Human–Robot Interaction Underwater: Communication and Safety Requirements

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***Abstract*—Safety is of particular interest when performing research related to human–robot interaction in unpredictable and hazardous underwater environment. Special attention is devoted to safety requirements within FP7 project "CADDY - Cognitive Autonomous Diving Buddy" in order to reduce hazards during experiments, since divers relying on technology for life support are exposed to additional risk of trauma as a consequence of impact with a marine vehicle.**

This paper focuses on the risk assessment of human–robot interaction in the underwater environment within the scope of CADDY project. Each vehicle comprising the CADDY fleet is analyzed for a number of risks, and an overall assessment is provided showing the appropriateness of selected vehicles for the application. Also, the acoustic communication scheme used in the project is described, as a means of efficient and robust navigation data exchange for the purpose of minimizing the risk of trauma due to unwanted contact between the vehicles and the diver.

I. Introduction

The study of symbiosis between humans and robots in the underwater environment merges numerous open challenges related to human–robot interaction, marine robotics, acoustic communications, and other research areas. Underwater environment is in its nature challenging due to unpredictable disturbances and lack of conventional communication and navigation sources. Placing a human in such harsh environment can lead to catastrophic consequences as a result of technical malfunction, or lack of attention.

To overcome these problems, FP7 project "CADDY – Cognitive Autonomous Diving Buddy" aims to establish an innovative set-up between a diver and companion autonomous robots (underwater and surface) that exhibit cognitive behaviour through learning, interpreting, and adapting to the divers behaviour, physical state, and actions, [1]. The CADDY concept, shown in Fig. 1, envisions a multicomponent system consisting of a surface segment, an underwater segment and the interface for the diver that allows the diver to communicate with both segments. The vehicle in the surface segment plays the role of a "private satellite" for the underwater part of the system – it provides global navigation information and acts as a router to the surface command centre. The vehicle in the underwater segment has to keep close to the diver, at a safe distance, in order to monitor, guide and assist the diver.

This challenging scenario cannot be tackled without defining a set of safety requirements. A large number of hazards can occur while performing experiments, from hazards related to malfunction of diver equipment to those that are a consequence of direct impact between the robots and the divers. In relation to the latter, special attention needs to be devoted to underwater communication and navigation requirements in order to minimize the risk of impact, or even unexpected contact between the diver and the robots.

This paper focusses on two segments that are a prerequisite for successful human–robot interaction in the underwater environment. First we address the issue of underwater communication and navigation scheme that is required to achieve reliable exchange of information between the three agents in the CADDY system. Propagated scarce navigation information is then used in distributed navigational filters on each vehicle in order to ensure safe operating distance and prevent possible trauma. Second, we deal with risk assessment of the overall system. Each vehicle is graded relative to significant risks, and an overall risk assessment is provided for each vehicle based on which the vehicles are graded as safe or unsafe for interaction with divers.

The paper is organized as follows. Section II briefly describes the vehicles that are used in the CADDY project while Section III describes the communication scheme that was devised and implemented for the purpose of communication (and navigation data exchange) between the three nodes (ASV, AUV and the diver). Section IV lists all the safety risks that are identified in the CADDY project, and provides thorough assessment taking into account all the involved vehicles. Risk mitigation strategy is employed and resulting risks are described. The paper is concluded with Section VI.

II. The CADDY fleet of autonomous vehicles

The CADDY fleet consists of the surface segment (autonomous surface vehicles) that includes $MEDUSA_S$ ("S" as index stands for "surface") as a primary vehicle, and *PlaDyPos* as a backup vehicle, while the underwater segment

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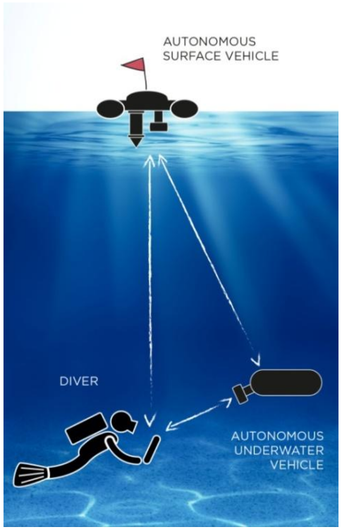


Figure 1: The CADDY concept.

(autonomous underwater vehicles) includes *BUDDY* AUV as the primary vehicle and *R2* as the backup vehicle.

The $MEDUSA_S$ vehicle, shown in Fig. 2a is a light, streamlined vehicle with 2 thrusters, 1035 mm long, and weighing 23-30 kg, capable of reaching speeds up to 1.5 m/s. The autonomous surface vehicle *PlaDyPos* shown in Fig. 2b is an omnidirectional autonomous vessel with 4 thrusters in X configuration 0.7 x 0.7 m, weighing around 30 kg, [2].

BUDDY AUV (shown in Fig. 2c) is the first autonomous underwater vehicle specifically designed for interaction with divers and was built specially for CADDY purposes, [3]. *BUDDY* is mounted with an underwater tablet as a means of interaction with the diver. *R2* (shown in Fig. 2d) is a fully actuated underwater robotic platform, rated up to a depth of 500 m. The redundant allocation of 4 horizontal and 4 vertical thrusters allows the vehicle to a complete motion capability as well as the hovering skill.

The third agent in the CADDY structure is the diver that communicates with the vehicles using a tablet in a waterproof housing. The tablet is connected to the diver–mounted acoustic modem via Bluetooth connection which has proven to work underwater at short distances.

III. Communication scheme in human–diver interaction

Reliable acoustic communication and navigation data transmission is a prerequisite for safe human–robot interaction. This section describes the designed and implemented acoustic interrogation scheme between the agents, that is achieved through SeaTrac USBL/modems developed within the CADDY project. It should be mentioned that the FP7 project MORPH also deals with an acoustic interrogation scheme among multiple underwater and surface vehicles [4], however they do not include a human diver.

The interrogation cycle, shown in Fig. 3, consist of active transmissions (*AT*) and passive receptions (PT). Passive

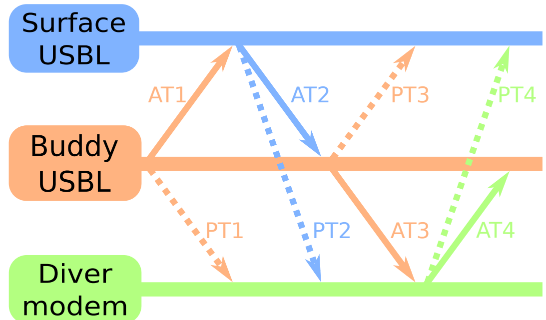


Figure 3: The acoustic interrogation cycle.

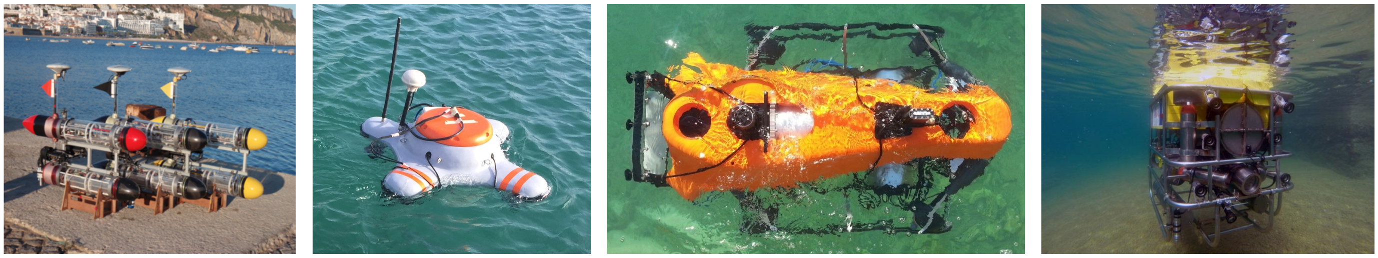
receptions are defined as acoustic messages which are not addressed to the receiving modem. The interrogation cycle is guided by *BUDDY* which initiates the ultra-short baseline (USBL) transmissions *AT1* and *AT3*. These are followed by *AT2* and *AT4* as USBL replies.

The diver and surface never independently initiate communication. The interrogation cycle where both *BUDDY* and surface USBLs would interchangeably interrogate remaining agents showed to be less robust in terms of data delay, cycle time and reception failures. Therefore, the main interrogation scheme utilizes only the *BUDDY* vehicle with the ability to hand-off interrogation to the surface USBL.

Each USBL interrogation request and reply contain fixed and variable data payloads with maximum payload never exceeding 72 bits. This makes for 36 bytes data exchange per cycle. Fixed payload encompasses navigation data, required for complete situation awareness, and main status/command bits. The variable data includes non-crucial status data, message exchange and command payloads.

Situational awareness is achieved by sharing navigation data among agents. Starting with *AT1* the *BUDDY* position, speed, course and *BUDDY* measured diver position are transmitted. The diver receives the same data over *PT1*. Positions are defined within a moving operating box that is limited to 100×100 area. In *AT2* the current surface position, speed and course are sent to *BUDDY*. With the *AT1-AT2* USBL interrogation all agent position data are shared. The absolute position of *BUDDY* is calculated using the USBL localization in combination with surface position. In worst case scenario this transmission takes around $3\,s$ with current speed of $100\,bps$. The data transmission actually takes up to $1.5\,s$ while the rest is attributed to the ping processing and acoustic payload overhead specific to the device.

The second data exchange shown in Fig. 3, *AT3-AT4*, is performed using similar payloads. The diver returns only torso heading and depth. The diver position is estimated on the diver tablet using the diver position updates. When *BUDDY* is far from the diver it can only use the USBL information to estimate the coarse diver position. However, close to the diver the forward looking multi-beam sonar allows fast and precise relative position measurements. The diver reply in *PT4* can be used by the surface to estimate relative bearing and



(a) MEDUSA$_S$ by IST (b) PlaDyPos by UNIZG-FER (c) BUDDY by UNIZG-FER (d) R2 by CNR

Figure 2: CADDY fleet of autonomous surface vehicles.

elevation of the diver to improve the coarse diver estimate. The transmission takes $3\,s$, in the worst case scenario, making the cycle time up to $6\,s$. Note that transmission of navigation data only actually takes $2\,s$ less per cycle leaving around 25 bytes for other variable data payload.

IV. Hazard identification

Hazards have to be identified in order to perform a qualitative evaluation of their significance and the measures for reducing risks. The main hazard that appears in the context of diving, is the hazard related to the fact that the human body is immersed in water. When introducing robotic vehicles, the following hazards appear as a result of human–robot interaction:

Trauma Considering the payload and the speed of an AUV interacting with a human diver, AUVs involved in the CADDY project are less likely to cause any lethal trauma by direct collision except when the collision area is the face or caused by a direct hit of the propeller.

Electrical shock The hazards of the use of electricity underwater are described in detail in the *Code of Practice for The Safe Use of Electricity Under Water*, [5]. The primary intent of the Code is to reduce electric shock.

Acoustical trauma Divers exposed to high levels of underwater sound can suffer from dizziness, hearing damage or other injuries to other sensitive organs, depending on the frequency and intensity of the sound. This may include neurological symptoms such as blurred vision, light-headedness, vibratory sensations in hands, arms and legs, and tremors in upper extremities, [6]. [7].

Electromagnetic hazards Salt water is a very good filter for electromagnetic waves, however, there is still a potential hazard while using laser-based technologies underwater. Also, some diver equipment are reported to fail when subjected to high EM fields, such as the wireless air integration units.

Psychological problems The existence of the AUV in the vicinity of the diver may impose a threat, thus reducing work efficiency and diminishing attention span of the divers. This can be overcome to a great extent over the time by habituation.

V. Formal risk assessment

A formal risk assessment needs to be carried out before any AUV operation involving divers. A simplified risk assessment has been proposed for the CADDY project. The first step is the description of hazards, as referred to in the previous section. The second step is to calculate the associated risks, usually as a product of probability of an event P, exposure to a hazard E and consequence C as it is shown in Table Ia. The resulting associated risk can be quantified as in Table Ib. The final step includes actions to mitigate the risks by taking the following measures: *(1)* isolate at source using engineering or technical means, *(2)* attempt to prevent exposure through administrative means (procedures or training), *(3)* protect people or equipment through personal protective equipment, and finally *(4)* monitor that taken measures are effective either by measuring incidents and near misses, or by monitoring the unsafe environment.

The risk assessment within the CADDY project has been performed based on previously described quantification using the following hazards of man–machine interaction: trauma, electrical shock, acoustical trauma, and electromagnetic hazards. The tables provided in the continuing part include both the risks at the start of the project and the risks with risk mitigation actions (shown in green).

A. Risk assessment on Trauma

Table IIa shows the risk assessment on trauma for the vehicles used in the CADDY project, both before and after (in green) risk mitigation actions were taken. The probability of trauma P for surface vehicles is *unlikely* (grade 1) since collision may only occur before or after diving especially during an unexpected emergency ascent swimming, while for AUVs it is *possible* (grade 3) during validation trials. The exposure to trauma E for surface vehicles is assumed to be at the level of *occasional* when compared to workplace equivalents once per week (grade 3), while for AUVs it is assumed *continuous* (grade 5). The consequence of the trauma C is a function of the number of propeller, power of each propeller and the momentum of each vehicle computed at maximum velocity and the form factor of the vehicle.

Risk mitigation Several risk mitigation techniques were used for decreasing the trauma risk after the initial assessment

Table I: Formal risk assessment

(a) Probability, Exposure and Consequence

Probability (P)	Exposure (E)	Consequence (C)	Value
unlikely	rare (1/year)	noticeable (1st aid)	1
unusual	unusual ($\approx$ 1/month)	significant (minor damage)	2
possible	occasional ($\approx$ 1/week)	serious (disruption)	3
expected	frequent ($\approx$ 1/day)	severe (close)	4
definite	continuous	catastrophic (fatal)	5

(b) Associated risk

Risk = P x E x C	Level	Description
100	1	Extreme danger
50 - 100	2	Very high: Stop use
20 - 50	3	High: Urgent attention
5 - 20	4	Medium: Attention needed
5	5	Low: acceptable risk

Table II: Risk assessment

(a) On trauma

Vehicle	P	E	C	Score	Risk
$MEDUSA_S$	1	$3 \rightarrow 1$	$3 \rightarrow 2$	$9 \rightarrow 2$	Med → **Low**
PlaDyPos	1	$3 \rightarrow 1$	$2 \rightarrow 1$	$6 \rightarrow 1$	Med → **Low**
BUDDY	$3 \rightarrow 2$	$5 \rightarrow 4$	$4 \rightarrow 1$	$60 \rightarrow 8$	Very h. → **Med**
R2	3	$5 \rightarrow 4$	$2 \rightarrow 1$	$30 \rightarrow 12$	High → **Med**

(b) On electrical shock

Vehicle	P	E	C	Score	Risk
$MEDUSA_S$	1	5	$2 \rightarrow 1$	$10 \rightarrow 5$	Med → **Low**
PlaDyPos	1	5	$2 \rightarrow 1$	$10 \rightarrow 5$	Med → **Low**
BUDDY	1	3	$2 \rightarrow 1$	$6 \rightarrow 3$	Med → **Low**
R2	1	3	$2 \rightarrow 1$	$6 \rightarrow 3$	Med → **Low**

(c) On acoustical trauma

Vehicle	P	E	C	Score	Risk
All	1	5	1	5	Low

(d) On EM hazards

Vehicle	P	E	C	Score	Risk
$MEDUSA_S$	1	5	1	5	Low
PlaDyPos	1	5	1	5	Low
BUDDY	1	3	1	3	Low
R2	1	3	1	3	Low

of the risk. These decreased values are shown in green in Table IIa.

The design of the BUDDY vehicle was changed to add propeller guards, making the form factor safer. The speed of the vehicle was reduced to maximum value of 1 knot. As a consequence, the weight of the vehicle reached 50 kg. Overall, the consequence grade C was reduced from 3 to 2. The use of the kill switches decreased the probability of an accident P from 3 to 2.

There are several changes in the diving procedures that reduced the exposure to collision E as well as the consequences C significantly. The use of redundant protected SCUBA, well trained first response team, the use of continuous stand-by rescue diver and personal protection like helmets, reduced the consequence of the collision C by 1 grade for all vehicles. Additionally, the use of through water communication system with full face masks reduced the exposure to ASV to the minimum grade 1, and decreased the AUV exposure by one grade. All procedural changes required training and exercises to rehearse the related skills.

B. Risk assessment on Electrical Shock

Table IIb shows the risk assessment on electrical shock for the vehicles used in the CADDY project. The probability to have an electrical shock P is *unlikely* (grade 1) for all vehicles. The exposure E for surface vehicles is assumed to be at the level of *occasional* when compared to workplace equivalents once per week (grade 3); whereas, for AUVs it is *continuous* (grade 5). The consequence C was assumed to be as low as possible (grade 1) since the *Code of Practice for The Safe Use of Electricity Under Water* [5] states that provided the voltage of any item that the diver may come in contact with is less than a safe level, the work may be carried out in safety. Voltage on all vehicles is safe voltage.

C. Risk assessment on Acoustical Trauma

Table IIc shows the risk assessment on acoustical trauma for the vehicles used in the CADDY project. Note that the probability is taken as the probability of being subjected to a trauma causing acoustical emission (unlikely). The risk assessment shows acceptable levels of acoustical trauma. In order to fully eliminate any acoustical issues, optical communication can be considered for low range communication, [8].

D. Risk assessment on EM hazards

Table IId shows the risk assessment on electromagnetic hazard for the vehicles used in the CADDY project. Risks for all vehicles are within the acceptable level.

VI. Conclusion

The work presented in this paper deals mostly with safety issues and requirements related to human–robot interaction in the underwater environment. Risk assessment has been performed on vehicles that are used within the scope of the CADDY project. Initial assessment has shown that some vehicles have high risk of trauma and medium risk of electrical shock. Since the goal is to reduce the risk to a minimum, risk mitigation measures were taken, resulting in significantly lower risk levels for all the vehicles used in experiments.

In order to guarantee safety during experiment, navigation data has to be transmitted efficiently between all agents in the multicomponent CADDY system. For this purpose, a reliable acoustic interrogation scheme has been designed and integrated in the system. The scheme ensures data propagation cycle in the duration not longer than 6 s. The cycle duration is highly dependant on the state-of-the-art acoustic communication equipment and leads to the conclusion that efficient navigation filters need to be implemented on each vehicle.

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