation in terms of endurance, versatility and autonomy. As robots will never be completely self-sufficient, situations will continue to arise where robots fail and humans need to intervene, particularly cases where autonomy fails or unexpected contingencies develop. Essential for future

---

[*] Corresponding author. Tel.: +1 604 822 2915; fax: +1 604 822 6901.
E-mail address: forrest@civil.ubc.ca (A.L. Forrest).

0032-0633/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.pss.2009.08.007

human–robotic space exploration is: (1) the evaluation of each platform at a given task and (2) optimizing coordinated platform performance tasked with a common scientific objective.

Several field robotic studies have been conducted in order to simulate surface applications in arid conditions (Bualat et al., 2007; Fong et al., 2008a) although it has also been proposed that underwater settings could serve as ideal analogue work environments for mixed human–robot exploration in space (Bellingham and Rajan, 2007; Forrest et al., 2008b). Unlike surface applications, subaqueous settings present similar challenges as those found in space exploration: the lethal environment requires life support for human exploration; limited visible light transmission preventing direct human sensory input; and limited radio frequency (RF) and most electromagnetic (EM) band transmission restricts most available modes of underwater communication. There are also a number of differences that result in unique challenges in both exploration domains: (1) mass constraints encountered in space are less important underwater; (2) tethering of vehicles (e.g., ROV in subsea applications) are not common in space; (3) platform design has to adjust for high-pressure, corrosive environments underwater as compared to the vacuum of space; (4) underwater currents generate high perturbations as compared to space environments. The key to improving the fidelity of underwater vehicles as analogues for space exploration is examining the differences and similarities between the two different modes of exploration.

Evaluation of mission success of multiple platforms, the focus of this work, is impossible without understanding the human–robotic interface (HRI), human operator training and how both of these relate to real-time and post-processing of data. Future underwater and space exploration will require the development of a common HRI for varied exploration platform operations in unknown environments. HRI development occurs naturally when new problems, both in lab and field settings, are encountered and surmounted in order to maximize the scientific return of a mission. New autonomous platforms are working towards dynamic sequencing of high-level science goals onboard which leads to: missions being able to take advantage of unforeseen science opportunities and increasing the human data collecting productivity rather than dealing with low-level activity planning. Lessons learned in analogue environments will contribute to the overall success of planetary missions, in particular ongoing semi-autonomous rover exploration of Mars and future human lunar exploration.

Benefits of using underwater environments are also gained by selecting sites that are relevant science analogue environments as has been demonstrated with the Deep Phreatic Thermal Explorer (DEPTHX) AUV project (Krajick, 2007), the TROV project under the Ross sea ice in McMurdo Sound, Antarctica (Hine et al., 1994), or the TROV project in Mono Lake, CA (Stoker et al., 1996). Lessons learned exploring the surface waters of Earth can then be applied to further exploration of our solar system and potentially the surface waters of other lunar bodies (e.g., Europa or Enceladus). The importance of fieldwork activities in analogue environments is that they push forward the fundamental scientific understanding of planetary bodies throughout the solar system, but also provide unique opportunities to study how real-world exploration programs, including the decision-making tree of resource allocation, are conceived and carried out with multiple platforms.

This research uses *UBC-Gavia* (an autonomous underwater vehicle, AUV), Outland *Scuttle* (a remotely operated vehicle, ROV) and DeepWorker (a manned submersible) as analogues for autonomous, remotely operated and manned exploration platforms for extra-terrestrial settings (e.g., Moon, Mars, etc.), respectively. The primary campaign objective was the evaluation of integrated human–robotic operations in the context of space exploration through the use of (1) a task efficiency index (TEI), (2) performance metrics (measuring engineering success), and (3) exploration metrics (quantifying the scientific mission success). Specific lessons learned, in the domains of HRI and operator training, are presented in the context of how they contributed to mission evaluation.

2. Site description and methodology

The purpose of each evaluation method was to quantify how different platforms behave in each of the field site contexts. Every method would ideally be applied at every field deployment; however, as this work represents the composite of several working groups through three different campaigns spanning 2006–2008, evaluation techniques differed. The developed *task efficiency index (TEI)* subdivided a given objective (e.g., travel to waypoint) into a series of timed tasks allowing an across platform comparison to be conducted. Other performance metrics (e.g., operator involvement, operator risk, energy consumed, etc.) could also have been selected as a basis of comparison. *Performance metrics*, sometimes termed functional primitives (Howard and Rodriguez, 2003), were mission specific and provided a good basis of comparison between various missions using the same platform (e.g., number of waypoints achieved, trackline covered, etc.). For each selected metric, a normalized ranking from 0 to 10 was developed in order that the different terms could be statistically combined. Beyond the engineering success of a given mission (the performance metrics), the *exploration metrics* were an important tool generic enough to rank the overall scientific return of a mission. These metrics were designed to be broad enough in scope to be useful and applicable to any exploration mission, yet focused enough to make a quality analysis of the scientific merit possible. A generic scale of 1–5 was selected as demonstrated in Table 1. This scale was to be measured at three different points; (1) mission planning, (2) post-flight debriefing, and (3) post data analysis. The post-flight debriefing would allow an individual pilot to record their impressions while the post data analysis (2 years later) would allow the data to be processed by both the exploration team and the scientific community.

The primary deployment site for both the AUV and manned submersible field campaigns was Pavilion Lake, a node of the Canadian Space Agency's (CSA) Canadian Analogue Research Network (CARN) (Osinski et al., 2006). *UBC-Gavia* deployments were conducted during summer and winter field campaigns of 2007 and 2008 as part of ongoing analogue studies on organo-sedimentary structures, known as microbialites, found at this site (Laval et al., 2000) while DeepWorker missions were conducted only during the 2008 summer field campaign. Pavilion Lake is a

Table 1
List of exploration metrics used to determine quantify overall success of a mission.

Metric	Descriptor	Definition
1	Limited	Data provides limited scientific value
2	Adequate	Data reaffirms existing hypotheses and facts
3	Significant	Data elucidates existing hypotheses in new areas or detail
4	Exceptional	Data resolves a major scientific question or highly significant hypothesis
5	Discovery	Data introduces a novel idea or hypothesis