PAPER

CADDY—Cognitive Autonomous Diving Buddy: Two Years of Underwater Human-Robot Interaction

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ABSTRACT

Divers operate in harsh and poorly monitored environments, in which the slightest unexpected disturbance, technical malfunction, or lack of attention can have catastrophic consequences. Motivated by these considerations, the "CADDY—Cognitive Autonomous Diving Buddy" FP7 project sets forth the main goal of developing a cooperative autonomous underwater robotic system to monitor and assist human divers, thus affording them increased levels of safety during the execution of challenging scientific and commercial missions. This article presents the main results obtained in the first 2 years of the project along the following main research topics: *Seeing the Diver*, where the focus is placed on the 3D reconstruction of a diver's model (pose estimation and recognition of hand gestures) through remote and local sensing technologies, thus enabling behavior interpretation; *Understanding the Diver*, with the objective of interpreting the model and physiological measurements of the diver in order to determine the state of the diver; and *Diver-Robot Cooperation and Control*, aimed at investigating the interaction of the diver with underwater vehicles endowed with rich sensory motor skills, focusing on cooperative control and optimal formation with the diver as an integral part of the overall vehicle-diver formation.

Keywords: cognitive robotics, marine robotics, human-robot interaction

Introduction

The CADDY (Cognitive Autonomous Diving Buddy) project started in January 2014 and is currently in its third and final year of execution. A consortium of seven partners (included in the list of author affiliations) was brought together to undertake research and development (R&D) work leading to the first cognitive robotic system capable of interacting with humans in the underwater environment. The main motivation for the project lies in the fact that divers operate in harsh and poorly monitored environments in which the slightest unexpected disturbance, technical malfunction, or lack of attention may have catastrophic consequences. They maneuver in complex 3D environments and carry bulky and therefore cumbersome equipment while performing their missions. To overcome these problems, CADDY set forth the goal of establishing an innovative setup between a diver and companion autonomous robots (underwater and at the surface) that exhibits cognitive behavior through learning, interpreting, and adapting to the diver's behavior, physical state, and actions.

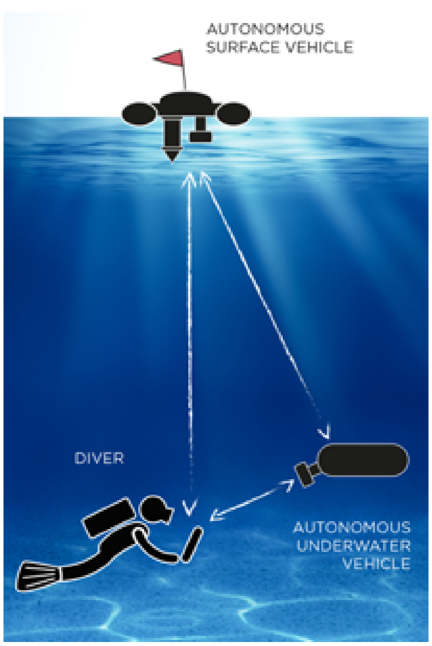
In the CADDY project, a human buddy diver is replaced with an autonomous underwater vehicle, while an autonomous surface vehicle is brought in to improve monitoring, assistance, and safety of the diver's mission, as depicted in Figure 1. The resulting system plays a threefold role similar to that of a regular human buddy diver: (a) the buddy "observer" that continuously monitors the diver; (b) the buddy "slave" that is the diver's "extended hand" during underwater operations, performing tasks such as "do a mosaic of that area," "take a photo of that," or "illuminate that"; and (c) the buddy "guide" that leads the diver through the underwater environment.

The envisioned threefold functionality is realized through scientific and technical objectives that have been set up for the project lifetime:

1. Develop a cooperative multicomponent system capable of interacting with a diver in unpredictable situations and supporting cognitive reactivity to nondeterministic actions in the underwater environment.
2. Establish a robust and flexible underwater sensing network with reliable data distribution and sensors capable of estimating the diver's pose and hand gestures.
3. Achieve full understanding of the diver's behavior through the interpretation of both conscious (symbolic hand gestures) and unconscious (pose, physiological indicators) nonverbal communication cues.
4. Define and implement the execution of cognitive guidance and control algorithms through cooperative formations and maneuvers in order to ensure diver monitoring, uninterrupted mission progress, execution of compliant cognitive actions, and human-machine interaction.
5. Develop a cognitive mission (re) planner that relies on the interpretation of diver gestures that, put together, play the role of complex words through which relevant information can be conveyed.

FIGURE 1

CADDY concept.



In order to achieve these objectives, three core research themes are identified: the "Seeing the Diver" research theme focuses on 3D reconstruction of the diver's model (pose estimation and recognition of hand gestures) through remote and local sensing technologies, thus enabling behavior interpretation; the "Understanding the Diver" theme focuses on adaptive interpretation of the model and physiological measurements of the diver in order to determine the state of the diver; and the "Diver-Robot Cooperation and Control" theme is the link that enables diver interaction with underwater vehicles with rich sensory motor skills, focusing on cooperative control and optimal formation keeping with the diver, as an integral part of the overall vehicle-diver formation.

This article is devoted to reporting the main achievements within these three research topics in the second year of the project. The central event of Year 2 of the project was the validation trials that took place in Biograd na Moru, Croatia, in October 2015. A detailed list of achievements during the first year of the project can be found in Mišković et al. (2015).

Further information on the CADDY project progress can be found on the website http://caddy-fp7.eu/, and live reports from experiments are available on our Facebook page https://www.facebook.com/caddyproject.

The article is organized as follows. The Development of the CADDY Multicomponent System section describes the development of the multicomponent robotic system foreseen in the scope of the CADDY project, while the Seeing the Diver: Remote Sensing and the DiverNet, Understanding the Diver, and Diver-Robot Cooperation and Control sections are devoted to the main results within the three core research themes, "Seeing the Diver," "Understanding the Diver," and "Diver-Robot Cooperation and Control." Each section gives a short overview of the state of the art in the area.

Development of the CADDY Multicomponent System

A large number of both surface and underwater autonomous marine vehicles are being used by industry and research institutions for operations such as underwater mapping and surveillance and, more recently, for underwater intervention tasks that involve robotic manipulation. The list of available vehicles is not given here for the sake of brevity. However, none of the existing vehicles are designed and developed for an interaction with divers, taking into account specific design requirements such as interfaces for diver interaction and safety issues.

This chapter describes the vehicles and technologies that comprise the CADDY multirobot system, designed to interact with the diver.

The primary surface vehicle used in CADDY experiments is MEDUSA$_S$ (Figure 2(a)), a light, streamlined vehicle with two thrusters, 1,035 mm long and weighing 23–30 kg. The backup surface vehicle is PlaDyPos (Figure 2 (b); Nađ et al., 2015), an omnidirectional autonomous vessel with four thrusters in an X configuration, 0.7 × 0.7 m and weighing around 30 kg. In the underwater segment, the primary underwater vehicle is BUDDY (Figure 2(c)), an autonomous underwater vehicle (AUV) built specially for the CADDY project (Stilinović et al., 2015). BUDDY is equipped with an underwater tablet that allows for interaction with the diver. In addition, it is equipped with a stereo camera, a monocular camera, and a multibeam sonar, all used for "Seeing the Diver" tasks. The backup underwater vehicles is e-URoPe (Figure 2(d)), a fully actuated underwater robotic platform with four horizontal and four vertical thrusters, 1.3 (length) × 0.9 (width) × 1.0 (height) m, rated to a depth of 200 m.

The third agent in the CADDY system is the diver. In order to allow for the interaction between robotic vehicles and the diver, a commercially available tablet enclosed in a waterproof housing and fully operational underwater is used as an interface. The android application developed in CADDY that runs on the tablet shows the diver position in the underwater environment and enables messaging with the surface while the diver is underwater.

Novel miniaturized USBL devices and underwater modems (with dimensions of 160 mm in height and 55 mm in diameter) were developed in the scope of the project for accurate positioning of the underwater segment of CADDY and to enable acoustic communications among the different CADDY components, respectively. In addition to highly reliable spread spectrum-based communication techniques, algorithms were also developed to simultaneously obtain accurate and repeatable positioning information from a USBL array transducer with an element spacing of only 20 mm (Figure 3; Neasham et al., 2015). The hardware platform is based on a powerful and flexible ARM processor device, providing a software upgrade path for higher data rates and improvements in positioning. This USBL will be used for conventional underwater navigation while performing field tests. The unit will also be used to acquire ground truth data against which to gage the performance of single-range-based localization schemes (see the section on Maximizing System

FIGURE 2

Marine robots used in the scope of the CADDY project.

(a) MEDUSA$_S$ (IST)
(b) PlaDyPos (UNIZG-FER)
(c) BUDDY AUV (UNIZG)
(d) e-UBoPe (CNR)

FIGURE 3

The new USBL/acoustic modem devices.

Observability by Using Extremum Seeking).

Seeing the Diver: Remote Sensing and the DiverNet

In order to interact with the diver, the CADDY cooperative robotic system must be able to perceive the diver and the surrounding environment. In line with this, the first core research theme is the "Seeing the Diver," with the objective of providing pose estimation and recognition of hand gestures (these results are crucial for other research themes). The sensing resources used for this task are remote and local sensing technologies.

Remote sensing underwater, using cameras and sonars, is mostly used to map large seabed areas and inspect critical infrastructures. The main challenges that are present in underwater environments are related to low visibility in turbid waters (Garcia & Gracias, 2011) and the impact of disturbances such as underwater currents, wind, and waves on the execution of commercial and scientific tasks. While mapping using mono cameras has reached a high level of maturity and is currently being exploited commercially, using stereo cameras for segmentation in the underwater domain still poses considerable problems. The main challenge is the development of techniques that are robust enough to work in environments that are often characterized with a low number of features (Nagappa et al., 2013).

As sonar technology becomes increasingly pervasive in the research community, advances in sonar-based mosaicking are reaching a high level of maturity; see, for example, the FP7 PANDORA project where the mapping of underwater structures (such as chains) has been accomplished (Hurtós et al., 2014). There is, however, very limited information on the use of sonar-based systems for the detection and tracking of small and dynamic objects such as divers or even parts of a diver body (Mišković et al., 2011).

While pose reconstruction using local sensing—that is, based on networks of inertial sensors—is common in the movie industry and in research related to human motions on dry land, we are not aware of any other work using this technology in the underwater environment. In the first year of the CADDY project, we have developed a body network of inertial sensors for pose reconstruction called DiverNet (Goodfellow et al., 2015).

It is important to mention that the state of the art in gesture recognition is focused primarily on RGB-D sensors. All of these methods rely on dense point clouds or detailed disparity maps in order to extract convex hull representations and detect fingertips and joints or 3D features encoding the curvature of the hand. However, RGB-D sensors cannot be used in underwater scenarios because infrared light will not follow a straight path in the propagation medium. Stereo cameras are not very accurate, especially when there are not many image features, as is the case of underwater diving; divers' suits are mostly plain black, and the background is plain blue. For this reason, the stereo-generated point clouds do not have enough precision to use state-of-the-art methods in a straightforward manner.

Remote sensing with a stereo camera, a monocular camera, and a multibeam sonar and local sensing with DiverNet are techniques that have been successfully tested as part of the "Seeing the Diver" research theme of the CADDY project. All of these techniques have proven to be efficient under different environmental conditions.

Monocular and Stereo Camera for Gesture Recognition

A large amount of video data with divers wearing artificially marked gloves has been collected during the CADDY experimental trials. Special gloves with markers were designed to make the process of automatic hand gesture recognition easier and more reliable, even under challenging light conditions and turbid waters. The data recorded using a stereo camera covered a variety of gestures embodied in the so-called diver symbolic CADDIAN language. More than 40 commands/messages that allow for diver-robot communications in the context of the CADDY project have been defined. The stereo camera imagery was used to produce 3D point clouds, as shown in Figure 4.

As a first step toward gesture classification, hand detection algorithms suited for real-time computation have been developed. Haar classifiers are used to detect possible locations of the hands in the monocular image. Then, stereo imagery is used to compute a disparity map and to filter all possible clutters in the image using depth information. Under the assumption that the diver is the closest "object" to the camera, the background can be thresholded. The second hypothesis is that the diver's hands are closer to the camera than the rest of the diver's body (see Figure 5). Note that these assumptions are mainly used as heuristics to focus attention on particular parts of the image, so as to enable fast processing.

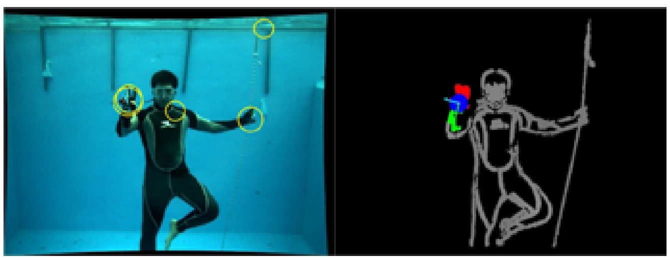
The next step represents the novel image processing techniques that have been developed for hand gesture classification in the underwater environment.

FIGURE 4

Resulting point clouds from the stereo images collected. Note that the contours of the diver are visible, but due to the lack of texture on the wetsuit, most of the diver is not properly reconstructed in 3D.

FIGURE 5

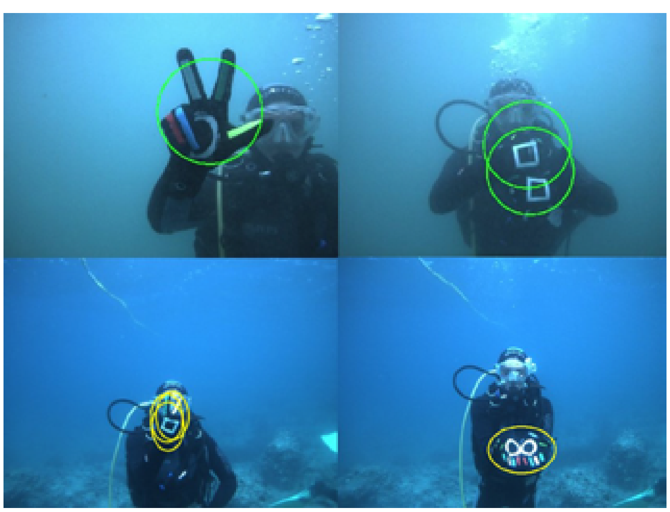
(Left) Monocular image with the hand candidate patches' output of the Haar classifier. (Right) Disparity image with the detected hand segments.



Due to camera noise and the fact that the disparity processing relies on image feature matching (which is not always 100% accurate), the hand candidates are evaluated by a new variation of a random forest classifier, namely, a Multi-Descriptor Nearest-Class-Mean Random Forest (MD-NCMF) (Chavez et al., 2015). A large number of CADDY gestures have been successfully detected during validation trials, a few of which are shown in Figure 6.

FIGURE 6

Detected gestures (clockwise from top left): take a photo, carry equipment, start communication, and go to the support vessel.



Sonar for Gesture Recognition and Diver Tracking

For the first time, high-resolution multibeam sonar data (using ARIS sonar) have been used to perform hand detection and gesture classification. The hand gesture recognition system is again divided into two steps: hand detection and gesture classification. Hand detection is performed using a cascade of boosted classifiers based on Haar-like features proposed in Viola and Jones (2001), as shown in Figure 7. For this purpose, the classifier is trained to detect five hand gestures containing a different number of visible fingers.

After the hand detection step, the area marked by the cascade classifier is used for further processing and gesture recognition. Two approaches were used for gesture recognition: first, a convex hull method that uses a binary thresholded image to extract the contour of the hand and computes a convex hull around the hand, resulting in the detection of fingertips (Figure 7). Second, a multiclass support vector machine (SVM) was used to classify the five different gestures shown in Figure 8.

Both methods show good results. However, by using a new method that combines both approaches (convex hull and SVM), we have managed to increase the robustness of the gesture recognition algorithms in such a way that gestures are recognized with more than 98% accuracy (Gustin et al., 2016).

An important step was made toward the goal of achieving diver tracking using sonar imagery. In order to position the BUDDY vehicle precisely relative to the diver, a diver tracking

FIGURE 7

Hand detection in sonar image using a cascade of boosted classifiers based on Haar-like features (red rectangle) and detected fingertips within the sonar image (white dots).

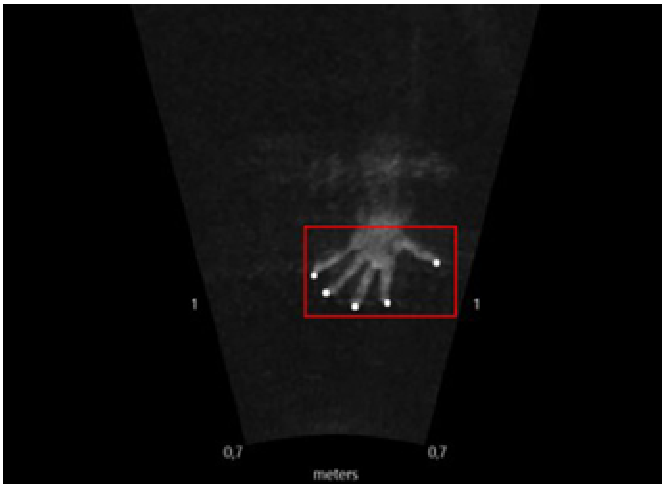


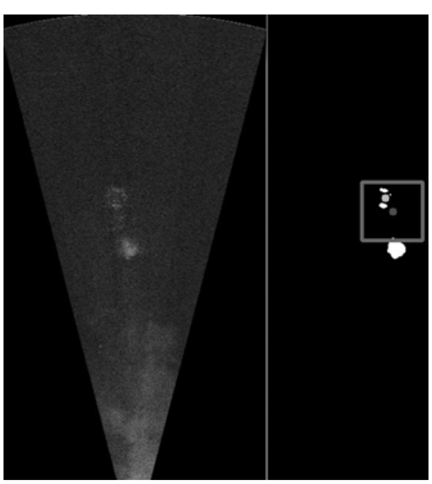
FIGURE 8

A set of hand gestures used for SVM recognition.

algorithm was developed. The greatest challenge in this task was to differentiate between the diver in the sonar image and the bubbles expelled by the diver. For this purpose, the diver tracking algorithms were augmented with a diver motion estimator. An example of successful diver tracking, even in the presence of air bubbles, is shown in Figure 9.

FIGURE 9

Region of interest within sonar image tracking the diver estimator instead of being locked on the bubbles that are dominant in the image.



DiverNet

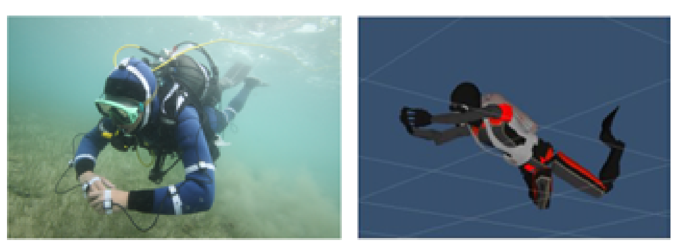
DiverNet, specially designed and manufactured for CADDY, is a network of inertial sensors that are mounted on the diver's suit in order to reconstruct his (or her) pose (Goodfellow et al., 2015). Each sensor node within DiverNet consists of a three-axis gyroscope (L3GD20H), a three-axis accelerometer (LSM303D), and a three-axis magnetometer (LSM303D). This is the first time a system of this kind has been successfully developed and tested for underwater use. Figure 10 shows how DiverNet is mounted on a diver and a virtual reconstruction of the diver's pose based on the DiverNet measurements.

The most recent enhancements to DiverNet have resulted in a fully functional unit that can be used for diver pose estimation as well as physiological parameter measurement. These enhancements include:

- the development of the wireless version that uses acoustic channel for data transmission (it ensures real-time monitoring/supervision of events triggered by diver's suspicious pose or irregular physiological parameters);
- a calibration method in order to improve DiverNet performance based on experience from real trials with divers; and
- the integration of a heart rate and breathing sensor that allows recording of the heart rate breathing data during the experiments.

FIGURE 10

(a) Diver with the DiverNet underwater and (b) visualization of DiverNet measurements in a form of a virtual stickman.



(a) (b)

Understanding the Diver

Interpreting human behaviors on dry land is a research topic of great interest for behavioral anthropologists and scientists. One of the methods that have attracted attention is placing a human who is under observation inside the pleasure-arousal-dominance (PAD) space (Mehrabian, 1996). When a human is observed, her/his extremities and posture are recorded, and afterward, the subject is interrogated via a questionnaire on her/his state. Then, the posture is mapped to the questionnaire results, providing a large data set that can be used to determine the link between posture and human state. In addition to this, research is conducted in the area of emotional breathing, where breathing patterns are recorded for the purpose of determining the emotional state of the subject. Although significant results have been obtained through experiments on dry land, there is no record of similar experiments being conducted on divers, in the underwater environment, except those done in the scope of the CADDY project. The fact that divers have limited motion capabilities underwater may be a beneficial factor for a behavior analysis—this is an aspect that is left to be investigated.

Using hand gestures that form a structured language is a common procedure among deaf people. There even exists software that uses image recognition to determine individual gestures, issued by a person, to interpret the communicated meaning. Recently, with the rise of the gaming industry, more complex sensors such as the Kinect have been developed for the purpose of detecting complex gestures. The situation is somewhat different in the underwater environment. Although divers use hand gestures to communicate, there does not exist a method for interpreting the communication. While land-based systems rely on the fact that only the hand issuing a gesture is dynamic, in the underwater environment, one of the challenges is to discriminate between the observing vehicle ego-motion and the movement of the hand.

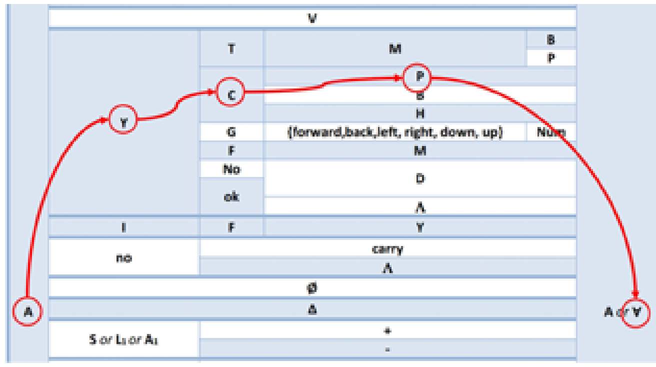
In the context of CADDY project, three major advances have been made in the area of "Understanding the Diver": the definition and interpretation of CADDIAN symbolic hand gesture language, algorithms for anomaly detection in divers, and interpretation of DiverNet measurements.

The CADDIAN Language

The CADDIAN language, based on diver symbolic gestures, has been developed together with a precise syntax used to describe complex scenarios that are required in the scope of the CADDY project (Chiarella, Bibuli, et al., 2015; Chiarella, Cutugno, et al., 2015). The developed syntax has also been extended with CADDY "slang" that utilizes simple gestures defined by the diving community.

FIGURE 11

Table of possible sequences—the table representation of the command "A Y C P ∀ " ("Come to the point of interest"). In the figure, it can be seen that, after the "C" gesture, only "P," "B," or "H" can follow in a semantically correct message and, after them, only "A" (i.e., a sequence of commands) or "∀" (i.e., the sequence of commands/the message ends).



In order to interpret and validate longer gesture sequences, a gesture sequence interpretation has been implemented through the realization of a parser, which accepts commands or messages belonging to the CADDIAN language. Each message/command is a sequence of symbols/gestures delimited, at the beginning, by a symbol of "Start communication" and, at the end, by the same symbol or by a symbol of "End of communication," as shown in Figure 11.

Anomaly Detection

Detecting strange diver behavior based on a large number of measurements is a prerequisite if timely reaction in case of hazardous situations is required. For this purpose, research on anomaly detection has started by implementing symbolic aggregation approximation algorithm (Keogh et al., 2005; Lin et al., 2004), which allows us to detect anomalies and motifs in real time. In our case, the experiments that we perform provide a collection of anomalies, such as T-posture, fast swimming, tablet use, and so forth, which are compiled in a catalog of classified anomalies. We are currently pursuing exploring the anomalies and compiling a catalog of detected anomalies.

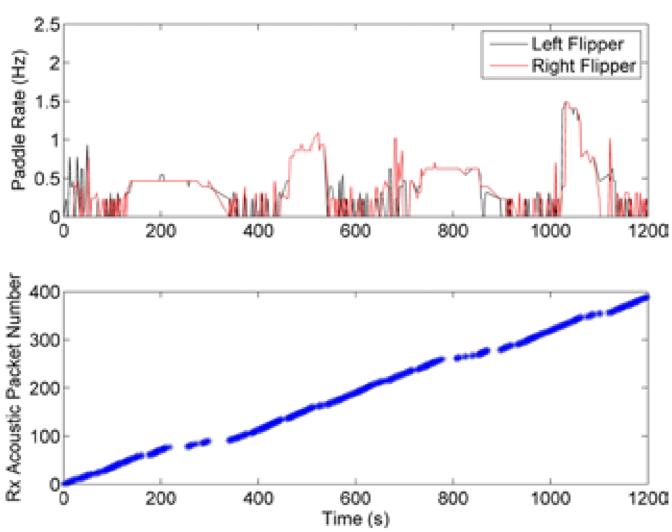
DiverNet Interpretation

In the course of an intensive series of field experiments, DiverNet measurements were processed onboard the diver, and high-level information in the form of left/right flipper frequency was sent to the surface wirelessly via acoustic channel. This information allows for the automatic detection of anomalies such as flipper loss or persistent unequal usage of flippers that may indicate injury.

An example of the interpretation of DiverNet data is shown in Figure 12. The first plot shows the frequency of paddling measured by the inertial sensors on the diver's flippers. The inertial measurements are processed onboard DiverNet, and the calculated frequency of paddling is transmitted in "real time" through the acoustic modem to the surface. The bottom plot shows the acoustic packet reception, clearly demonstrating that packets are regularly transmitted to the surface. These data have been obtained during real validation trials. It can be noticed that anomalies in the form of different paddling rates between two flippers (indicating, e.g., a lost flipper at a time of 1,120 s) can now be easily detected from the surface.

FIGURE 12

An example of wireless transmission of DiverNet measured data.



Diver-Robot Cooperation and Control

The last decade has witnessed significant advances made in the area of cooperative marine robotics, namely, in what concerns the development of supporting systems for navigation and control. As an example, the FP7 MORPH project deals with the cooperation among five heterogeneous marine vehicles (one surface and four underwater) in order to map complex underwater environments using distinct yet complementary resources (Kalwa et al., 2015). Some of the greatest challenges include communication among the units because acoustic communications are characterized by low bandwidth, delays, and temporary losses due to the nature of acoustic wave propagation. These issues can be dealt with by running relative motion estimators in each of the vehicles; by knowing the nominal mission, each vehicle can efficiently estimate the behavior of every other vehicle and feed these estimators with intermittent measurements. The challenge that still remains is how to incorporate one "vehicle" whose behavior cannot be predicted, that is, a diver. Some results have been obtained by the IST team prior to the CADDY project whereby a triplet of autonomous surface vehicles was used to guide a diver through the underwater environment (Abreu et al., 2015). In the context of CADDY, a surface platform was used to both track and guide the diver in the underwater environment (Mišković et al., 2015). The challenge to be solved is how to incorporate an underwater vehicle in this diver-interacting formation.

One of the key issues in the underwater environment is navigation. Due to the lack of standard GPS, underwater navigation is a challenging task that can be performed by integrating motion-related data obtained with an ultrashort baseline positioning unit (based on acoustic measurements), a Doppler velocity log (which measures the inertial velocity of an underwater vehicle and estimates the vehicle's position using dead reckoning), coupled with data acquired by occasional surfacing for the purpose of navigation filter corrections using GPS available at the water surface. A more ambitious, novel approach to underwater navigation is to rely on the measurements of the range between the underwater vehicle and a single point, the position of which is known (i.e., a surface vehicle). The main issue that arises in this context is the observability of the system under study when only range measurements are used. This can be solved by ensuring persistently exciting motion of the surface vehicle (Bayat et al., 2015; Pedro et al., 2015). Research has been conducted in this area, but the challenge is to try to ensure that persistently exciting maneuvers can indeed be executed while, at the same time, not requiring that any of the platforms involved (human or robotic) deviate substantially from predefined nominal paths. This type of research has not been conducted using divers as targets that must be tracked and guided underwater.

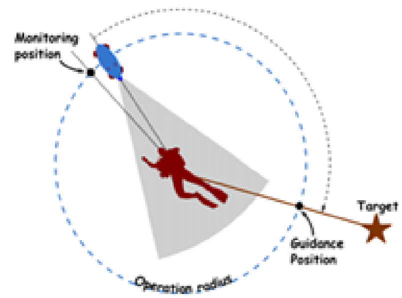
In the CADDY context, the "Diver-Robot Cooperation and Control" task involved intensive R&D efforts in three key areas: (a) development of the algorithms used to coordinate the motion of autonomous surface and underwater vehicles relative to the diver in order to ensure constant monitoring and guidance of the latter, (b) exploiting single-range navigation techniques (in the form of extremum seeking (ES) methods) in order to maximize system observability, and (c) execution of buddy tasks, such as covering an area in a lawn mower pattern and obtaining a mosaic using a novel SLAM solver.

The "Pointer" Experiment

The "pointer experiment" describes a scenario where the diver moves freely in the underwater environment while the underwater vehicle positions itself at a safe distance from the diver so that it points toward the desired goal point while remaining in the diver's field of view, as shown in Figure 13. An algorithm based on virtual target path following has been proven to offer a simple controller structure for implementing this behavior. The algorithm is derived using a Lyapunov-based approach and has been tested in real conditions. This behavior of diver-robot cooperation consists of the following experiments: "approach," "rotating," and "tracking" experiments that define the BUDDY behavior relative to the diver and "BUDDY/diver tracking" behavior that defines unmanned surface vehicle behavior relative to the BUDDY and diver positions.

FIGURE 13

Pointer experiment layout.



The Approach Experiment

In the approach experiment, the BUDDY vehicle starts from a large distance behind the diver's back and positions itself in front of the diver without compromising the safety radius. Standard positioning controllers without collision detection would make the BUDDY converge directly toward the goal point, causing it to pass through the safety radius, while the proposed algorithm safely avoids the diver, as shown in Figure 14.

The Rotating Experiment

In the rotating experiment, the diver changes orientation, while the BUDDY vehicle must position itself in front of the diver (regardless of diver orientation) while keeping a

FIGURE 14

Field results of the approach experiment with virtual diver: (a) the distance reduction to the safety radius. The vehicle trajectory is shown in (b), and the distance distribution along the path is shown in (c).The box plot shows the median value with the box between the 25th and 75th percentiles and whiskers showing min-max values.

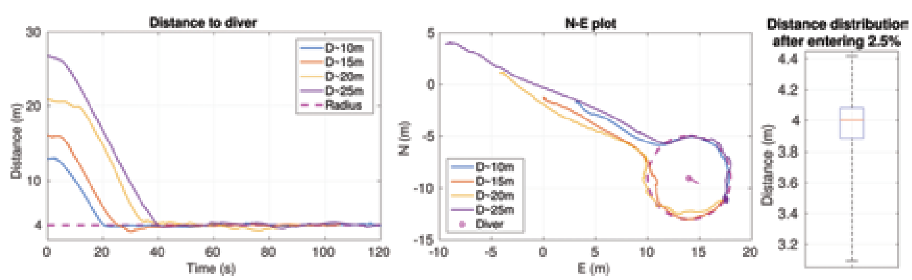
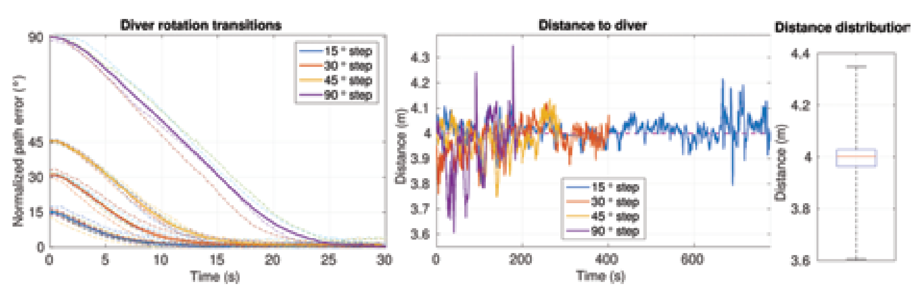


FIGURE 15

Forty-eight field results of the rotating experiments with a virtual diver are shown in this figure. The normalized path (angular) error is shown in (a). The distance to the diver during transitions and the distance distribution are shown in (b) and (c), respectively.



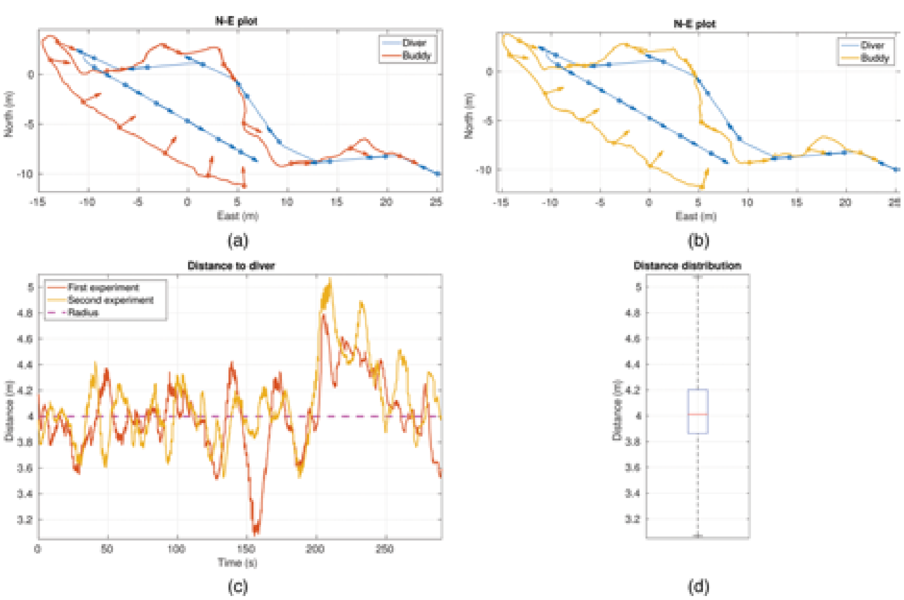
safe distance at all times. A few experimental results, with different diver rotations, are shown in Figure 15, proving that successful convergence to the point in front of the diver is achieved.

The Tracking Experiment

In the tracking experiment, the BUDDY vehicle must keep distance and orientation relative to the diver, while the diver is moving in the horizontal plane and arbitrarily changing orientation. Field results of two tracking experiments with a virtual diver moving at 0.2 m/s are shown in Figure 16. The northeast plots for each experiment are shown in Figures 16(a) and 16(b). Distance to the diver and its distribution are shown in Figures 16(c) and 16(d), respectively. Observe that the vehicle adapts to changes in the virtual diver orientation during the zigzag part. In the second part, the vehicle begins to overtake the diver. Note that 20 m are needed for the vehicle to start getting in front of the diver. This is attributed to the fact that the maximum achievable sway speed is ≈0.3 m/s.

FIGURE 16

Field results of two "tracking" experiments with BUDDY AUV tracking a virtual diver.

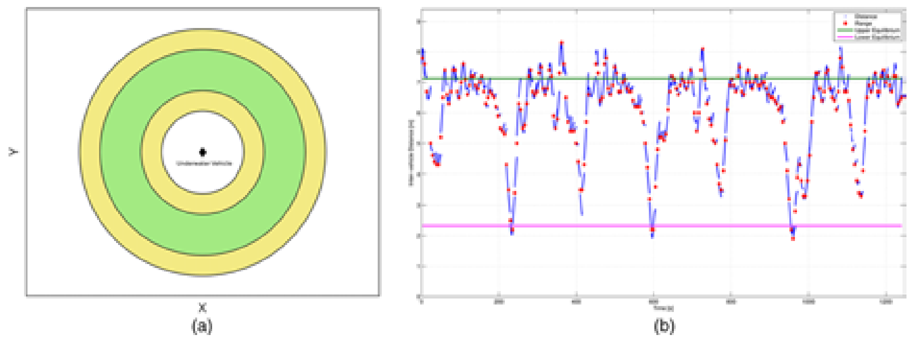


The BUDDY/Diver Tracking Experiment

This experiment includes the scenario where the surface vehicle tracks the BUDDY AUV and the diver. The implemented algorithm forces the surface vehicle to remain inside a certain area, while improving, among other things, the acoustic communications with the underwater vehicle and, at the same time, trying to avoid being on top of it in order to avoid air bubbles that are emitted by the diver. An example of the results obtained is shown in Figure 17. The overall performance was good with a maximum error of 1.2 m.

FIGURE 17

(a) The location of the underwater vehicle (in the center), the area where the surface vehicle would ideally remain (in green), and the equilibrium area (in yellow). (b) The intervehicle distance over time.



Maximizing System Observability by Using ES

The ES approach for underwater target localization using only range measurements was introduced and tested in simulation during the first year of the CADDY project (Mandić & Mišković, 2015). In the second year, we focused on testing the proposed algorithms in real conditions. Basic ES algorithm successfully localized underwater targets, but alternative versions with Extended Kalman filter-based gradient estimation showed better results due to the better speed of convergence. The results of an example of the ES experiment performed in real conditions are shown in Figure 18.

A novel method for maximizing system observability by using ES was developed and tested as part of the validation trials, as reported in Mandić et al. (2015). The proposed methodology ensures that the observability is maximized by ensuring that the cost

FIGURE 18

ES experimental results: PlaDyPos trajectory (top) and range to the target measurement (bottom).

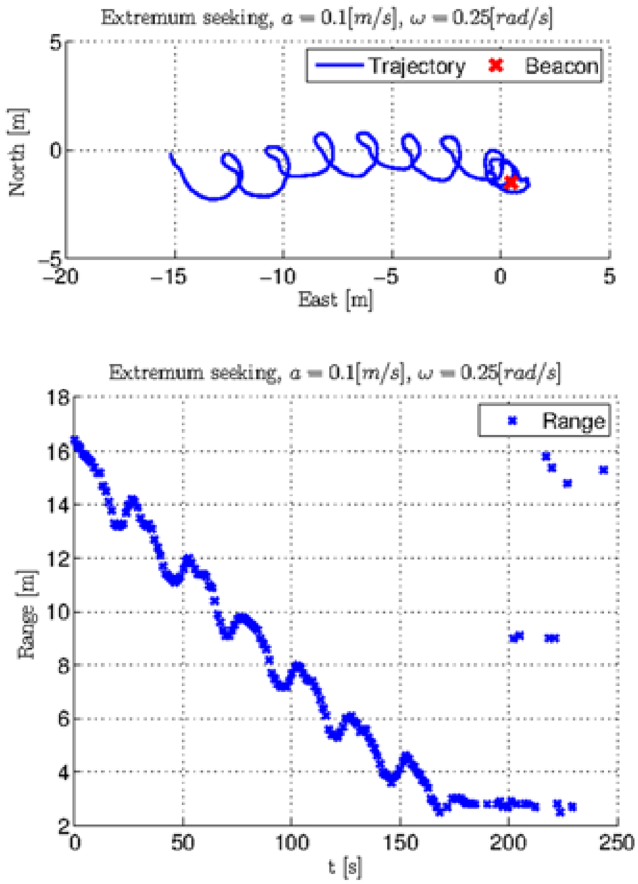
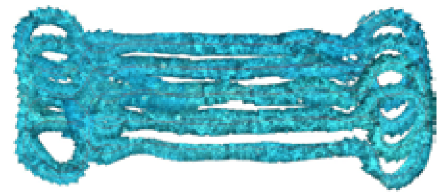


FIGURE 20

The figure shows a sample overview map (orthographic projection) from the 2015 integration trials in Biogradna Moru. Stereo imagery was recorded by the $Medusa_D$ vehicle with the Bumblebee XB3. The robot trajectory is marked as a red line.



function (the inverse of observability measure) is kept bounded. Experiments were conducted for the cases of static and mobile underwater vehicles, proving the applicability of the method in the field.

Execution of Compliant Buddy Tasks

In the area of execution of compliant buddy tasks, we have developed an automatic selection system for the execution of the appropriate autonomous robotic tasks. For automatic task selection, activation, and intertask conflict management, a Petri net-based execution control system is under current development. This system will be crucial during field experiments with divers issuing commands to the BUDDY vehicle.

An experiment was conducted in which the person on dry land issued a command to perform a mosaic using hand gestures and the underwater vehicle delivered the mosaic of the area. The data obtained by the lawn mower pattern were used with a novel robust SLAM solver called Generalized Graph SLAM that was used to obtain a mosaic of the surveyed area (Pfingsthorn & Birk, 2016) (Figures 19 and 20).

FIGURE 19

Lawn-mowing pattern mission inside a pool. The nominal mission is represented in white, the vehicle path is in red, and the vehicle pose is shown with the help of yellow circles. The survey area is defined by the diver in real time when initiating the mission (for the data shown in the figure, the area was 20 m × 45 m). On the first validation trial, the nominal mission consisted of a lawn-mowing pattern with a distance of 1 m between legs, at 1.5-m altitude from the seafloor, and at a nominal speed of 0.3 m/s.

Conclusion and Future Work

This article describes the results of R&D work carried out during the first 2 years of the CADDY project, funded by the FP7 programme. In addition to the development of the robotic system consisting of autonomous surface and underwater vehicles and an interface to the diver, three main research areas are defined within the project: “Seeing the Diver,” “Understanding the Diver,” and “Diver-Robot Cooperation and Control.”

As part of the “Seeing the Diver” research topic, we report remote sensing techniques (stereo camera, mono camera, and multibeam sonar) that have been successfully exploited. All of these have proven to be efficient under different environmental conditions. In addition to this, DiverNet, a network of inertial measurement units distributed on the diver's body, was developed for the purpose of reconstructing the pose of the diver.

In the area of "Understanding the Diver," we have reported three major advances: definition and interpretation of CADDIAN symbolic hand gesture language, which enables natural communication between the diver and the BUDDY AUV; algorithms for anomaly detection in divers that provide timely indication of possible hazardous states; and interpretation of DiverNet measurements.

In the "Diver-Robot Cooperation and Control" research theme, we also report achievements in three main areas of research. First, the pointer experiment is described that is used to coordinate autonomous surface and underwater vehicles relative to the diver in order to ensure constant monitoring and guidance of the diver. Second, single-range navigation techniques (in the form of ES) that are used to maximize system observability are reported. Finally, focus is placed on the execution of buddy tasks, such as covering an area in a lawn mower pattern and obtaining a mosaic using a newly developed SLAM solver.

Future research will continue its focus on the three main research areas defined within the project. Specifically, experiments for the final validation trials will be planned, with the goal of demonstrating the fully operational cooperative robotic system capable of guiding, observing, and assisting divers during their underwater activities. Using the developed robots and algorithms, we will demonstrate the scenario where robots guide the diver to the point of interest defined by the diving supervisor from the surface while keeping their formation relative to the diver and reporting the diver's behavior during the process.

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