Overview of the FP7 project “CADDY - Cognitive Autonomous Diving Buddy”

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***Abstract*—This paper summarizes the main accomplishments of the first year of the FP7 project “CADDY - Cognitive Autonomous Diving Buddy”. The main objective of the project is to replace a human buddy diver with an autonomous underwater vehicle and add an autonomous surface vehicle to improve monitoring, assistance, and safety of the diver’s mission. While all envisioned objectives of the project are listed, the paper focuses on the results that were obtained in the following areas of research: development of the multicomponent robotic system, “Seeing the Diver” (underwater perception), “Understanding the Diver” (cognition in the form of interpreting diver sign language, behaviour and physiological parameters), and diver–robot cooperation and control.**

I. INTRODUCTION

The FP7 CADDY project, [1] is funded by the European Commission and was started in January 2014. A group of 7 partner institutions (University of Zagreb, Croatia; Consiglio Nazionale delle Ricerche, Italy; Instituto Superior Tecnico, Portugal; University of Newcastle, UK; Jacobs University, Germany; University of Vienna, Austria; Divers Alert Network Europe, Malta) came together in order to pursue collaborative R&D work aimed at enhancing cognitive robotics in the underwater arena; specifically, to develop robots capable of cooperating with divers.

The main motivation for the CADDY project was the fact that divers operate in harsh and poorly monitored environments in which the slightest unexpected disturbance, technical malfunction, or lack of attention can have catastrophic consequences. They manoeuvre in complex 3D environments and carry cumbersome equipment while performing their missions. To overcome these problems, CADDY 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 diver’s behaviour, physical state, and actions. The main CADDY concept is shown in Fig. 1 where three components are illustrated: an autonomous surface vehicle, an autonomous underwater vehicle, and the diver.

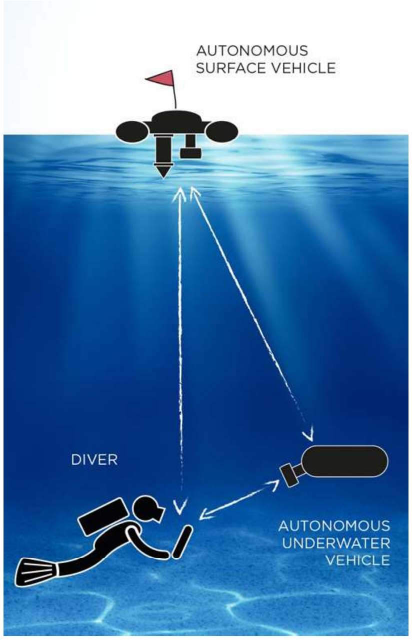

Fig. 1. CADDY concept: autonomous underwater and surface vehicle interacting with the diver.

The autonomous surface vehicle is responsible for communicating with the diver and the autonomous underwater robot, as well as serving as a communication relay link to a command centre. It also plays the key role of navigation aid for the underwater agents – it must adapt its motion to optimize communication efficiency and navigational accuracy of underwater agents. The autonomous underwater vehicle, on the other hand, manoeuvres in the vicinity of the diver, and exhibits cognitive behaviour with regard to the diver actions by determining the diver’s intentions and the state of the diver’s

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body.

The CADDY project replaces a human buddy diver with an autonomous underwater vehicle and adds a new autonomous surface vehicle to improve monitoring, assistance, and safety of the diver's mission. The resulting system plays a threefold role similar to those that a human buddy diver should have: i) the buddy "observer" that continuously monitors the diver; ii) 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 iii) the buddy "guide" that leads the diver through the underwater environment.

This envisioned threefold functionality will be realized through S&T objectives which must be achieved within three core research themes: the "**Seeing the Diver**" research theme focuses on 3D reconstruction of the diver model (pose estimation and recognition of hand gestures) through remote and local sensing technologies, thus enabling behaviour 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; while 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 formation.

This paper presents an overview of the activities that have taken place during the first year of the project – the partners have made substantial progress in both technological as well as scientific objectives that were set in the project, including the following:

1) Development of a cooperative multi-component system capable of interacting with a diver in unpredictable situations and supporting cognitive reactivity to the non-deterministic actions in the underwater environment.
2) Establishing a robust and flexible underwater sensing network with reliable data distribution, and sensors capable of estimating the diver pose and hand gestures.
3) Achieving full understanding of the diver behaviour through interpretation of both conscious (symbolic hand gestures) and unconscious (pose, physiological indicators) nonverbal communication cues.
4) Defining and implementing cognitive guidance and control algorithms through cooperative formations and manoeuvres in order to ensure diver monitoring, uninterrupted mission progress, execution of compliant cognitive actions, and human-machine interaction.
5) Developing a cognitive mission (re)planner that relies on interpreted diver gestures that make more complex words.

Sections II to V of the paper focus on the results obtained in the scope of the main research themes: development of the multicomponent robotic system, "Seeing the Diver" perception), "Understanding the Diver" (cognition in the form of interpreting diver sign language, behaviour and physiological parameters), and diver–robot cooperation and control. Conclusions and indications of future work are listed in Section VI.

II. DEVELOPMENT OF THE MULTICOMPONENT SYSTEM

PlaDyPos by UNIZG-FER, MEDUSA$_S$ by IST, and Charlie by CNR are the **autonomous surface vehicles** that have been refurbished to act as the diver's "private satellite". In addition to this, MEDUSA$_D$ by IST and R2 of CNR have been modified to serve as the **autonomous diving buddy**. UNIZG–FER have finished a prototype of the BUDDY AUV, the first autonomous underwater vehicle with an underwater visual interface for the diver. Fig. 2 shows primary ((b), (c)) and substitute ((a), (d)) surface and underwater vehicles to be used in CADDY project.

A **new set of modems and navigation systems** units was developed by UNEW. This system, characterized by small dimensions, rate of 100bps, and USBL fix repeatability of less than 1 degree at update rate of more than 1 fix per second, perfectly fits in the CADDY concept which requires reliable acoustic communication between the diver, the buddy, and the surface vehicle.

III. "SEEING THE DIVER" - REMOTE SENSING AND THE DIVERNET

We have conducted a large number of experiments in which diver remote sensing techniques such as multibeam sonar, stereo and mono camera were used to record the diver. An example of images taken using stereo camera and a sonar are given in Fig. 3. Further steps will include processing the obtained data to reconstruct the diver pose and/or diver hands.

Instead of **calibrating cameras underwater** directly, JACOBS developed a technique to estimate the underwater calibration parameters based on the much easier and well understood in-air calibration and basic measurements of the underwater housing used. The proposed technique is shown to work well for monocular images, as well as for use in a practical stereo setup underwater.

A **visual diver detection** method based on multiple image descriptors and region detectors has been developed and tested. The results show significant improvement relative to methods that use only one of the two descriptors. An example of the obtained results, and comparison with state–of–the–art techniques is given in Fig. 4.

DiverNet is a specially CADDY designed and manufactured network of inertial sensors that are mounted on the diver in order to reconstruct the pose of the diver, [2]. This is the first time a system of this kind has been successfully developed and tested for underwater use. Fig. 5 shows mounting of DiverNet on a diver and a virtual reconstruction of the diver pose based on the DiverNet measurements.

IV. "UNDERSTANDING THE DIVER" CADDIAN LANGUAGE AND LINKING DIVER PARAMETERS TO EMOTIONS

Initial results in the area of hand recognition using vision processing have been obtained, [3]. The **CADDIAN language**, based on diver symbolic language, has been developed. More than 40 commands/messages that allow diver-robot communication within the scope of CADDY project have been defined.

In addition to this, a number of **experiments with physiological measurements** on divers were conducted by UNIVIE,

(a) PlaDyPos by UNIZG–FER (b) MEDUSAS by IST (c) BUDDY AUV by UNIZG–FER (d) R2 by CNR

Fig. 2. The fleet of autonomous surface and underwater vehicles used in the CADDY project.

(a) (b) (c)

Fig. 3. (a) Sonar and stereo camera mounted, filming the diver, during one of the diver recording experiments, (b) an example of a stereo camera acquired diver image. Flat tempered glass stereo camera underwater housing has proven to reduce image distortions, and(c) an example of multibeam sonar acquired diver image.

under the supervision of DAN Europe: emotional breathing, analysis of breathing through the regulator, posture analysis, and linking to the person's emotional state. Initial results have shown that respiration rate and turbulence, as well as heart rate and turbulence are the best candidates for the identification of emotional states. The results of experiments also show that breathing rate is significantly lower when breathing air through a regulator that is used for SCUBA diving. DiverNet was used to detect diver posture while diving. The results of matching **diver posture** to three factors pleasure, arousal and dominance are being processed.

V. DIVER-ROBOT COOPERATION AND CONTROL

As a part of enhanced AUV control and underwater localization, a **more informed loop detection in SLAM** using a novel multi-descriptor appearance-based place recognition extension has been developed, see [4], [5], [6], [7]. Results show improved place recognition performance of up to 80% on underwater stereo imagery when using both an image descriptor (SURF) as well as a surface descriptor in conjunction, instead of just one image descriptor.

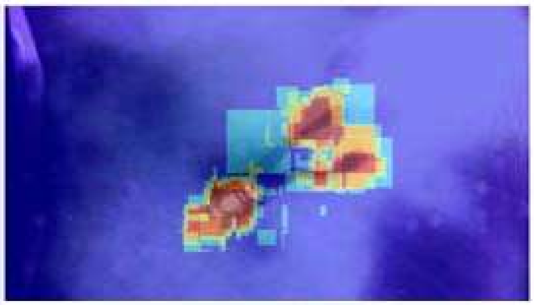
The following **cooperative scenarios** have so far been executed and tested in real-life environments with vehicles and divers.

- **Scenario 1: Surface-Leader Tracking (Fig. 6).** AUV (yellow line) in the role of a "buddy guide" has to follow the ASV (autonomous surface vehicle, white line) that is moving in a predefined path using GPS.
- **Scenario 2: Underwater-Leader Tracking (Fig. 7).** AUV in the role of a "buddy guide" follows a path underwater (yellow line) while the ASV tracks the AUV (blue line) using an USBL. Red dots are USBL fixes.
- **Scenario 3: Diver Tracking (Fig. 8).** Diver moving along a predefined transect while the ASV is performing tracking based on intermittent USBL measurements. The plot in Fig. 8 gives N-E coordinates during the diver tracking experiment.

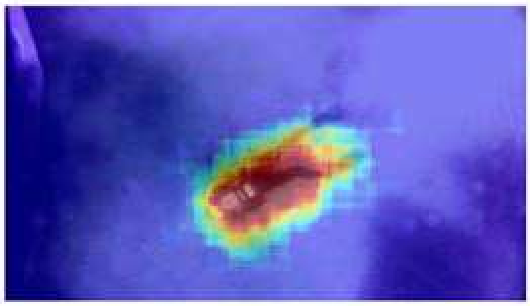
Range-only based navigation was successfully demonstrated. In order to eliminate the high cost of USBL devices, ASVs that have only range measurements from the AUV and/or diver, perform persistently exciting manoeuvres in such a way as to minimize the errors associated with the localization of AUVs/divers. The **Range-Based Target Localization** problem is, to a certain extent, the dual of the Range-Based Positioning (often called Range-Based Navigation) problem, where the objective is to estimate the position of an underwater vehicle by using measurements of its range to a transponder deployed in a fixed position (e.g. moored to the sea floor), [8], [9], [10]. Three approaches are investigated in this range-based target localization area:

1) **Energy minimization:** The objective is to compute vehicle trajectories as to maximize the information available for range-based positioning (quantified by Fisher Information Matrix (FIM) determinant) and

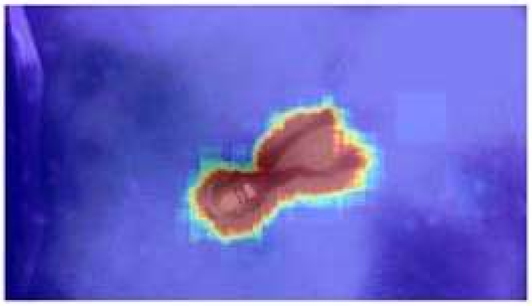
(a) Original diver image from a down-looking camera onboard the ASV.



(b) Diver detection using Daisy image descriptor and Harris Affine Regions detector.



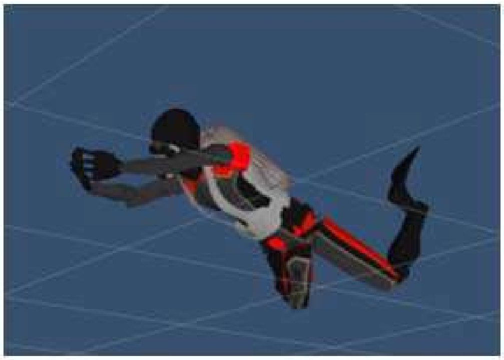
(c) Diver detection using SIFT descriptor and Maximally Stable Extremal Regions detector.



(d) Combined result using both detector/descriptors in a multi-descriptor approach.

Fig. 4. Diver detection using a mono camera mounted on the diver tracking autonomous surface marine platform.

(a) Diver with the DiverNet underwater.



(b) Visualization of DiverNet measurements in a form of a virtual stick-man

Fig. 5. DiverNet – a body network of inertial sensors for diver pose reconstruction underwater.

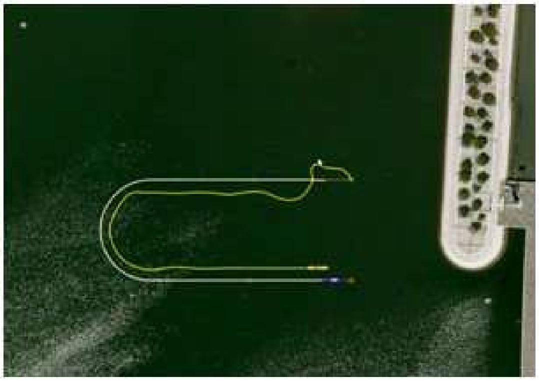


Fig. 6. Scenario 1: Surface-Leader Tracking – surface leader vehicle in blue and underwater follower vehicle in yellow.

minimizing the energy consumption along the trajectories. Some initial results capturing the tradeoff between energy and information are shown in Fig. 9.

2) **Minimizing the deviation from a nominal (desired) trajectory:** The vehicle is requested to follow as closely as possible a nominal trajectory, but at the same time is given some freedom to maneuver about that trajectory doing persistently exciting motions so as to improve the accuracy of the position estimates. Results with different priorities given to trajectory tracking are shown in Fig. 10.

3) **Extremum seeking:** In general, extremum seeking uses a combination of harmonic signals to find extremal value of a nonlinear function. UNIZG–FER is working on applying this methodology for diver tracking, i.e. to minimize the distance between the surface platform and the diver. Fig. 11 shows three different setups used to investigate the speed of convergence towards a stationary target.

Fig. 7. Scenario 2: Underwater-Leader Tracking – underwater leader vehicle in yellow and surface follower vehicle in blue.

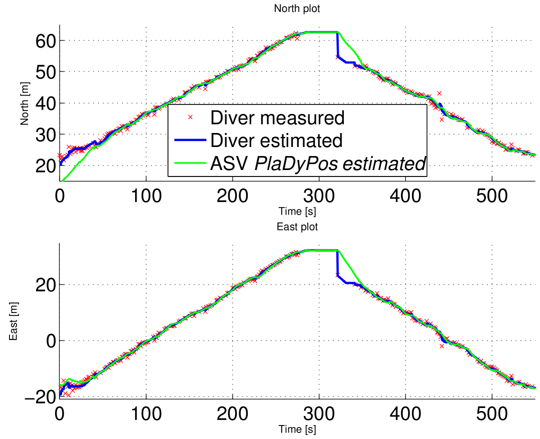


Fig. 8. Scenario 3: Diver tracking results.

VI. CONCLUSIONS AND FUTURE WORK

This paper gave a short overview of the most significant results during the first year of the CADDY project. Most of the effort was focused on developing and modifying existing systems and vehicles in order to use them in experiments with divers. Advances were also made in underwater perception, cognition, and cooperative control.

Future work will continue in the directions of extending the capabilities of the CADDY system. The first validation trials are planned for the second year of CADDY project – this event will be used to test the developed algorithms and to execute initial experiments with divers.

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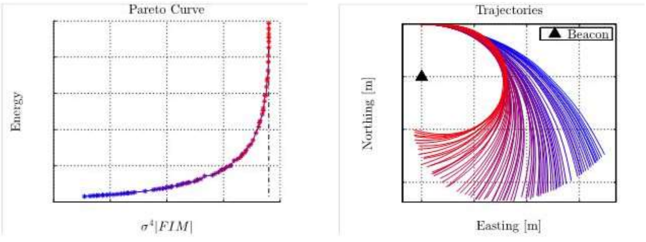
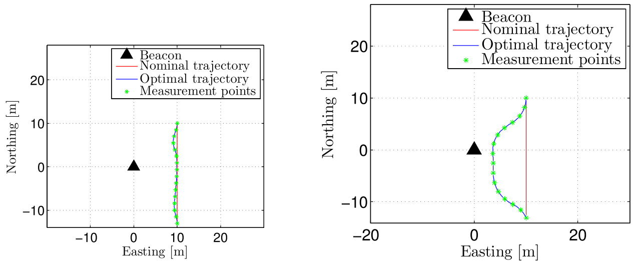


(a) (b)

Fig. 9. Range–only navigation with the criteria of energy minimization. The Pareto curve in (a) shows the tradeoff between information and energy, while (b) shows vehicle trajectories obtained along different points of the Pareto curve.



(a) (b)

Fig. 10. Range–only navigation by minimizing the deviation from a nominal trajectory. (a) shows the case where priority is given to trajectory tracking, while (b) shows the case where priority is given to the maximization of $|\text{FIM}|$.

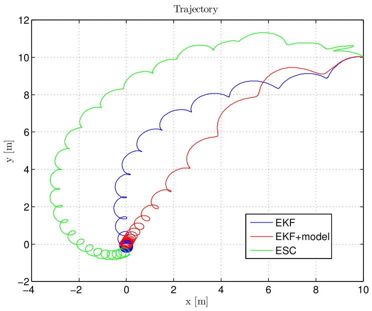


Fig. 11. Extremum seeking approach to range–only navigation.

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