

Towards a Framework for Human Factors in Underwater Robotics

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This paper presents a study identifying the human-, robot-, task-, and environmental-related factors that impact the feasibility and usability of semi Autonomous Underwater Vehicles (sAUVs) from a human factors perspective. A multi-method approach was utilized. First, a subject matter expert (SME) interview was used to analyze video data of operators interacting with sAUVs. The results suggest considerations for the capabilities and limitations of the human and robot, in relation to the dynamic demands of the task and environment. A preliminary human factors conceptual model to depict and categorize these components was proposed. Next, a questionnaire was administered to sAUV roboticists (N=15) that assessed their perceptions related to the level of challenge associated to each of the factors identified in the model. The data suggest that all of the factors identified in our conceptual model are, in fact, challenging. In particular, our data suggest that situation awareness, communication, task complexity, visibility, and the robot's user interface were some of the most challenging variables in sAUV operation.

INTRODUCTION

Unmanned underwater vehicles (UUVs) are robots that travel underwater with or without human operator's input. In general, UUVs can be categorized as remotely operated underwater vehicles (ROVs), autonomous underwater vehicles (AUVs), and semi autonomous underwater vehicles (sAUVs). UUVs are often used for "environmental monitoring and damage assessment, security applications, oil and gas installation monitoring and repair, and pipeline inspection" (Sattar et al., 2008) and over the past decade, militaries have been increasingly using UUVs for conducting operations such as intelligence, surveillance, and reconnaissance, oceanography data collection, and most notably, mine countermeasures (Ho, Pavlovic & Arrabito, 2011)

The use of unmanned systems around the world has increased over the past three decades (Ho, Pavlovic & Arrabito, 2011). Due to a high number of operator-related mishaps on unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs), a great deal of research is focused on understanding human performance and factors towards monitoring and controlling the vehicles (Ho, Pavlovic & Arrabito, 2011). Although the use of UUVs is relatively new, the increasing use of UUVs is dramatic, and extensive human factors research on unmanned systems has not extended to UUVs. Similar to UAVs and UGVs, UUVs have the potential to help achieve different tasks, within the underwater context. Marine environments comprise the largest part of our planet, as approximately 72% of the planet's surface is ocean (Ocean, 2014). Marine environments also store much of the world's natural energy and food supply, thus the health of the marine life and environment is crucial to maintaining the well-being of the planet. Due to the vastness of marine life ecosystems, many unique challenges are presented when conducting UUV research. Human perception underwater is significantly degraded for a variety of reasons, for examples divers' vision may be compromised by lighting conditions, or tactile sensation might be impaired by the water temperature, pressure, density, and thermal protection (wet/dry suit) (Shilling, Werts, & Schandelmeier, 1976). Issues with

controlling vehicles and the displays used to monitor vehicles; situation awareness (SA) and workload issues related to controlling ROVs and monitoring multiple AUVs; trust in highly autonomous AUVs and associated subsystems; and potential limitations of human-robot communication were also discussed in Ho, Pavlovic, and Arrabito (2011). Within the complex underwater environment context, underwater exploration is a difficult and potentially life threatening operation for researchers (Girdhar, Giguère, & Dudek, 2013). UUVs have the possibility to help overcome some of these challenges. Thus, some UUVs have been developed by researchers to have the capability to help achieve certain tasks.

In this study, we focus on a sAUV of the AQUA family (Dudek et al., 2007) on which the onsite operator uses a specific gesture/visual language called "Robochar" to control the underwater robot to achieve a specific task (Dudek, Sattar, & Xu, 2007) (e.g. to drive a square path or move straightforward). The onsite operator uses visual cues: tags with fiducial markers to operate the sAUV (Dudek, Sattar, & Xu, 2007; Meger et al., 2014).

A better and deeper understanding on UUVs from a human factors perspective is a critical component and will warrant further study. Within the underwater environment scenario, the interaction between human, robot, task, and environment is highly constrained, and the quality or even the success of the interaction may be influenced by many factors. It will be a beneficial approach to understanding sAUV interaction between those four components (human, robot, task and environment) from a human factors perspective. Our approach will consider the capabilities and limitations of the person and robot, in relation to the task demands and the complexity of the operational environment.

Goals of Research

The purpose of this research is to identify the human-, robot- task-, and environment-related variables important to consider in sAUV deployment. Our goal is to propose a preliminary conceptual framework of these variables, and confirm with sAUV roboticists the level of challenge each

variable poses. We use a multi-method approach involving subject matter experts and roboticists of varying experience in a think aloud protocol and questionnaire methodology. Identification of variables that impact sAUV deployment will provide insight to future research directions and robot design improvements.



Figure 1. A diver controlling the robot using a cue-card

METHOD

We used a two-part approach to understanding human factors and underwater robotics. First we involved a subject matter expert in the development of a preliminary conceptual model (Wu et al., 2015). Next we administered questionnaires to sAUV roboticists to confirm whether the variables in our model are in fact challenging aspects of sAUV deployment. The questionnaires also provide insight as to which variables are perceived as the most challenging.

Part 1: Subject Matter Expert Interview

First we analyzed video footage of operators using sUAVs in field experiments. The videos were recorded between 2010 and 2013 (Girdhar, Giguère & Dudek, 2013; Shkurti et al., 2011). Twenty-five videos were analyzed; on average, each video was about 60 seconds in duration. A sAUV subject matter expert (SME) described each video scenario using a think-aloud protocol. Specifically, we asked the SME to (1) describe the task depicted in the video and (2) discuss any challenges he perceived. The SME's think-aloud was audio recorded. Three human factors researchers were present during the think-aloud video session, and noted observed challenges individually. A challenge was coded as related to the human, robot, task, or environment. For example, if the SME discussed buoyancy challenges related to surge, this was coded as "environment, external disturbance." The discussion was semi-structured, allowing the researchers to ask for clarification or follow up questions. The think-aloud video session lasted approximately 2 hours.

After the think-aloud session, the three researchers reviewed their individual notes to refine their identified variables, and begin to organize and categorize the variables into four

categories: human, environment, robot, and task. The researchers collaboratively compared their notes and categorizations. Discrepancies were discussed, and a final categorization of variables was determined. This collaborative analysis took place for over 2 hours, until consensus was met. The final categorization, displayed as a conceptual model, is depicted in Figure 2. The interaction between these variables was also recorded, and outlined in the results section below.

Part 2: Questionnaires with sAUV Roboticists

Participants. Fifteen uAUV roboticists (14 male, 1 female) completed the questionnaire. The participants ranged in age from 24 to 56 ($M = 37$, $SD = 10.12$). Participants reported typically having 2-6 years of experience in robotics (range 1-10+). The operational environment varied, with 9 participants reported using the robot in the ocean (3 warm coastal, 5 cold coastal, 1 open ocean), 4 in lakes and fresh water, and 2 reported other (one reported laboratory testing, one reported all environments).

Not all participants necessarily had experience with the same sUAV platform or user interface. Some participant reported using primarily a tethered GUI operation ($n=4$), programming language ($n=5$), tag UIs ($n=4$), tablet UIs ($n=1$) and other ($n=1$, reported 'all forms of interaction').

Procedure. An underwater robotics HRI questionnaire was administered to operators of sUAVs. The questionnaire was distributed through the mailing lists 'robotics worldwide' and 'euRobotics', and academic robotic departments. The questionnaire was split into sections. The first section included questions related to demographics. Following the demographic questions was a section designed to assess the level of challenge the operators experience while using an underwater robot. The questions were organized by category (human, robot, task, and environment), and within each category, each factor identified by the findings in Part 1 of the study was listed (e.g., under the "environment" category, variables included depth, obstacles, water temperature, etc.). For each factor, participants rated their perception of challenge on a 1-5 scale, with: 1 = not challenging, 2 = a little challenging, 3 = somewhat challenging, 4 = quite challenging, and 5 = extremely challenging, respectively. Part three of the questionnaire included the standardized system usability scale (SUS) and three open-ended questions asking their recommendations to improve commanding or controlling UUVs. In this study, we only focus on results from part one and part two of the questionnaire.

RESULTS

Part 1: Results from Subject Matter Expert Interview

A conceptual model is presented in Figure 2. The model categorizes four components of the system: human, robot, task, and environment identified in the SME think aloud review of field trial video footage.

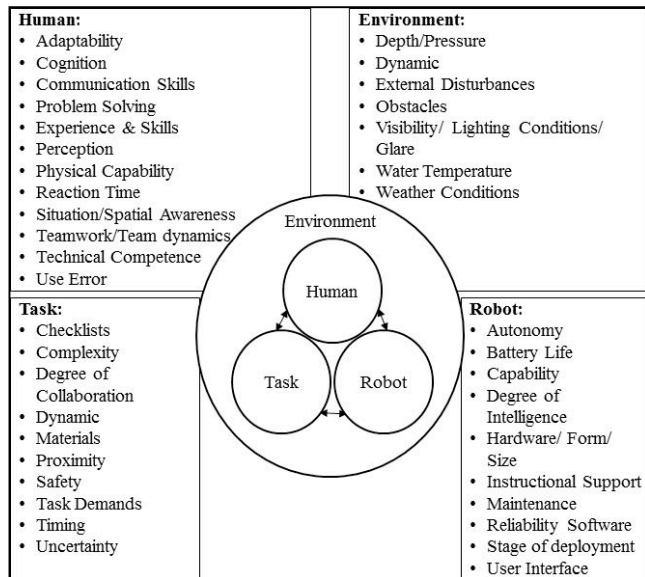


Figure 2. Human factors model for the sAUV HRI

Human. Based on the videos, primary human interacting with the sAUV is the operator. The operator has a large number of capabilities and limitations relevant to using the sAUV, ranging from adaptability to technical competence. During each interaction the operator must not only maintain an awareness of the ocean environment, but must also maintain a relatively stable position. Novice scuba divers found stabilization difficult, and thus negatively affected their efficiency in providing commands to the robot. The operator had to also communicate with the surrounding divers as a team, primarily relying on hand gestures.

The SME described several physical/cognitive challenges to diving, such as the “Martini effect” (described as cognitive impairment equivalent to 1 martini per 10 meters of depth), the ability to maintain proper body temperature, and fatigue from diving for long periods of time. The SME made clear that the identified challenges discussed above occur simultaneously. The operator had to constantly use/interact with the robot, adapt to changing environmental conditions, and interact/communicate with other divers. The above described multitask scenario likely places working memory demands on the operator.

Robot. The robot depicted in the video data was an Aqua2 vehicle, however there are many different types and brands of sAUVs. The hardware/software capabilities and the level of autonomy of each sAUV will impact the nature of the HRI.

In the current research, this particular robot reads tags with a fiducial marker, and displays menu options on a small interface. The small screen real estate limited the amount of output that could be displayed on the menu interface, creating a deep navigation hierarchy. Although tedious, the method appeared to be successful, and the developers were able to create a menu system utilizing four different tags.

Sometimes if an error occurred the divers needed to respond adaptively and physically intervene to stop the robot from colliding with the seafloor, or from moving in the wrong direction. When a proper command was given, the robot

autonomously moved through the environment and collected visual, depth, and inertial data. The operator then switched to a supervisory role.

Task. Before the dive, the SME indicated that operators needed to ensure that the equipment was well prepared, and did this typically through the use of maintenance checklists. While diving, the method of input was via the fiducial marker tags.

The operator had to physically hold/stabilize the sAUV while scanning each tag. Scanning each tag via the robot’s rear camera would activate a menu system. The diver needed to manipulate the markers, held together on a ring, to choose different tags for different commands. Close proximity to the robot was important during all aspects of the task: providing input, monitoring the robot’s behavior, and ensuring not to lose the robot under low visibility environmental conditions.

Environment. The coral reef environment studied in the videos was dynamic. Surge and current caused the diver and robot to drift. Many obstacles in the environment, such as coral, marine life, or shipwrecks/debris, were dangerous for the divers. Interaction with these obstacles also affected the robot’s operation and task completion, because robot/human collision with delicate coral, uneven ocean floor, or marine life would be damaging to the well-being of the reef.

Weather was also reported as a challenging factor; storms or thunder would prevent the research from occurring. Finally, visibility was also a major variable of SME discussion. Light would reflect off the tags, making scanning difficult. The divers disturbing ocean floor sand, or darkness due to depth also affected visibility.

Part 2: Results from Questionnaires

Next we administered a questionnaire to sAUV roboticists. When asked to rate the level of challenge related to sAUV operation (on a 5 point scale), descriptive statistics showed that all medians were 3.0 or 4.0, and all means were 2.6 or higher, validating that the factors identified in the conceptual model are, in fact, challenging.

We grouped the 40 variables into general categories: human, robot, task, and environment. The categories were mutually exclusive, such that each variable could be in only one category. Figure 3 contains the mean rating (on scale of 1 to 5) for perceived challenge of the 40 variables. Within each category, the variables are depicted ordered from greatest mean rating to least mean rating. In other words, they are listed from top to bottom, within each category, from most challenging to least challenging.

To determine if participants had a significant perception of challenge for each variable, we performed one-sample Wilcoxon sign-rank tests to compare each variable median against 3.00, where 3.00 = “somewhat challenging.” See Table 1 for the variables that participants significantly perceived as challenging compared to 3.00. Thirteen variables, out of 40, were significant at the $p < 0.05$ level (after controlling for Type 1 error using a Bonferroni correction, no variables were significant at the $p < .001$ level).

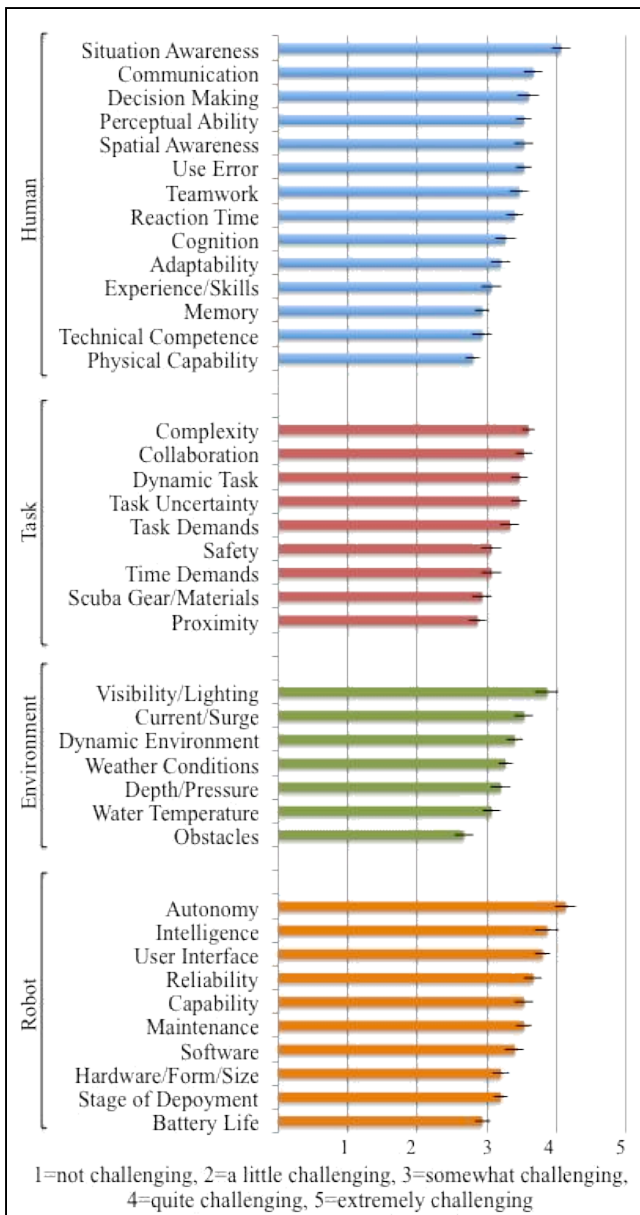


Figure 3. Mean challenge ratings.

The data in Figure 3 and Table 1 reveal a number of interesting trends. Under the human category, situation awareness was rated as the most challenging variable in sAUV operation.

Situation awareness is the human's ability to identify, process, and comprehend what is happening around you. In this context SA may include an awareness of other divers, the robots' performance and status, environmental changes, and the dynamic task. Coupled with potential failures of the robot (robot reliability being identified as a challenging variables), SA is a great consideration for completing a task.

Variables related to collaboration between humans, and between the humans and robot, are evident. Communication was rated as challenging, as well as collaborative tasks that require both human and robot input.

Table 1. Median compared to 3.0 = "somewhat challenging"

Factor	M	SD	Mdn	Range	z	p
Human						
Situation Awareness	4.07	1.03	4.0	2-5	-2.81	.005
Communication	3.67	1.18	4.0	2-5	-2.06	.040
Decision Making	3.60	0.69	4.0	2-5	-2.32	.021
Use Error	3.53	0.74	4.0	3-5	-2.31	.021
Task						
Complexity	3.60	0.74	3.0	3-5	-2.46	.014
Collaboration	3.53	0.92	4.0	2-5	-2.00	.046
Environment						
Visibility	3.87	0.99	4.0	1-5	-2.48	.013
Current/Surge	3.53	0.92	4.0	2-5	-2.00	.046
Robot						
Autonomy	4.13	1.06	4.0	1-5	-2.68	.007
Intelligence	3.87	0.99	4.0	2-5	-2.57	.010
User Interface	3.80	0.87	4.0	2-5	-2.65	.008
Reliability	3.67	1.05	4.0	2-5	-2.15	.031
Capability	3.53	0.84	4.0	2-5	-2.00	.046

Note: M = participants' mean challenge rating on a 5-point scale (1 = not challenging, 3 = somewhat challenging, 5 = extremely challenging). SD = standard deviation of ratings. Mdn = participants' median rating. Range = the minimum and maximum responses. p = probability of type 1 error for a one-sample Wilcoxon sign-rank test comparing each factor median to 'somewhat challenging' (= 3)

Autonomy was identified as a challenging robot-related variable. Based on our SME interview (Part 1) this is likely due to a couple factors. First, the respondents were roboticists, thus the challenge rating may be due to the difficulty in programming/developing a semi autonomous robot. Second, given the high difficulty rating for SA, autonomy may increase the likelihood of "operator out of the loop" creating uncertainty in predicting robot behavior and increasing the dynamic nature of the task.

The user interface (M=3.80) was identified as challenging. This was primarily driven by "quite challenging" and "extremely challenging" responses related to the Tethered GUI interface, and the tag user interface specifically. These are two interfaces available for sAUVs that require the user to command the robot through a series of steps. During tethered operations, the user was located remotely on a boat and viewed the UI via a laptop screen, which provided views from the UUV's cameras and information about the status of the vehicle. When operating from a surface vessel, intense focus on the screen can induce nausea. During untethered operations, however, a diver presents a sequence of markers in response to menu option on a small display located on the robot. Both command options require a considerable amount of mental workload.

DISCUSSION

This study is an initial step in gaining an understanding of the human-, robot-, task-, and environmental-related factors that impact the feasibility and usability of semi Autonomous Underwater Vehicles (sAUVs) human-robot interaction (HRI). This was achieved in a two-part methodology. First, we interviewed a subject matter expert using a think aloud protocol during a review of videos from field trials. The goals were to identify variables that impact the sAUV HRI. These variables were categorized into a preliminary conceptual model (Figure 2). Next, we administered a questionnaire to sAUV roboticists to rate the level of challenge for each variable identified in the conceptual model. The data suggest that variables such as situation awareness, communication, task complexity, visibility, robot autonomy/intelligence, and the user interface were some of the most challenging variables. By identifying these challenges, we lay a foundation to begin to consider human factors interventions to potentially increase safety, efficiency, and performance of sAUV operations.

There are a few considerations regarding the scope of this study. First, our sample size was low ($n=15$). This is due, in part, to the small community of underwater roboticists. Second, the conceptual model was based on review of video footage. Actual field observations will likely reveal additional variables regarding equipment setup, collaboration between team members (both underwater and on the boat), time constraints, and so on. Lastly, our conceptual model currently functions like a framework by simply listing the challenging variables associated with sAUV deployment. The model does not detail interaction between these variables, and this would be a much needed future step. If relationships could be identified between variables, the model could potentially inform the development of predictive models and more intelligent sAUVs that can adapt to the humans' changes in SA or workload. Future work can aim to eliminate some of these identified challenges to optimize existing systems so that divers and sAUVs can safely research marine life and coral reef environments.

In summary, we identified a number of challenges associated with underwater robotics. This initial investigation is an important first step in better understanding the unique challenges of underwater robotics from a human factors perspective.

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