PROJECT PERIODIC REPORT

Grant Agreement number: 611373

Project acronym: CADDY

Project title: Cognitive Autonomous Diving Buddy

Funding Scheme: Collaborative project, Small or medium-scale focused research project (STREP)

Date of latest version of Annex I against which the assessment will be made: 08/07/2013

Periodic report: 1st ☐ 2nd ☑ 3rd ☐ 4th ☐

Period covered: from 01/01/2015 to 30/06/2015

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Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate)[1]:

  ☑ has fully achieved its objectives and technical goals for the period;

  ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations.

  ☐ has failed to achieve critical objectives and/or is not at all on schedule.
- The public website, if applicable

  ☑ is up to date

  ☐ is not up to date
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: ....

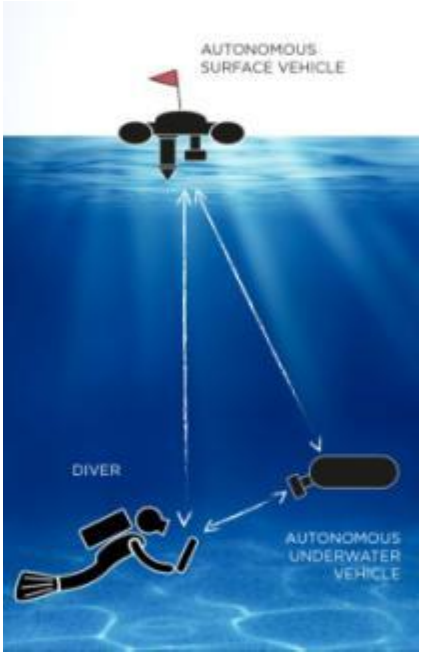
Date: ..../ ..../ ....

For most of the projects, the signature of this declaration could be done directly via the IT reporting tool through an adapted IT mechanism and in that case, no signed paper form needs to be sent

[1] If either of these boxes below is ticked, the report should reflect these and any remedial actions taken.

3.1 Publishable summary

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 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.



CADDY concept

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.

The envisioned threefold functionality will be realized through S&T objectives which are to 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.

In the second year of the project the partners have made substantial progress to meet both technological as well as scientific objectives that were set in the project. Here is a short summary of the most important results.

- **Development of the multicomponent system**

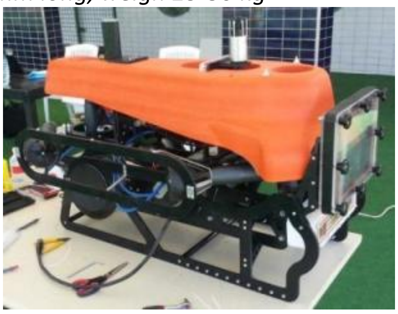
Within CADDY, we have formed a multicomponent robotics system consisting of the following vehicles covering both surface and underwater segments:

MEDUSA$_S$ by IST

- *primary surface vehicle*
- *surface vessel with two 150 mm diameter tubes*
- *1035 mm long, weigh 23-30 kg*

PlaDyPos by UNIZG-FER

- *backup surface vehicle*
- *omnidirectional vessel with 4 thrusters in X configuration 0.7 x 0.7 m, weight cca. 30 kg*



BUDDY AUV by UNIZG

- *primary underwater vehicle*
- *first AUV custom made for interaction with divers*
- *fully actuated with 6 thrusters*
- *stereo and mono camera, high-res multibeam sonar*
- *mounted UW tablet for providing feedback to diver*

e-URoPe by CNR

- *backup underwater vehicle*
- *fully actuated underwater robotic platform with 4 horizontal and 4 vertical thrusters allows complete motion capability and hovering*
- *1.3 (L) x 0.9 (W) x 1.0 (H) m, rated up to200 m*

A **new set of modems and navigation systems** units has been developed by UNEW. The main difference to already existing devices available in the market are small dimensions regardless of the fact that all the electronics is embedded in the modem/USBL housing.

- **"Seeing the diver" – remote sensing and the DiverNet**

Significant achievements have been made in diver gesture and posture recognition using mono cameras, stereo cameras, sonars. In addition, an innovative body network of inertial sensors has been developed which allows for the first time near real time visualization of diver posture.

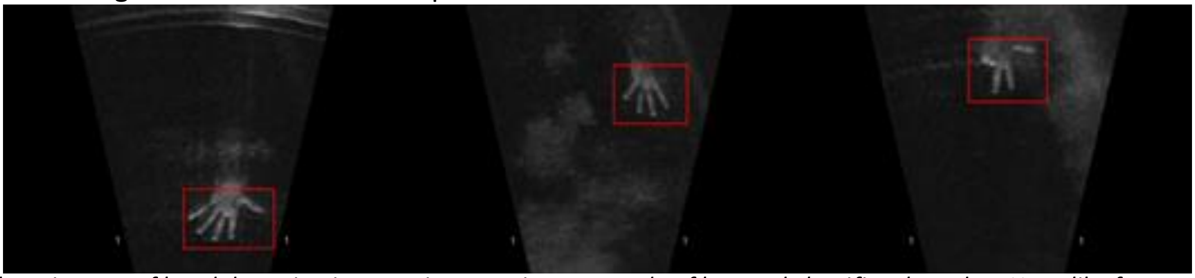
- **Mono camera for gesture recognition:** A large amount of data of divers wearing artificially marked gloves have been collected. The gloves were designed with the aim of making easier and more reliable the process of the automatic hand gesture recognition

Gesture execution during swimming pool trials. Marked gloves allow easier detection of the diver gestures even under challenging light conditions and turbid waters.

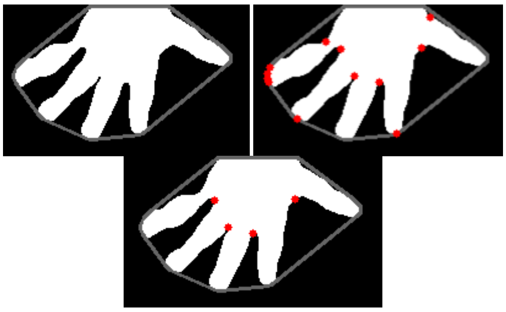
– **Stereo camera for pose and gesture recognition:** 3D point clouds of diver posture and hand gestured were produced using a stereo camera. Initial processing gave very promising results.

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. This will be mitigated by a fused approach: A classifier will label diver pixels, and estimates will be filled in to the range image accordingly.

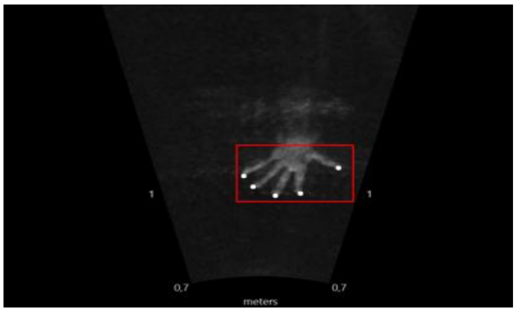
– **Sonar for gesture recognition**: For the first time, high resolution multibeam sonar data have been used to perform hand detection and gesture classification. Different signal processing algorithms were used for both tasks, and a novel method for increasing the reliability of the detected gesture has been developed.



Three images of hand detection in sonar image using a cascade of boosted classifiers based on Haar-like features.

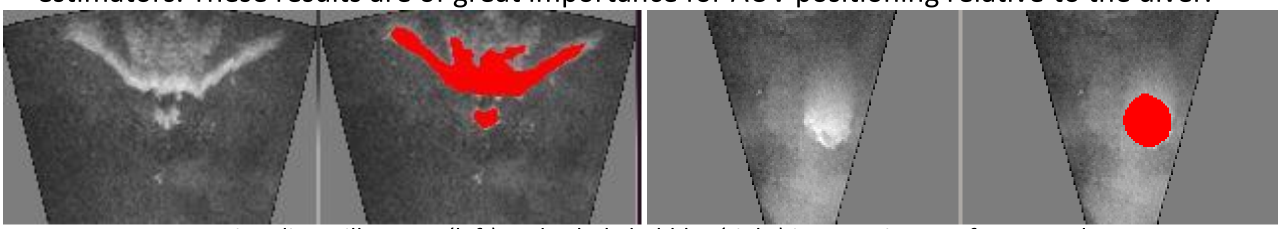


Gesture recognition from sonar by convex hull method. Convex hull (top left); all convexity defects (top right); filtered convexity defects (bottom)

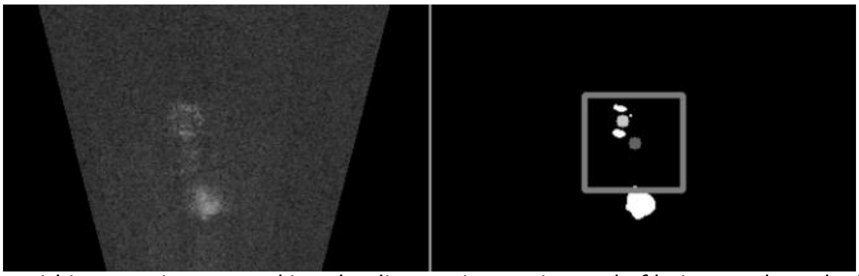


Detected fingertips within the sonar image (white dots)

– **Sonar for pose recognition:** Sonar imagery was used to detect the posture of a diver. An important step has been made in diver tracking using sonar imagery by using diver motion estimators. These results are of great importance for AUV positioning relative to the diver.



Detecting diver silhouette (left) and exhale bubbles (right) in sonar images from Pag data



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

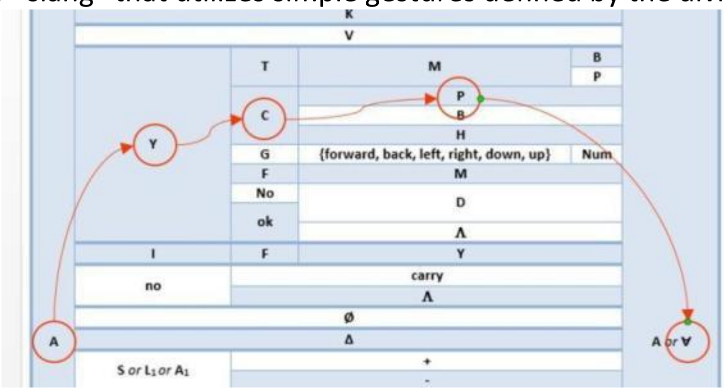
The **DiverNet** software has been extended, allowing easy calibration during field trials. In addition, a breathing belt was integrated allowing recording of breathing data for behaviour analysis.

Diver with DiverNet getting prepared for trials in the Y-40 pool (Montegrotto Terme, Italy), the deepest pool in the world.

A diver being recorded during trials. The diver's actions are tagged using a custom developed software by UNIVIE.

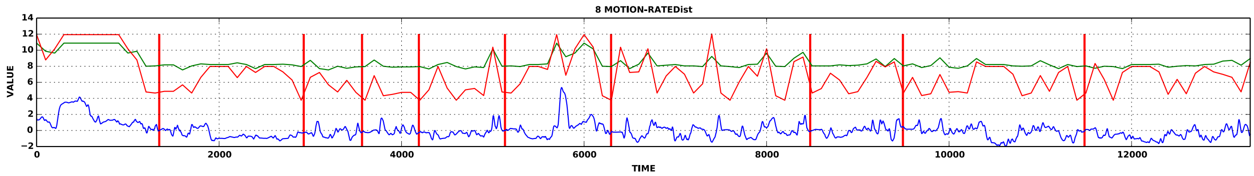
- **"Understanding the diver" – CADDIAN language and linking diver parameters (respiration, heart rate, posture) to emotions**

In the first year of CADDY project, a **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 CADDY. The developed syntax may be a bit complex for divers, therefore it has been extended with CADDY "slang" that utilizes simple gestures defined by the diving community.



"Table of possible sequences" - the table representation of the command “A Y C P ∀”(“Come to the point of interest”). In figure it can be seen that after the “C” gesture only “P” or “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).

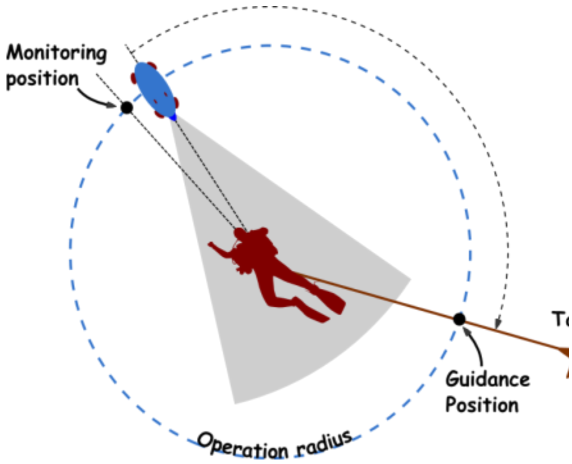
In addition, we have continued with data collection experiments in order to obtain a large dataset to be used for behavioural analysis. Using the obtained data, work on **anomaly detection** has started by implementing symbolic aggregation approximation algorithm which allows us to detect anomalies and motifs in real time.



On the x –axis are the video frames, the blue line is the motion rate, the green line is the simple distance and the red line represents the Euclidian distance of a word to all other words in the window. As you can see the t-postures from the behaviour file which are presented as vertical red lines all fall on depressions in the similarity. Thus it seems to be possible to identify certain behaviours and anomalies with this method from motion rate alone.

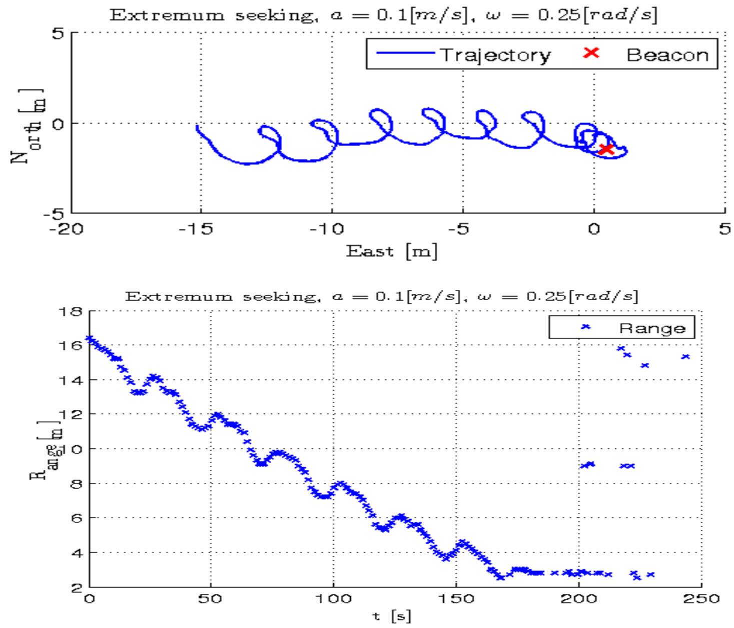
- **"Diver-Robot Cooperation and Control"**

In the second year of the project we have focussed on the **"pointer experiment"**, where the diver is arbitrarily moving in the underwater environment and the underwater vehicle is positioning itself at a safe distance relative to the diver so that it points towards the underwater target while remaining in the diver's field of view. Algorithms based on virtual target path following have been proven to offer a simple controller structure for implementing this behaviour. The algorithm was derived using a Lyapunov based approach and s was implemented in the simulator, ready to be tested in real conditions.



The "Pointer experiment" layout

The **extremum seeking** (ES) approach for underwater target localization using only range measurements was introduced and tested in simulation during the first year of the project. In the second year we focussed on testing the proposed algorithms in real conditions. Basic extremum seeking algorithm successfully localized underwater target, but alternative versions with EKF based gradient estimation showed better results due to the better speed of convergence.



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

In the area of execution of **compliant buddy tasks**, we have developed an automatic selection system for the execution of the proper autonomous robotic tasks. For the automatic selection, activation and inter-task 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.

Additional work was done in improving the implementation of the **"Make Mosaic" task**, namely the module that will perform the simultaneous localization and mapping. Specifically, the work has recently focused on the map representation.

More on 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.

3.2 Project objectives for the period

3.2.1 Overview

TO1. 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.

While most of the vehicle development work was finalized in the first year of project, in the second year we focused on final efforts to make the vehicles fully operational. Special attention was placed on integrating safety features in the form of kill switches on the BUDDY AUV. Additionally, each partner performed final integration trials that included testing vehicle functionalities. The final decision was made on the choice of primary and backup vehicles for the surface and underwater segment of the CADDY project.

Surface segment: The primary surface vehicle will be MEDUSAs (IST) while the backup vehicles is PlaDyPos (UNIZG-FER).

Underwater segment: The primary surface vehicle will be BUDDY (UNIZG-FER), an AUV built specially for CADDY purposes. BUDDY is mounted with an underwater tablet as a means of interaction with the diver. In addition it is equipped with a stereo camera, mono camera, multibeam sonar, all used for "seeing the diver". The backup vehicles is e-URoPe (CNR) a hybrid between AUV and an ROV.

Interfacing the diver: An underwater tablet casing has been designed and produced in the first year of the project. An Android application for interfacing with the diver has been developed.

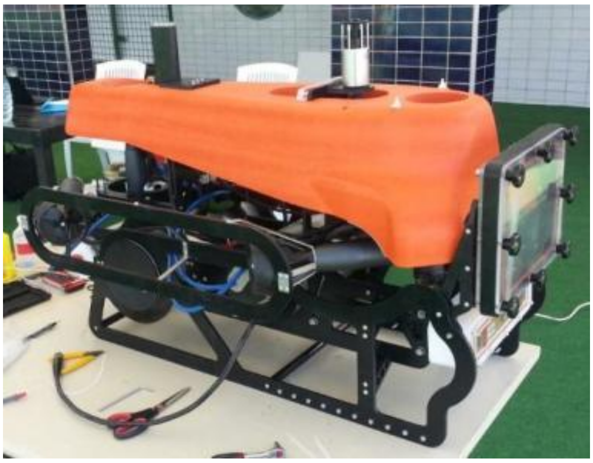
This objective has been successfully completed.

MEDUSAs by IST

- *primary surface vehicle*
- *surface vessel with two 150 mm diameter tubes*
- *1035 mm long, weigh 23-30 kg*

PlaDyPos by UNIZG-FER

- *backup surface vehicle*
- *omnidirectional vessel with 4 thrusters in X configuration 0.7 x 0.7 m, weight cca. 30 kg*



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- *primary underwater vehicle*
- *first AUV custom made for interaction with divers*
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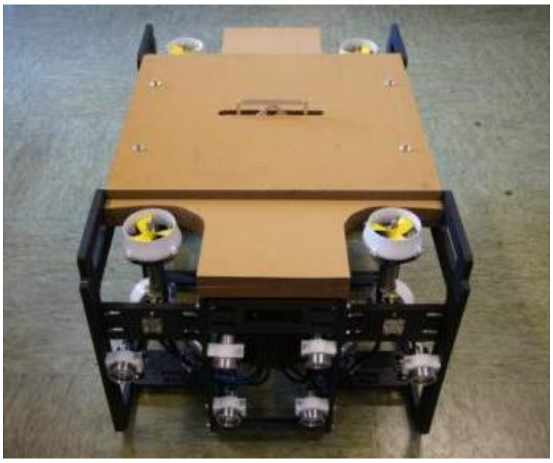


e-URoPe by CNR

- *backup underwater vehicle*
- *fully actuated underwater robotic platform with 4 horizontal and 4 vertical thrusters allows complete motion capability and hovering*
- *1.3 (length) x 0.9 (width) x 1.0 (height) m, rated up to a depth of 200 m*

TO2. Establishing a robust and flexible underwater sensing network with reliable data distribution, and sensors capable of estimating the diver pose and hand gestures.

TO2.a. Testing and evaluation of sensors that will enable pose estimation and hand gesture identification in the underwater environment.

The following set of remote sensing techniques has been successfully tested in the first year of the project: stereo camera, mono camera and multibeam sonar. All of these have proven to be efficient under different environmental conditions. Additionally, in the first year, DiverNet, a network of inertial measurement units distributed on the diver's body.

In the second year, we conducted additional **diver recording trials** at Y-40 pool (deepest pool in the world) in Montegrotto Terme, Italy, and in Lisbon, Portugal. Additionally, we collected all the data obtained during numerous diver recording trials, and published them in an **online repository** implemented as a cloud server by UNIVIE located in Vienna, Austria (https://caddy.anthro.univie.ac.at/caddycloud). Interested users can ask for access to the database, thus enabling them access to a large amount of data suitable for processing.

The **DiverNet** software has been augmented with a calibration method that proved to be a requirement during trials with divers. It consists in diver assuming a "T" pose that is used for calibration of sensors. A breathing belt was integrated with the DiverNet, allowing recording of breathing data during the experiments.

This subobjective is partially completed – in order to complete it fully, by the end of the year, a wireless version of the DiverNet will be developed. This will allow transmission of DiverNet measurements via acoustic channel.

Diver with DiverNet getting prepared for trials in the Y-40 pool (Montegrotto Terme, Italy), the deepest pool in the world.

A diver being recorded during trials. The diver's actions are tagged using a custom developed software by UNIVIE.

TO2.b. Propagation of the acquired data through the network to each agent with strong emphasis on securing reliable data transmission to the command centre for the purpose of automatic report generation and timely reporting in hazardous situations.

In the first year, a new generation of small scale USBL and acoustic modems have been developed specifically for CADDY purposes. During the second year, emphasis was put on hardware and software enhancements in order to enable consistent performance on all units within CADDY consortium and to support the ongoing commercialization of the units.

The main area of **hardware development** has been in the construction of the USBL array transducer elements to maximise accuracy of phase measurements and repeatability in construction. The construction was modified so that the ceramic elements were mounted on a small seat of acoustically matched polyurethane before over-moulding with the same material. This would eliminate any interaction with the mounting structure which was suspected to be the cause of variable response. The **USBL algorithm** has now been modified to guarantee that the USBL uses the first acoustic arrival (most accurate) to calculate position fixes, thus eliminating the multipath signal detection instead of the original signal.

New USBL/acoustic modem housing.

The work on developing an **automatic report generation system** that allows consumers (divers) consumers to build an application to select data that needs to be included in the report has started. Special attention is devoted to specifying how alarms are generated and to automatic alerting the desired authorities should an emergency arise. Every entity in the system will be accessible to the consumer through different widgets that allows acquisition, processing or manipulation of data. All widgets will be implemented as Robot Operating System (ROS) rqt plugins which can be connected together into different perspectives which are deployed depending on application and consumers preferences. The status reporting system will be aligned with an already existing unified diver exposure database called DSL (using the DL7 standard) used by DAN Europe for 15 years

TO2.c. Adaptive learning mechanism for communications scheduling based on the detection of bubble streams produced by the diver.

SO1. Achieve full understanding of diver behaviour through interpretation of both conscious (symbolic hand gestures) and unconscious (pose, physiological indicators) nonverbal communication cues.

SO1.a. Develop efficient and near real-time algorithms for diver pose estimation and gesture recognition based on acoustic and visual conceptualization data obtained in a dynamic and unstructured underwater environment.

In the first year of the project, this topic addressed only through visual diver detection from the surface platform by using algorithms based on multiple descriptors. During second year of the project, this objective has been raised to a new level by applying the following methodology for diver pose estimation and gesture recognition.

- **Mono camera for gesture recognition.**

During the gesture recognition trials using a mono camera, special attention was placed on different light conditions during the trials. In order to facilitate the recognition from the mono camera, artificially marked gloves have been used. With the aim of making easier and more reliable the process of the automatic hand gesture recognition, the diver gloves have been modified adding: quad-markers on both the palm and the backside of the glove; and colour bands on each finger (with a different colour for each finger). The analysis and preliminary computations on the gathered images are currently ongoing.

Gesture execution during swimming pool trials. Marked gloves allow easier detection of the diver gestures even under challenging light conditions and turbid waters.

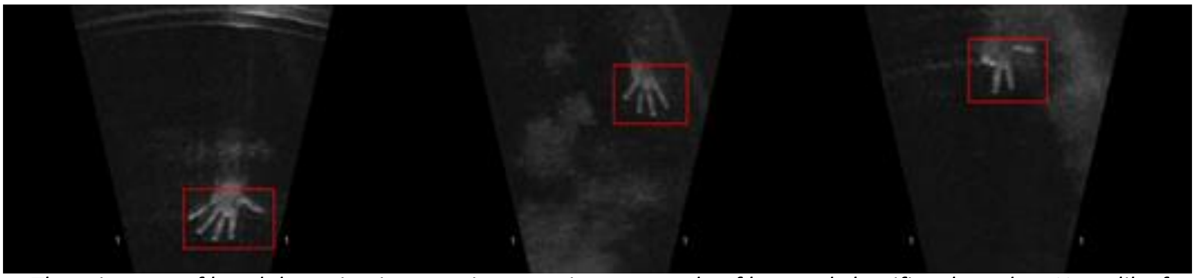
- **Stereo camera for pose and gesture recognition**

The data recorded using a stereo camera covered a variety of gestures belonging to the CADDIAN language – both static and dynamic. A range of conditions was also tested: different distances to the camera, viewing angles etc. The recorded data was then processed to produce 3D point clouds. This early-stage processing gave very promising results.

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. This will be mitigated by a fused approach: A classifier will label diver pixels, and estimates will be filled in to the range image accordingly.

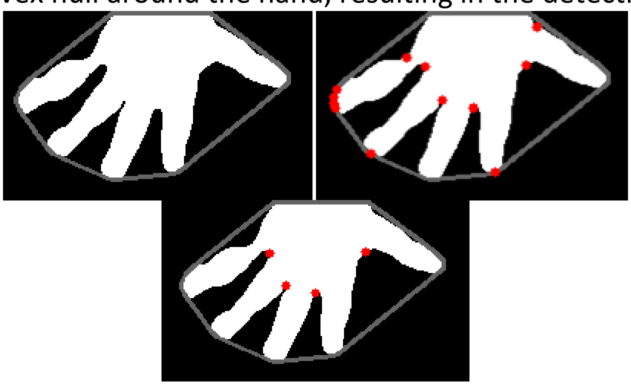
- **Sonar for gesture recognition**

Hand gesture recognition system is 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 by Viola and Jones. For this purpose classifier is trained to detect five hand gestures containing different number of visible fingers.

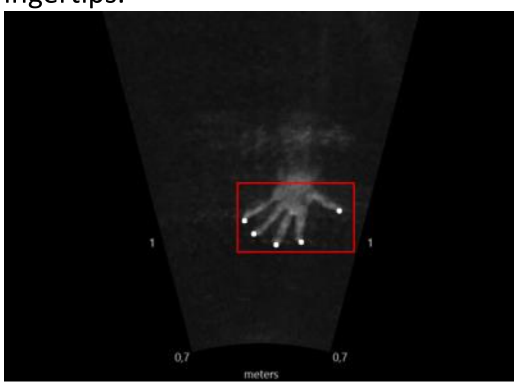


Three images of hand detection in sonar image using a cascade of boosted classifiers based on Haar-like features.

After hand detection step, area marked by cascade classifier is used for further processing and **gesture recognition**. Two approaches were used for gesture recognition. First, a convex hull method that uses binary thresholded image to extract the contour of the hand and calculate a convex hull around the hand, resulting in the detection of fingertips.



Gesture recognition from sonar by convex hull method. Convex hull (top left); all convexity defects (top right); filtered convexity defects (bottom)



Detected fingertips within the sonar image (white dots)

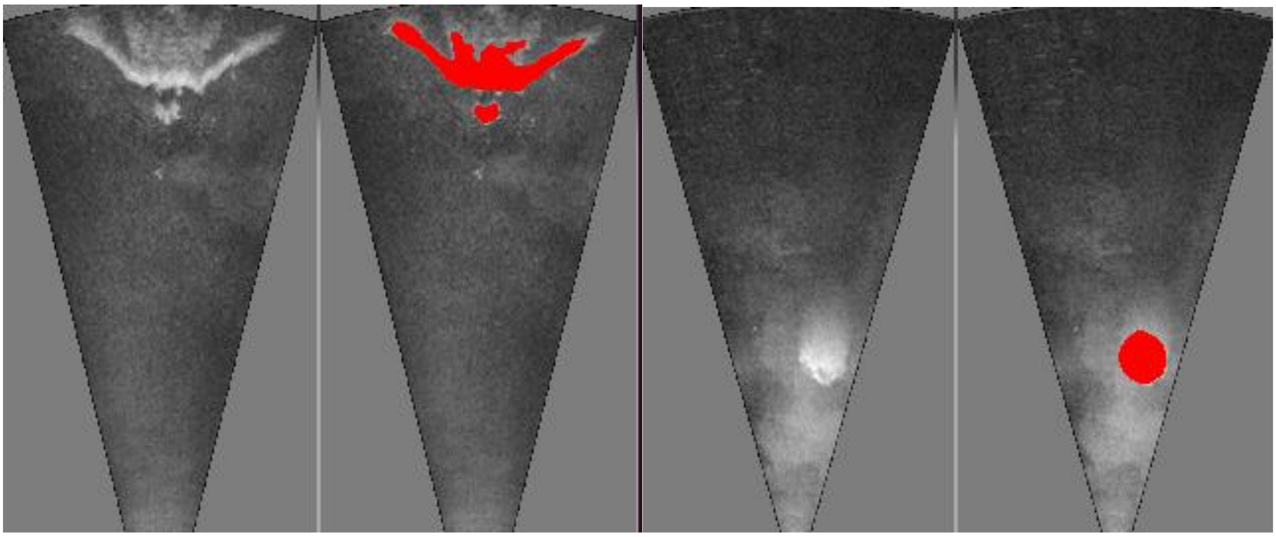
Second, a multiclass support vector machine was used to classify five different gestures shown below.

A set of hand gestures used for support vector machine (SVM) recognition.

Both methods show good results. However, by 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 when a gesture is recognized, the recognition is performed with more than 98% accuracy.

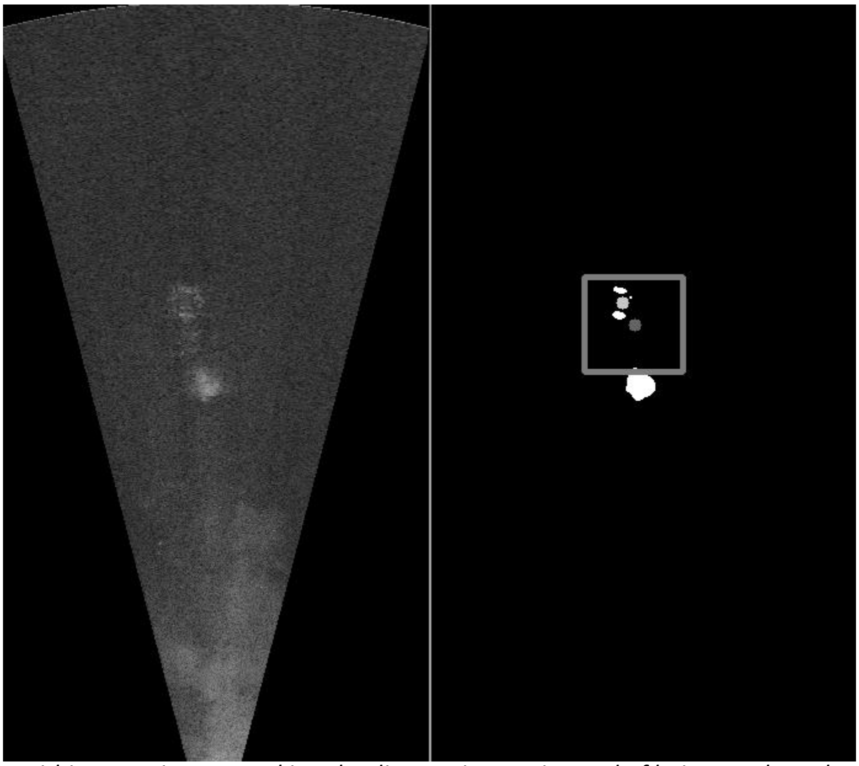
- **Sonar for pose recognition**

The sonar image was thresholded and the contours which are a result of diver presence were detected. First, the image is blurred to smooth the sonar noise. After that OpenCV's adaptive threshold function is used to create a binary image, setting high-value regions to white. Since the Cartesian space sonar image is used, which has a sector shape, and all the image processing algorithms work on rectangular images, the outside of the useful sonar image is coloured in neutral grey to avoid artefacts on the edge region. The detected contours are later processed to find the ones that might represent the diver.



Detecting diver silhouette (left) and exhale bubbles (right) in sonar images from Pag data

As an integral part of the sonar pose estimation, is the diver tracking algorithm. In order to position the BUDDY vehicle precisely relative to the diver, a diver tracking algorithms has to be developed. The greatest challenge in this is to differentiate between the diver in the sonar image and the bubbles exerted by the diver. For this purpose, the diver tracking algorithms is augmented with a diver motion estimator.

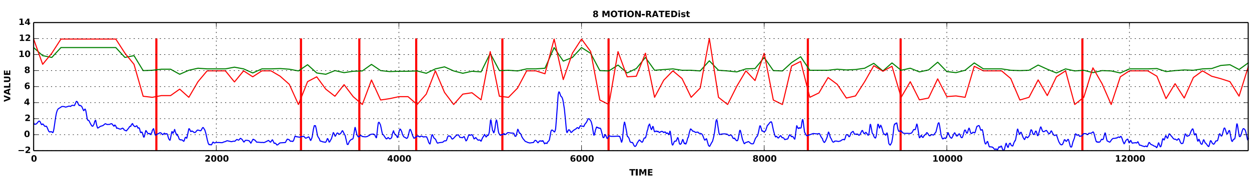


Region of interest within sonar image tracking the diver estimator instead of being stuck on the bubbles that are dominant in the image.

SO1.b. Develop adaptive algorithms for interpretation of diver behaviour based on nonverbal communication cues (diver posture and motion) and physiological measurements.

In the first year we focused on extensive data collection. In the second year, the processing of this data took its full pace. A **software for synchronized reproduction** of video and DiverNet data has been developed to simplify the analysis of large amounts of data.

Using the obtained data, work on **anomaly detection** has started by implementing symbolic aggregation approximation algorithm which allows us to detect anomalies and motifs in real time.



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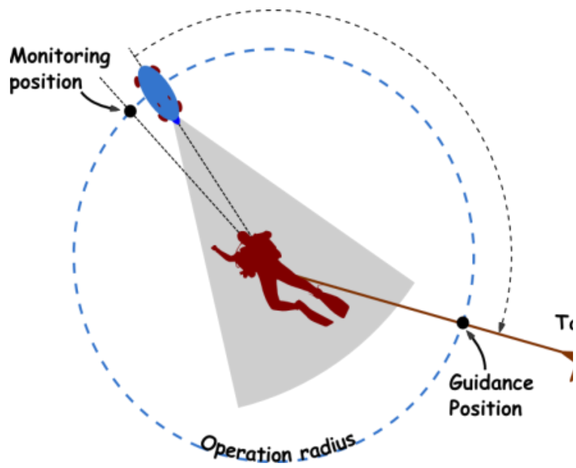
SO2. Define and implement execution of cognitive guidance and control algorithms through cooperative formations and manoeuvres in order to ensure diver monitoring, uninterrupted mission progress, execution of compliant cognitive actions, and human-machine interaction.

SO2.a. Develop and implement cooperative control and formation keeping algorithms with a diver as a part of the formation.

In the first year, the following set of experiments has been conducted: 1) **"surface leader"**, where the underwater vehicle has to track the surface vehicle that is running along a predefined track; 2) **"underwater leader"**, where the underwater vehicle is following a predefined path while the surface vehicle is tracking it; and 3) **"diver leader"** where the diver is moving in the underwater environment while tracked by the surfaced vehicle using data obtained via acoustic channel.

In the second year of the project we have focussed on the **"pointer experiment"**, where the diver is arbitrarily moving in the underwater environment and the underwater vehicle is positioning itself at a safe distance relative to the diver so that it points towards the underwater target while remaining in the diver's field of view. Algorithms based on virtual target path following have been proven to offer a simple controller structure for implementing this behaviour. The algorithm was derived using a Lyapunov based approach and s was implemented in the simulator, ready to be tested in real conditions.

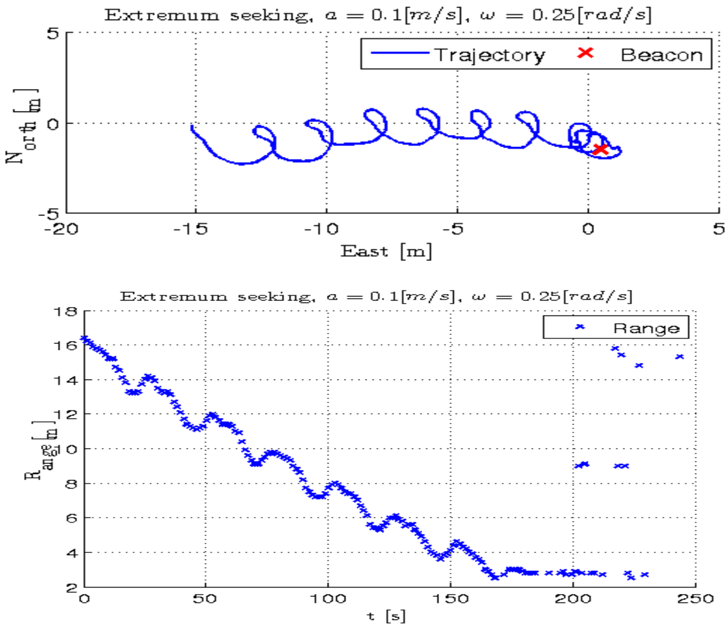


The "Pointer experiment" layout

SO2.b. Develop cooperative navigation techniques based on distributed measurements propagated through acoustically delayed sensing network.

The **extremum seeking** (ES) approach for underwater target localization using only range measurements was introduced and tested in simulation during the first year of the project. In the second year we focussed on testing the proposed algorithms in real conditions. By using only range measurements surface vehicle was able to localize underwater target, i.e. diver, and stay on top of its position. Test setup consisted of PlaDyPos platform with USBL modem which provided range measurements from VideoRay ROV which simulated the diver. Basic extremum seeking algorithm successfully localized underwater target, but alternative versions with EKF based gradient estimation showed better results due to the better speed of convergence.

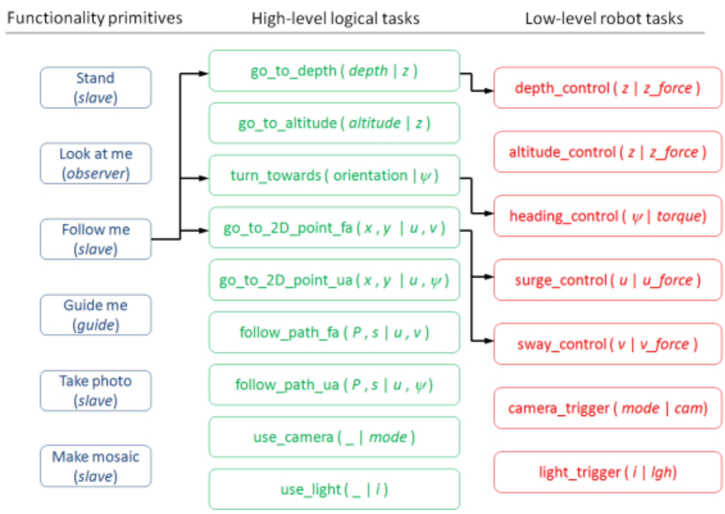
Great advantage of ES is the fact that constant disturbances acting on vehicle, i.e. gravity, buoyancy, currents are automatically compensated by ES control loop which was supported by experimental data. Over 40 tests using extremum seeking algorithms were successfully conducted in changing conditions which shows robustness of approach.



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

SO2.c. Execution of compliant buddy tasks initiated by hand gestures.

The aim of providing a compliant behaviour of the overall robotic system, with respect to the operations undertaken by the diver, is made available through the development of an **automatic selection system** for the execution of the proper autonomous robotic tasks. For the automatic selection, activation and inter-task conflict management, a Petri net based execution control system, is under current development. The developed system is capable of detecting and avoiding logical conflicts that may appear when two conflicting high-level logical tasks are activated.



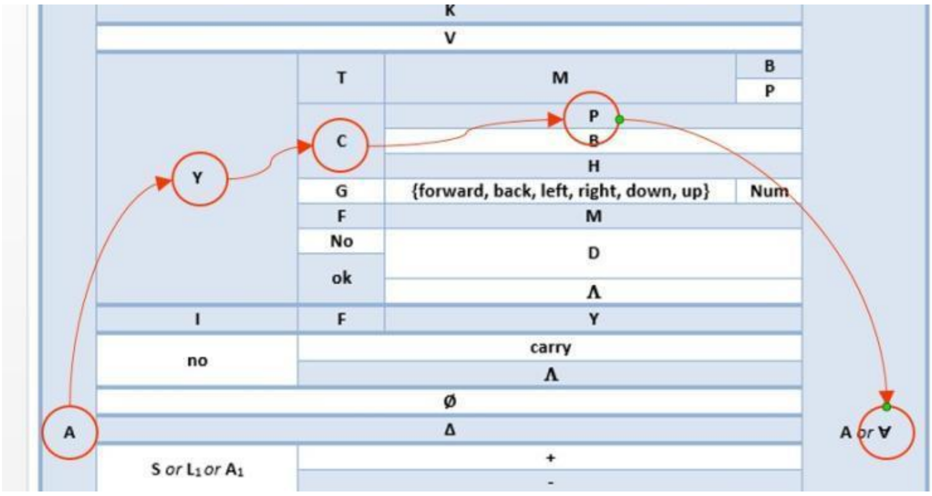
An example of "follow me" primitive activation for fully-actuated robot. Such a primitive requires the system to turn on the following functionalities: "go_to_depth" to reach and maintain a desired depth; "go_to_2D_point_fa" to track a 2D point for fully-actuated platforms; "turn_towards" enabling the auto-heading to always look towards the diver.

Additional work was done in improving the implementation of the **"Make Mosaic" task**, namely the module that will perform the simultaneous localization and mapping. Specifically, the work has recently focused on the map representation. A coloured occupancy map implemented with the octomap (https://octomap.github.io/) library was developed, including a corresponding visualization in RViz.

SO3. Develop a cognitive mission (re)planner which functions based on interpreted diver gestures that make more complex words.

SO3.a. Develop an interpreter of a symbolic language consisting of common diver hand symbols and a specific set of gestures.

The new version of CADDIAN language has been created following the reviewers' suggestions for a simpler language or better for a language which has a simpler minimal set of gestures recognizable by all divers all over the world. The new version of CADDIAN also contains a sequence table (i.e. "Table of possible sequences") where the whole language is represented. The table has been created to be useful for the classifier, given the fact it shows which gesture can follow a given one.



"Table of possible sequences" - the table representation of the command "A Y C P ∀" ("Come to the point of interest"). In figure it can be seen that after the "C" gesture only "P" or "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).

SO3.b. Development of an online cognitive mission replanner.

3.2.2 Follow-up of previous review

The main recommendations from the reviewers concerning the period under review are:

- ***The reports should make clearer or specifically remark the following two aspects:***
  - ***The actual progress of the projects developments with respect to the state of the art.***
  - ***The work that was already done in the project with respect to the work planned as future actions or still to be done.***

The structure of the report was been revised in a sense that state of the art, as well as indications of the work already done in the project are clearly emphasized.

The main recommendations from the reviewers for the next period are.

- ***Regarding the reports: improve them according to the comments above.***
- ***Regarding the development of a new language of signs for underwater communication: make it as limited and simple as possible. The reason is that, otherwise, it could become a barrier for acceptability of the divers.***

Additional efforts were made by the partners to simplify the developed CADDIAN language according the end-users' and reviewers' inputs. Even though the proposed CADDIAN structure is required for issuing complex commands to the BUDDY AUV, we have acknowledged the need for a set of simpler, easy-to-generate, gestures similar to those that are used among the diver population. For this reason "CADDIAN slang" has been developed with a short list of simple commands that will be recognized by the BUDDY AUV.
Deliverable *D3.1 Initial list of gestures and syntax* has been modified with the new inputs. It is expected that the syntax will be further modified based on end-user requirements.

- ***Regarding the devices used for experimentation: focus on one particular device trying to get maximum benefit from it, instead of investing time and effort in having several different devices operative.***

This comment has been fully acknowledged. For this reason we have focused the development around primary and backup vehicles as follows. The primary surface vehicle will be MEDUSA$_S$ (by IST) with a backup vehicle PlaDyPos (by UNIZG-FER). The primary underwater vehicle will be BUDDY (by UNIZG-FER) with a backup vehicle e-URoPe (by CNR).

- ***Regarding the identification of the diver behaviour/emotion: the tools are being developed in dry land, even when they are promising, try to move a soon as possible to underwater world.***

Additional data collection experiments with divers performing underwater tasks has been completed in order to extend the database of diver behaviour. All the developed technology which has been tested on dry land has also been used in the underwater environment. Analysis of this behavioural data is in progress.

3.3 Work progress and achievements during the period

3.3.1 Progress overview and contribution to the research field

Three core research themes have been set within the CADDY project: 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. The following part summarizes the progress in each research theme and emphasizes main contributions.

- **Development of the multicomponent system**

State-of-the-art: There is a large number of both surface and underwater autonomous vehicles that are being used by industry and research institutions for operations such as underwater mapping, surveillance and recently even for underwater 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 interaction with divers, taking into account specific design requirements such as interfaces for diver interaction and safety issues.

In addition to that, current accomplishments in underwater acoustics and positioning increase on a daily basis due to a large need for high bandwidth underwater communication and positioning. Having in mind that GPS signal and electromagnetic waves cannot penetrate under water, acoustics are commonly used in the underwater environment. Underwater modems and ultra-short baseline (USBL) positioning devices by Woods Hole Oceanographic Institute, Evologics Gmbh, Tritech, etc. present state of the art devices with bandwidths measured in kilobits per second, are characterized with high price and somewhat larger dimensions, which are not applicable in scenarios that involve interaction with divers.

Achievements:

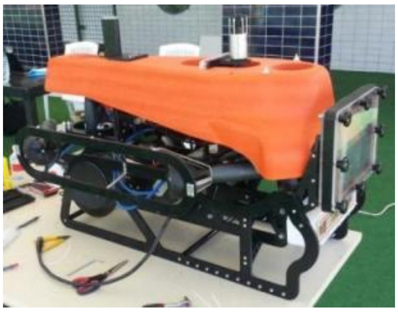
Within CADDY, we have formed a multicomponent robotics system consisting of the following vehicles covering both surface and underwater segments:

***MEDUSA$_S$* by IST**

- *primary surface vehicle*
- *surface vessel with two 150 mm diameter tubes*
- *1035 mm long, weigh 23-30 kg*

PlaDyPos by UNIZG-FER

- *backup surface vehicle*
- *omnidirectional vessel with 4 thrusters in X configuration 0.7 x 0.7 m, weight cca. 30 kg*



BUDDY AUV by UNIZG

- *primary underwater vehicle*
- *first AUV custom made for interaction with divers*
- *fully actuated with 6 thrusters*
- *stereo and mono camera, high-res multibeam sonar*
- *mounted UW tablet for providing feedback to diver*

e-URoPe by CNR

- *backup underwater vehicle*
- *fully actuated underwater robotic platform with 4 horizontal and 4 vertical thrusters allows complete motion capability and hovering*
- *1.3 (L) x 0.9 (W) x 1.0 (H) m, rated up to200 m*

A **new set of modems and navigation systems** units has been developed by UNEW. The main difference to already existing devices available in the market are small dimensions regardless of the fact that all the electronics is embedded in the modem/USBL housing.

- **"Seeing the diver" – remote sensing and the DiverNet**

State-of-the-art: Remote sensing in the underwater using cameras and sonars is mostly used for underwater mapping of large seabed areas and underwater structures. Main challenges that are present in the underwater environments are related with low visibility in turbid waters and constant influence of disturbances in the form of underwater currents, wind and waves. While mapping using mono cameras has reached its maturity and is currently being exploited commercially, using stereo cameras for segmentation in the underwater still poses an issue. Main challenges remain in using SLAM techniques that are robust enough to work in environments that are often characterized with low number of features. As sonar technologies are becoming more available to the research community, advances in sonar-based mosaicking are also noted, e.g. in FP7 PANDORA project where mapping of underwater structures (such as chains) has been accomplished. There is very little note of using sonars for detection and tracking of small objects such as divers or even parts of a diver body.

While pose reconstruction using networks of inertial measurements is common in movie industries and research related to human motion on dry land, there has been no mention of using these technologies in the underwater environment. Only as part of CADDY project has DiverNet, a body network of inertial sensors for pose reconstruction, been developed in the first year.

Achievements:

Significant achievements have been made in diver gesture and posture recognition using mono cameras, stereo cameras, sonars. In addition, an innovative body network of inertial sensors has been developed which allows for the first time near real time visualization of diver posture.

- **Mono camera for gesture recognition:** A large amount of data of divers wearing artificially marked gloves have been collected. The gloves were designed with the aim of making easier and more reliable the process of the automatic hand gesture recognition

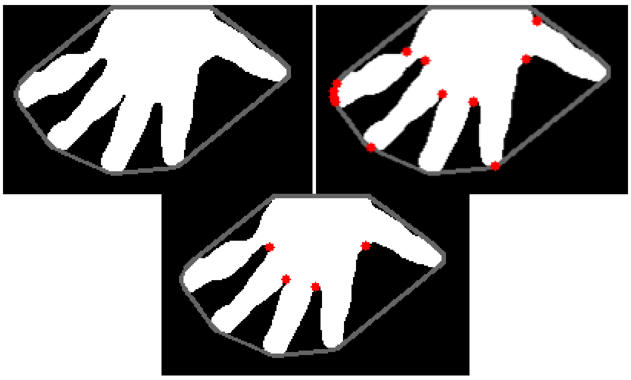
Gesture execution during swimming pool trials. Marked gloves allow easier detection of the diver gestures even under challenging light conditions and turbid waters.

- **Stereo camera for pose and gesture recognition:** 3D point clouds of diver posture and hand gestured were produced using a stereo camera. Initial processing gave very promising results.

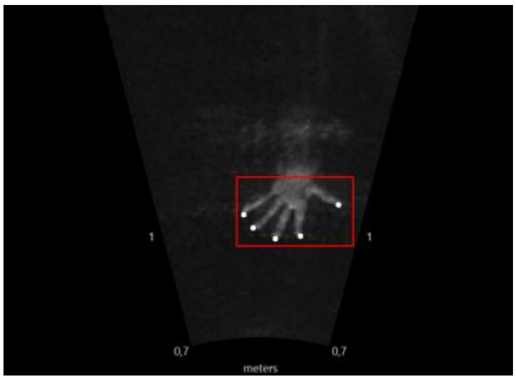
Resulting point clouds from the stereo images collected. Note that the contours of the diver are visible, but due to the lack of texture on the wetsuit, most of the diver is not properly reconstructed in 3D. This will be mitigated by a fused approach: A classifier will label diver pixels, and estimates will be filled in to the range image accordingly.

- **Sonar for gesture recognition**: For the first time, high resolution multibeam sonar data have been used to perform hand detection and gesture classification. Different signal processing algorithms were used for both tasks, and a novel method for increasing the reliability of the detected gesture has been developed.

Three images of hand detection in sonar image using a cascade of boosted classifiers based on Haar-like features.

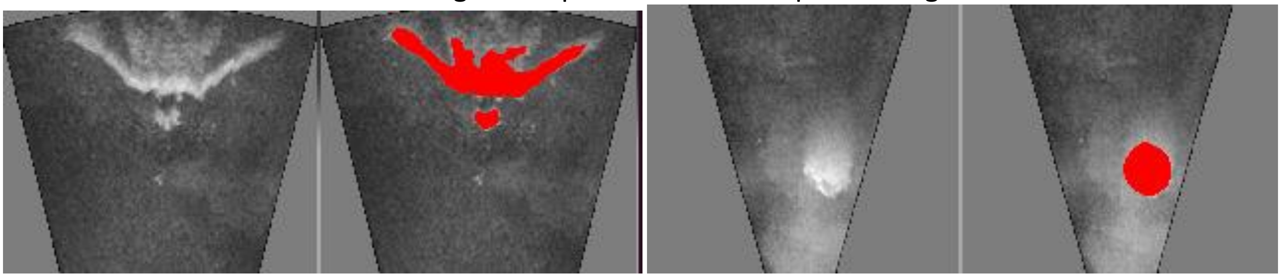


Gesture recognition from sonar by convex hull method. Convex hull (top left); all convexity defects (top right); filtered convexity defects (bottom)

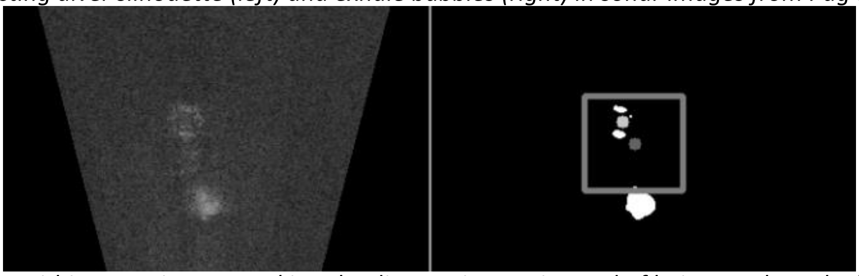


Detected fingertips within the sonar image (white dots)

– **Sonar for pose recognition:** Sonar imagery was used to detect the posture of a diver. An important step has been made in diver tracking using sonar imagery by using diver motion estimators. These results are of great importance for AUV positioning relative to the diver.



Detecting diver silhouette (left) and exhale bubbles (right) in sonar images from Pag data



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

The **DiverNet** software has been extended, allowing easy calibration during field trials. In addition, a breathing belt was integrated allowing recording of breathing data for behaviour analysis.

Diver with DiverNet getting prepared for trials in the Y-40 pool (Montegrotto Terme, Italy), the deepest pool in the world.

A diver being recorded during trials. The diver's actions are tagged using a custom developed software by UNIVIE.

- **"Understanding the diver" – CADDIAN language and linking diver parameters (respiration, heart rate, posture) to emotions**

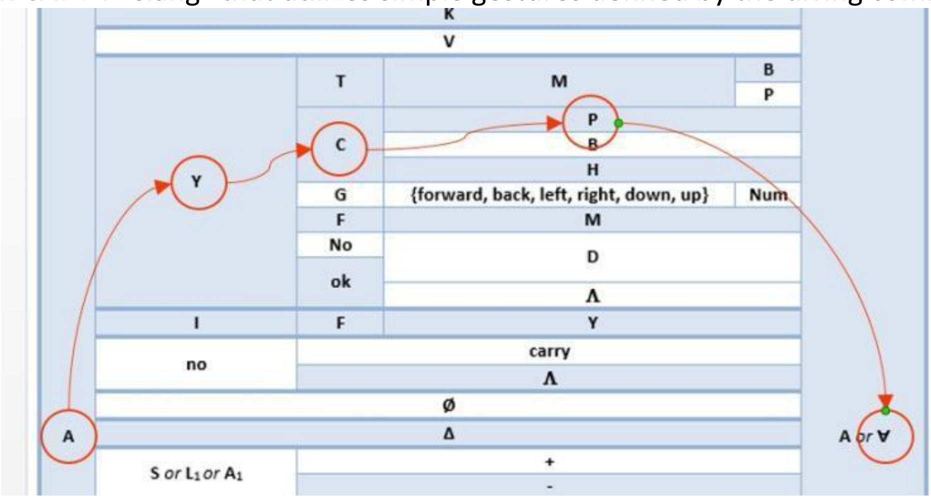
<u>State-of-the-art</u>: Interpreting human behaviour on dry land is a research topic of great interest for behavioural anthropologists and scientists. One of the methods that has attracted attention is placing a human that is under observation inside the pleasure-arousal-dominance (PAD) space.

When a human is observed, her/his extremities and posture are recorded, and afterwards the subject is interrogated via a questionnaire on their state. Then the posture is mapped to the questionnaire results, providing a large dataset that can be used to determine the link between the posture and human state. In addition to that, 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. Even though significant results have been obtained through experiments on dry land, there is no record of similar experiments being conducted on divers, under water, apart from those within CADDY project. The fact that divers have limited motion capabilities underwater, may be a beneficial factor for behaviour analysis – this is an aspect that is left to be investigated.

Using hand gestures that form a structured language is a common thing among deaf people. There even exist software that use 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 Kinect, have been developed for the purpose of detecting complex gestures. The situation is somewhat different in the underwater environment. Even though 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.

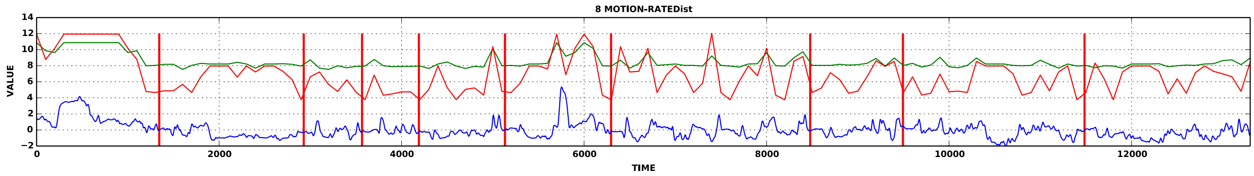
<u>Achievements:</u>

In the first year of CADDY project, a **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 CADDY. The developed syntax may be a bit complex for divers, therefore it has been extended with CADDY "slang" that utilizes simple gestures defined by the diving community.



"Table of possible sequences" - the table representation of the command “A Y C P ∀” (“Come to the point of interest”). In figure it can be seen that after the “C” gesture only “P” or “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 addition, we have continued with data collection experiments in order to obtain a large dataset to be used for behavioural analysis. Using the obtained data, work on **anomaly detection** has started by implementing symbolic aggregation approximation algorithm which allows us to detect anomalies and motifs in real time.



On the x –axis are the video frames, the blue line is the motion rate, the green line is the simple distance and the red line represents the Euclidian distance of a word to all other words in the window. As you can see the t-postures from the behaviour file which are presented as vertical red lines all fall on depressions in the similarity. Thus it seems to be possible to identify certain behaviours and anomalies with this method from motion rate alone.

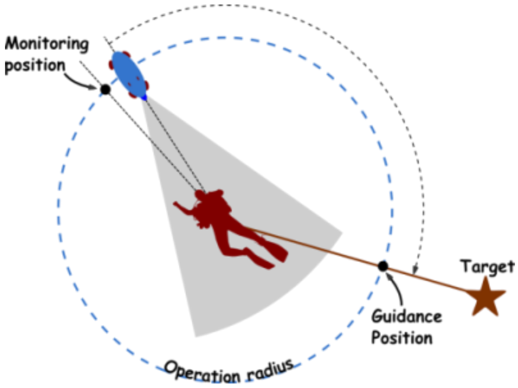
- **"Diver-Robot Cooperation and Control"**

State-of-the-art: There have been significant advances made in the area of cooperative marine control recently. As an example, FP7 MORPH project deals with cooperation between 5 heterogeneous marine vehicles (one surface and 4 underwater) in order to map underwater environments in a coordinated way. Some of the greatest challenges include communication between the units – acoustic communications are characterized with low bandwidth and delays due to the nature of acoustic wave propagation. These issues can be dealt with is precise estimators are embedded in each vehicle – by knowing the mission, each vehicle can efficiently estimate the behaviour of every other vehicle, and feed these estimators with intermittent measurements. The challenge that still remains is how to incorporate one "vehicle" whose behaviour cannot be predicted, i.e. a diver. Some results have been obtained by IST team prior to CADDY project where a triplet of surface vehicle was used to guide the diver through the underwater environment. Within CADDY, a surface platform was used to both track and navigate the diver in the underwater environment. The challenge to be solved is how to incorporate an underwater vehicle in this diver interacting formation.

One of the largest issues in the underwater environment is underwater navigation. Due to the lack of standard GPS, underwater navigation is a challenging task which is resolved by using ultra-short baseline positioning units (based on acoustic measurements), Doppler velocity speed measurements for dead reckoning, or occasional surfacing for the purpose of navigation filter correction by using GPS available at the surface. A more ambitious, novel approach, is to use single range measurements, from a single point (i.e. a surface vehicle). The main issue that arises is the observability of the navigation filter when only ranges are used – this can be solved by ensuring persistently exciting motion of the surface vehicle. Research has been conducted in this area, but the challenge is to try to ensure these persistently exciting manoeuvres, while deviating from the predefined path as little as possible. This type of research has not been conducted using divers as targets that should be tracked/navigated.

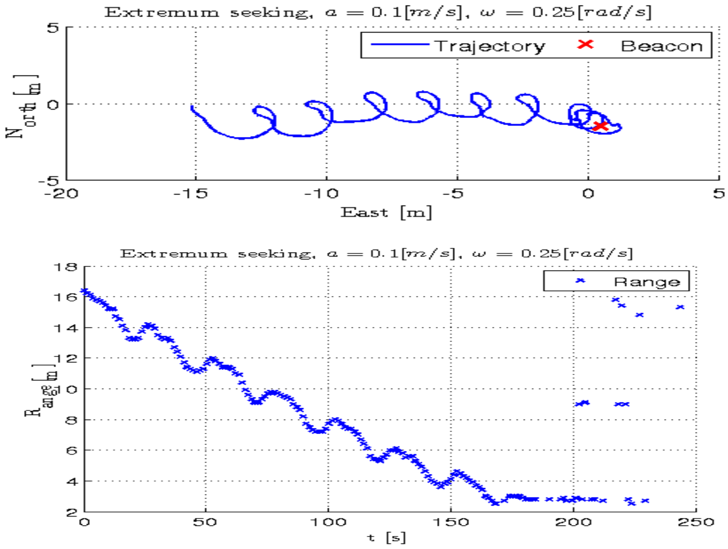
Achievements:

In the second year of the project we have focussed on the **"pointer experiment"**, where the diver is arbitrarily moving in the underwater environment and the underwater vehicle is positioning itself at a safe distance relative to the diver so that it points towards the underwater target while remaining in the diver's field of view. Algorithms based on virtual target path following have been proven to offer a simple controller structure for implementing this behaviour. The algorithm was derived using a Lyapunov based approach and is was implemented in the simulator, ready to be tested in real conditions.



The "Pointer experiment" layout

The **extremum seeking** (ES) approach for underwater target localization using only range measurements was introduced and tested in simulation during the first year of the project. In the second year we focussed on testing the proposed algorithms in real conditions. Basic extremum seeking algorithm successfully localized underwater target, but alternative versions with EKF based gradient estimation showed better results due to the better speed of convergence.



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

In the area of execution of **compliant buddy tasks**, we have developed an automatic selection system for the execution of the proper autonomous robotic tasks. For the automatic selection, activation and inter-task 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.

Additional work was done in improving the implementation of the **"Make Mosaic" task**, namely the module that will perform the simultaneous localization and mapping. Specifically, the work has recently focused on the map representation.

3.3.2 Work packages progress

WP1 Robotic diver assistance system

T1.1. The surface segment (UNIZG-FER, IST)

As part of the effort to afford the members of the CADDY project marine vehicles to test and assess the efficacy of the methods developed for cooperative motion control, the MEDUSA vehicles of IST were upgraded and fully tested, as explained below.

To reduce the exposure to human divers, a new carbon fiber frame was installed on the MEDUSA vehicles in order to hide any sharp edges. Thruster blades are also well covered with a protective nozzle.

Fig. 3.1.1 a) A MEDUSA$_S$ vehicle with the new carbon fiber frame b) thrusters protective nozzle

For navigation and control purposes, the Seatrac USBL unit was installed in the lower body of one the MEDUSA vehicles. Preliminary trials aiming at assessing the performance of the unit were conducted at the EXPO 98 site, Lisbon, Portugal; they will be described later in this document.

Fig. 3.1.2 Seatrac USBL mounted on Medusa Yellow

T1.2. The underwater segment

BUDDY AUV (UNIZG-FER)

Great effort was made in first three months in second year to increase diver safety on Buddy vehicle while working with divers. We added protectors on each side of the vehicle so that diver's hands can't get in between the thrusters (Fig. 1.2.1).

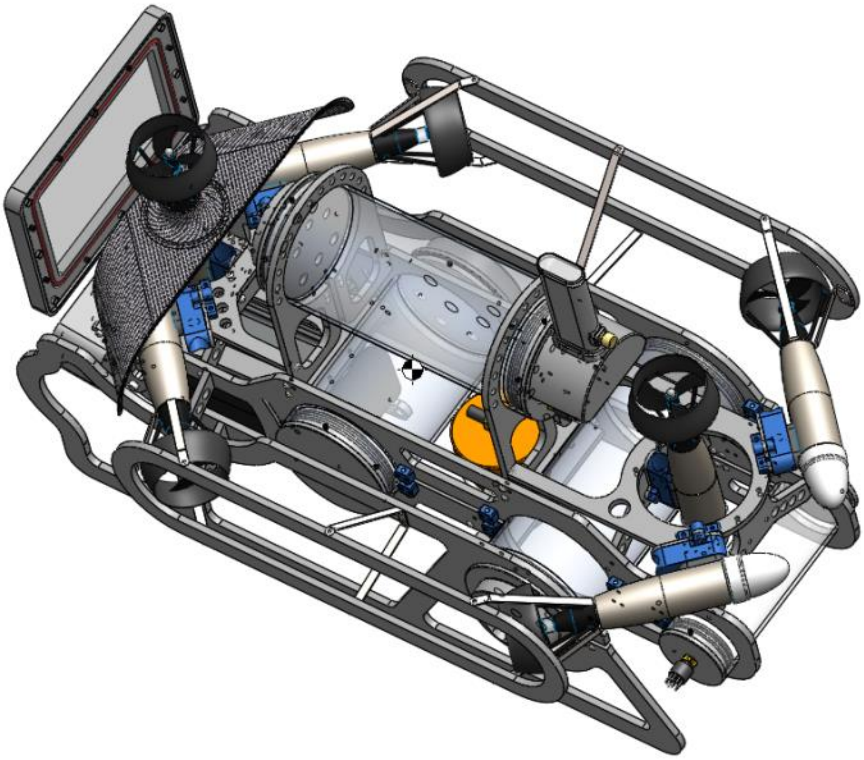


Figure 1.2.1. Buddy side protectors

One of safety requirements that was requested is adding kill switches to the outer shell of the Buddy vehicle. Kill switch has function to cut power to the thrusters to avoid injuries of the diver if the vehicle starts to behave unusual. There are two types of kill switches installed on the vehicle:

- Haptic kill switch – if the IMU inside the vehicle senses push or kick from the diver, i.e. if accelerometer values become atypical, CPU cuts power to solid state relay which powers the thrusters.
- Reed kill switch – there are five reed relays installed on the vehicle. Two of them are in the front, two on each side and one reed relay is on the back of the vehicle. If magnet is removed from the reed switch, like haptic kill switch, it cuts power to solid state relay which delivers power to the thrusters.

Figure 1.2.2. Haptic and reed kill switch

In addition to improving safety on the vehicle, floating block foam was purchased and cutting of the foam to desired shape is almost finished (Fig. 1.2.2.). The foam is able to withstand pressure up to 190 m with crush point of 300 m.

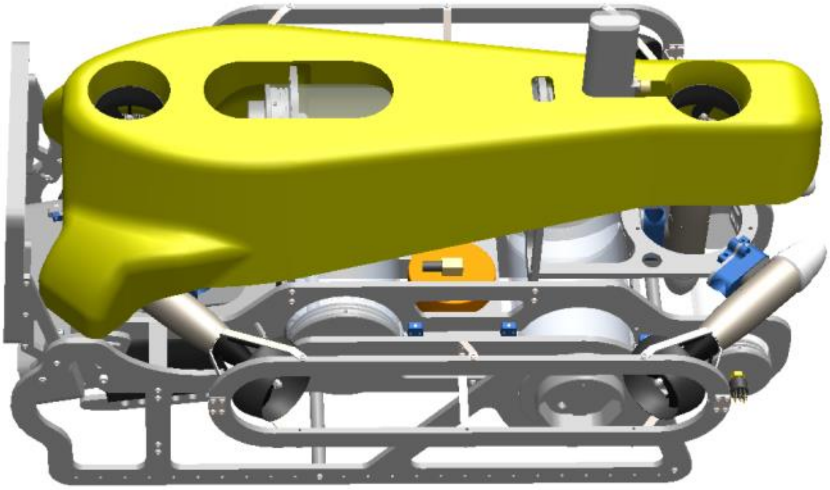


Figure 1.2.3. Floating block model

To increase flow of the front vertical thruster, custom fiberglass fairing was made (Fig. 1.2.3.).

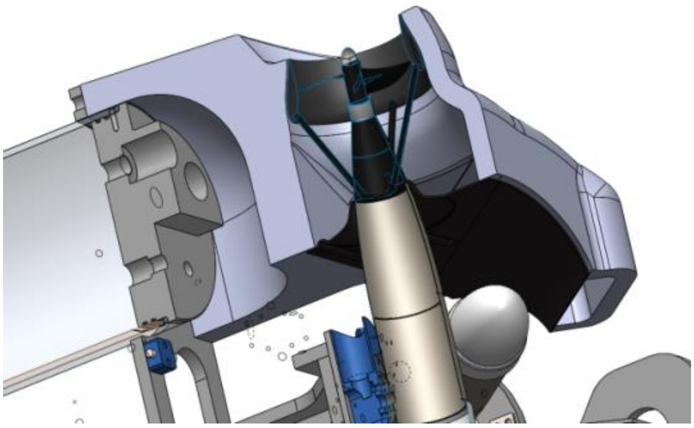


Figure 1.2.4. Floating block model

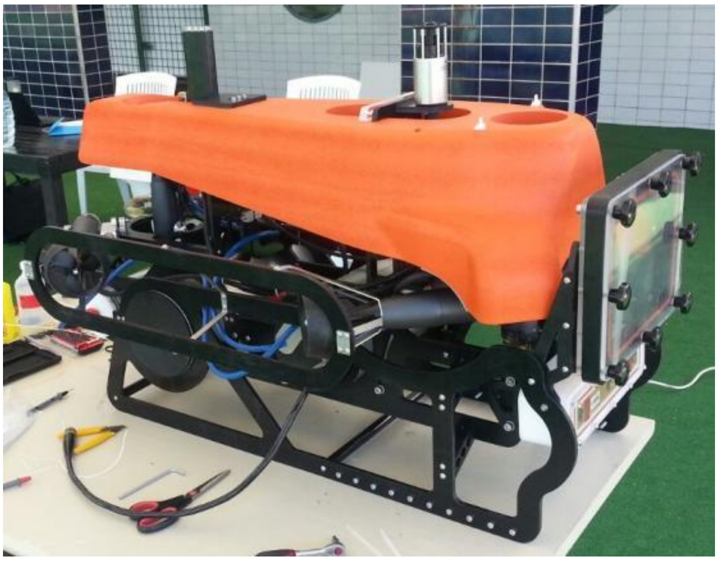



Figure 1.2.5. Sea trials, Biograd, May 2015

e-URoPe AUV/ROV development (CNR)

The hybrid AUV/ROV robotic platform e-URoPe is characterized by reduced dimensions, 1.0 (length) x 0.7 (width) x 0.5 (height) m, and maximum operating depth of 200 m. The vehicle guarantee the complete navigation capabilities thanks to fully actuated propulsion configuration (4 horizontal and 4 vertical thrusters) and the presence of inertial sensors for attitude and acceleration measurements, combined with a DVL system for velocity reading. The integration of the compact USBL device provided by UNEW allows the relative position localization providing a more accurate navigation capability during coordinated manoeuvres. The exploitation of the optic fiber link (in ROV mode) allows the transmission of high-bandwidth sensor data (as cameras and multi-beam sonar systems) as well as online functionality verification and debugging.

The main parts of e-URoPe AUV/ROV are reported in the following figures:

- frame - Fig. 1.2.6
- cylinder for electronics - Fig. 1.2.7
- cylinder for batteries - Fig. 1.2.8
- buoyancy - Fig. 1.2.9
- thruster - Fig. 1.2.10

The exploded and assembled vehicle drawings are respectively shown in Fig. 1.2.11 and Fig. 1.2.12.

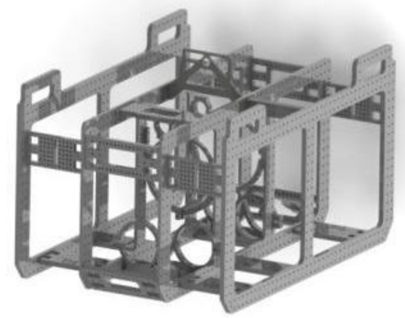


Fig. 1.2.6. Vehicle frame

Fig. 1.2.7. Cylinder for electronics

Fig. 1.2.8. Battery cylinder

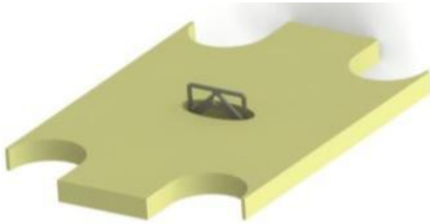


Fig. 1.2.9. Buoyancy

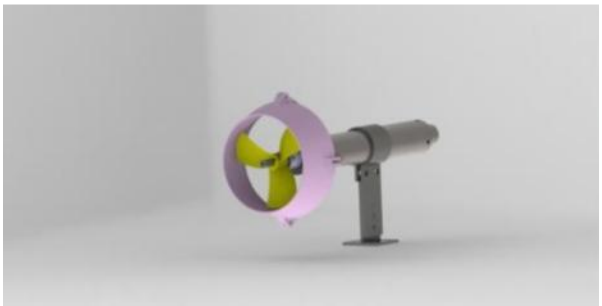


Fig. 1.2.10. Thruster

Fig. 1.2.11. Exploded drawing

Fig. 1.2.12. Complete vehicle

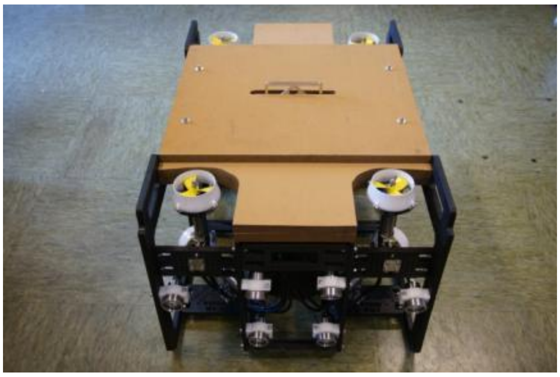


Fig. 1.2.13. Actual vehicle assembly

For the thruster characterization, a set of tank trials identification phases have been carried out to: i) determine the best propeller choice in terms of produced thrust and power consumption; ii) characterize the thrust curve. The selected propeller is a 3-blade Kaplan B65, while the thrust curve is reported in Figure 1.2.14, where the measured thrust value are reported and super-imposed with a quadratic interpolating curve.

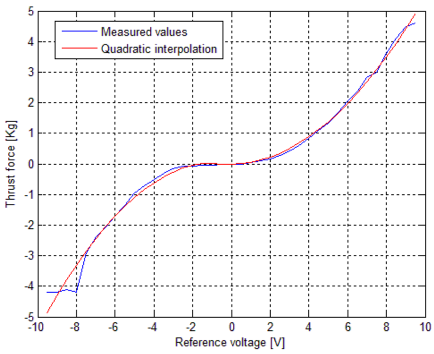


Fig. 1.2.14. Thruster curve and interpolating function

T1.3. Interfacing the diver to the surface and underwater segments (CNR, IST, UNIZG-FER)

Android application for the diver tablet (UNIZG-FER)

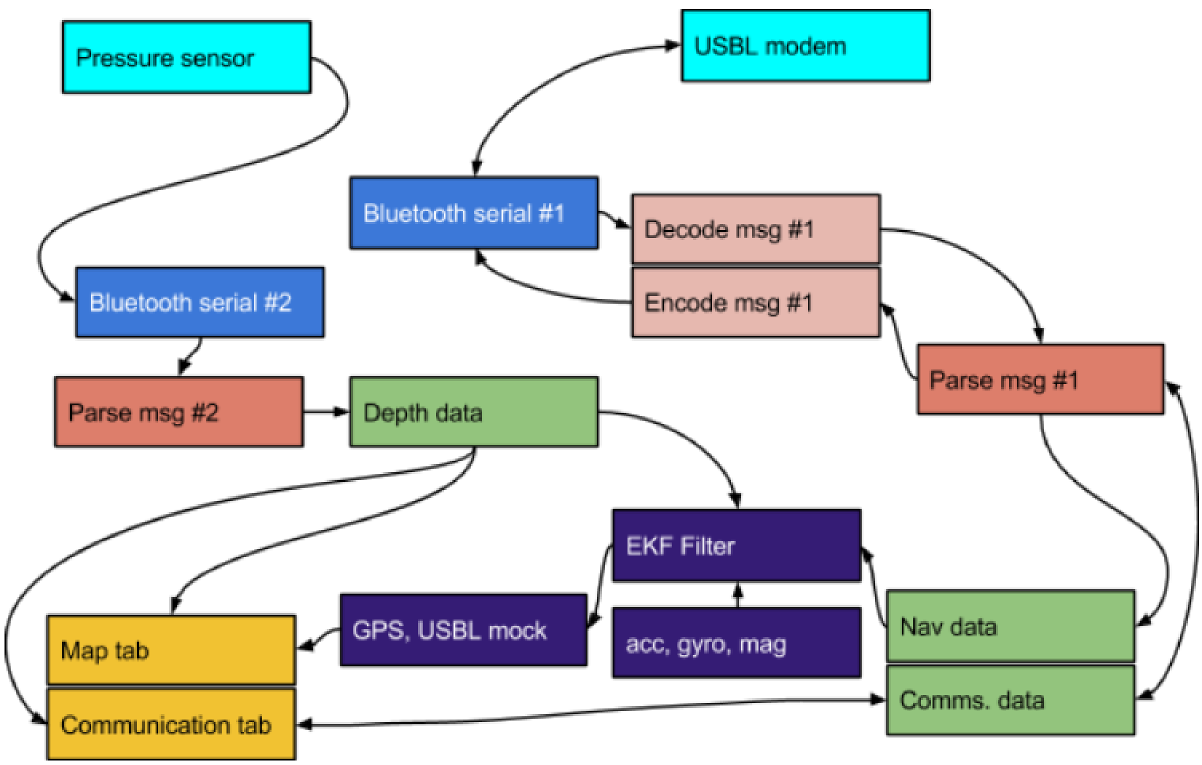


Fig 1.3.1. Android tablet application structure

Figure 1.3.1 shows the proposed final structure of the Android application for the diver tablet. The core module of the application is the Bluetooth serial device acquisition module, which handles connection threads and general communication between the diver tablet's Bluetooth device and the SeaTrac X100 series Micro-USBL tracking and data modems via serial ports (several of which can be opened simultaneously). A menu of selectable devices is presented to the diver, making it is possible to connect to any Bluetooth device that the tablet has previously been paired with. The module includes a message handler which encodes and decodes messages in string and binary formats, enabling efficient sending and receiving within the constraints of the USBL modem specifications, and a message parser which extracts and formats received data, preparing it for further use. For testing purposes, messages sent and received via serial communication are displayed on-screen in ASCII format.

Attached to the Bluetooth module is the chat module in the communication tab, which enables the diver to communicate either by typing out messages, or by selecting from a range of preset ones to send.

Received position, depth, and navigation data of the diver, platform and buddy nodes is forwarded to the map module, which displays all relevant information in a separate tab on a fully interactive Google maps overlay.

T1.4. Data distribution network

<u>Hardware enhancements (UNEW)</u>

The electronic design of the Seatrac units delivered in D1.2.1 has proven to be robust, powerful and flexible (via software changes). Hence no significant changes were considered necessary other than changing the pressure range of the integral depth sensor to provide maximum accuracy for the shallow water operations envisaged during CADDY.

The main area of hardware development has been in the construction of the USBL array transducer elements to maximise accuracy of phase measurements and repeatability in construction. Initial USBL units delivered to UNIZG had transducer elements selected from a production batch to be well matched in phase response. However, to enable consistent positioning performance on all units within the CADDY consortium and to support the ongoing SEAtrac commercialisation, it was necessary to review the design of these transducers to try to eliminate variability.

Figure T1.4.1 shows the results of USBL array calibration in UNEW's anechoic testing tank with a transponder 1m away and at the same depth. The plots show the phase differences between each pair of elements (baseline) in the 4 element array, (a) showing the baselines which are co-planar in the horizontal plane and (b) showing the baselines which have vertical separation. As the USBL head is rotated through 360 degrees, plots (a) and (b) should show 3 sinusoidal traces with 120 degree offsets, zero mean and no value exceeding +/-136 degrees. The device tested shows substantial deviation from the expected result due to differing transducer element response. Plot (c) shows the effect this has on the computed azimuth and elevation angles with large deviations in the expected pattern (elevation should stay at zero and azimuth should ramp linearly between 0 and 360 degrees). Plot (d) shows the "fit error" which is a measure of the confidence in the computed fix.

After reviewing the transducer design it was decided to modify construction so that the ceramic elements were mounted on a small seat of acoustically matched polyurethane before over-moulding with the same material. This would eliminate any interaction with the mounting structure which was suspected to be the cause of variable response. Figure T1.4.2 shows the calibration result of a USBL head with the new transducer construction. We can see that the baseline phase shifts are now much closer to the theoretically predicted result as are the calculated azimuth and elevation angles (the remaining fluctuation in elevation angle can be largely attributed to the imprecise mechanical arrangement for rotation of USBL heads in the tank). The fit error is also seen to be substantially lower across all angles.

The improved transducer construction will be used in all future Seatrac units for the CADDY project and existing units will be upgraded as soon replacement units are available.

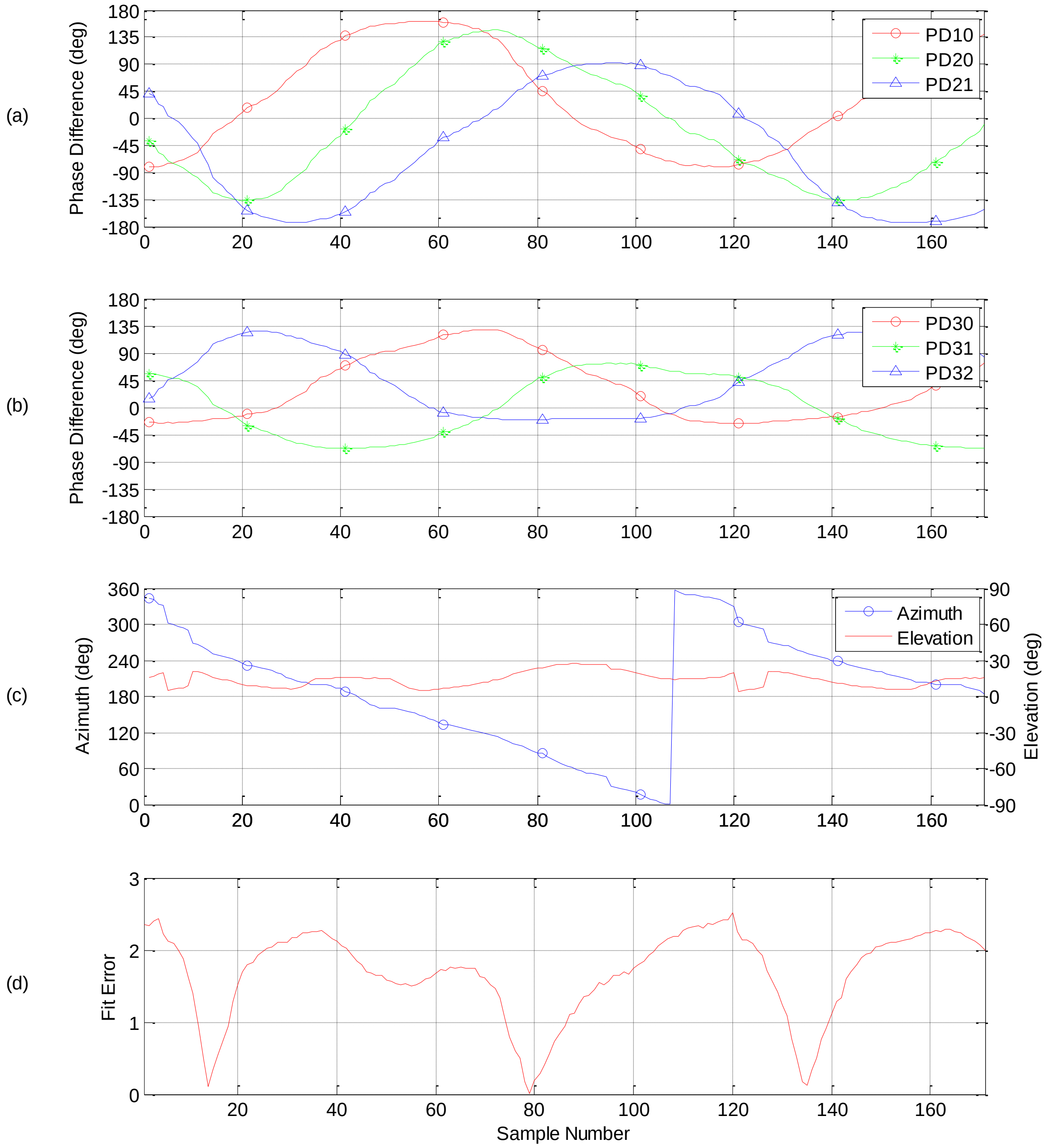


Figure T1.4.1. USBL array calibration results with old transducer construction

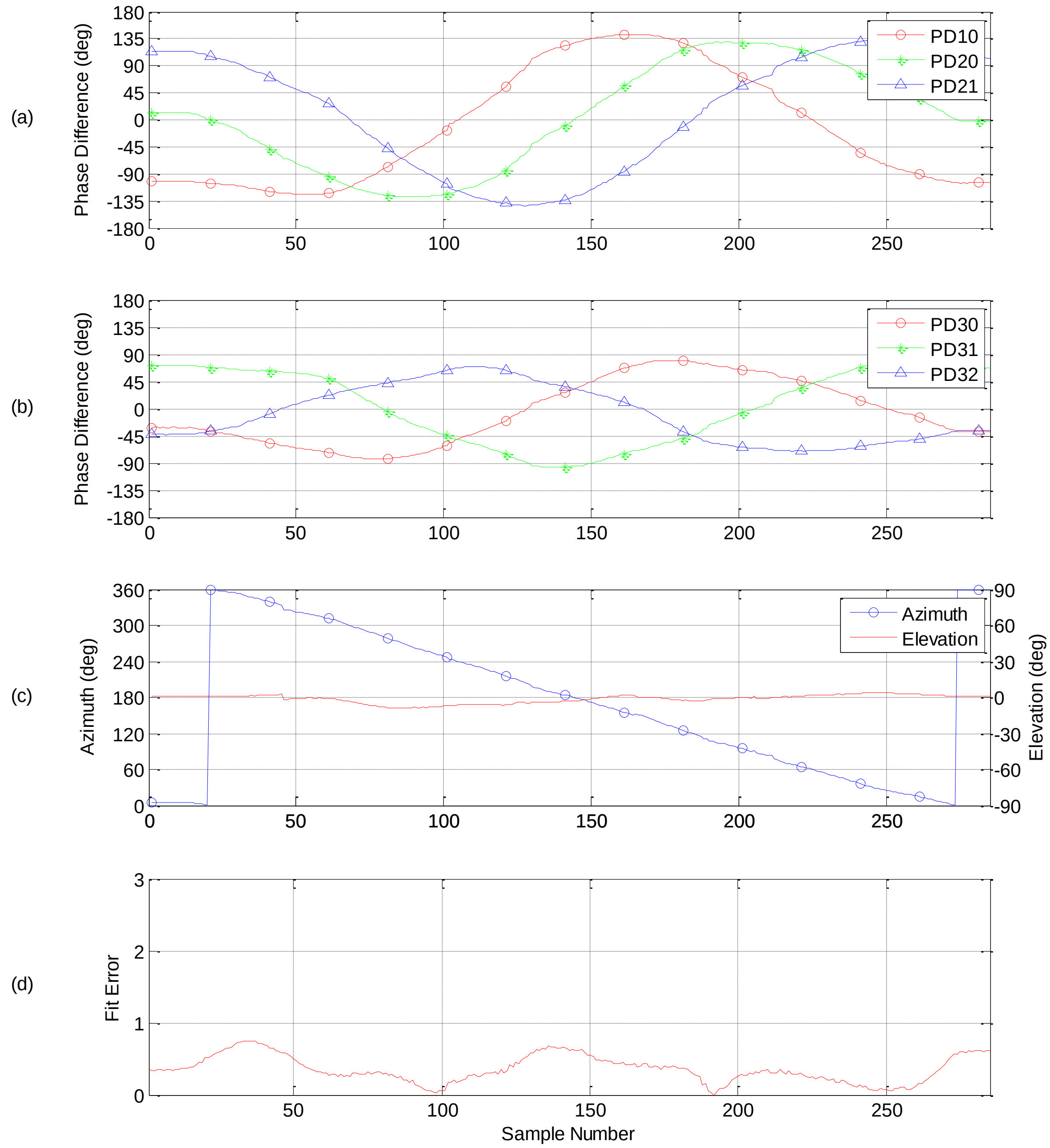


Figure T1.4.2. USBL array calibration results with new transducer construction

The Seatrac housing has also been modified to incorporate a new cage design which has less distortion of the acoustic field and hence minimal impact on USBL performance. The cage is now constructed from plastic with better acoustic impedance matching and fewer posts. In trials the USBL errors are only marginally increased while providing a high degree of protection against impacts to the delicate array structure.

Figure T1.4.3. New Seatrac housing

Enhancements to ultra- short baseline (USBL) positioning algorithm (UNEW)

Although positioning results for the initial Seatrac devices were very encouraging, various experiments described in D1.2.1 indicated ways that the algorithms could be further improved to increase accuracy and repeatability of fixes. One potential issue was how the algorithm synchronises onto closely spaced multipath arrivals as shown in figure T1.4.3. It is intuitive to synchronise on the signal with the greatest energy (and hence SNR) but the complexities of underwater propagation often result in a multipath signal that is stronger than the most direct path. Locking onto a multipath signal can often result in inaccurate position fixes as the direction of arrival does not match the direction of the source. This is particularly problematic when multiple paths fluctuate in amplitude and swap rank, resulting in fluctuating fixes.

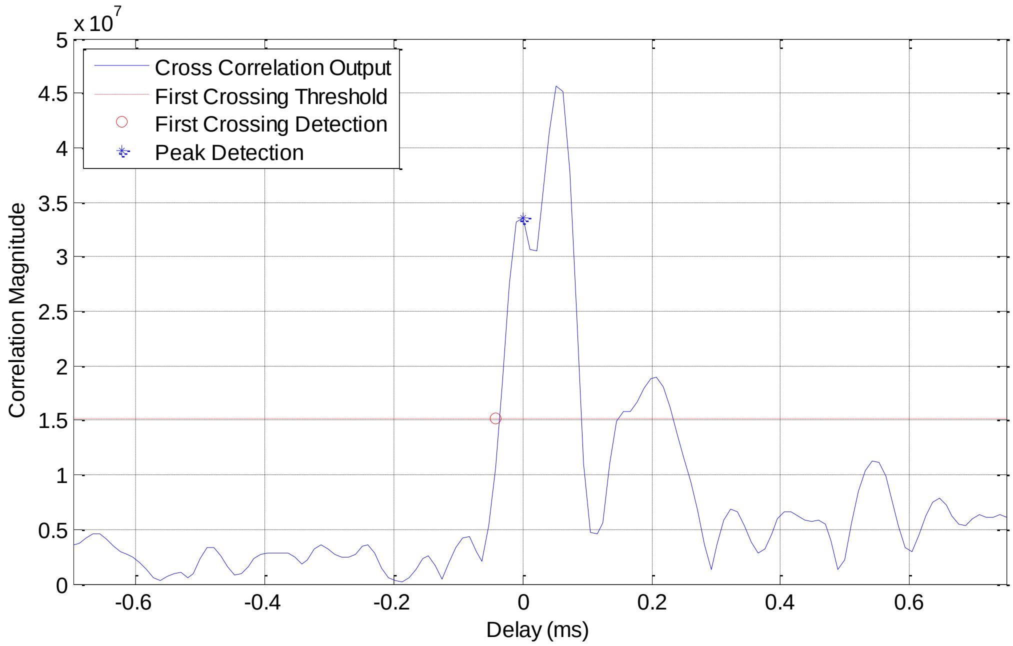


Figure 1.4.3- channel impulse response showing USBL synchronisation

The USBL algorithm has now been modified to guarantee that the USBL uses the first acoustic arrival (most accurate) to calculate position fixes. The algorithm now calculates a dynamic threshold based on the largest arrival amplitude and uses this to detect the rising edge of the first signal path, regardless of the multipath profile. A peak finding algorithm is then used to locate the maxima of this first arrival which is the optimum value for USBL calculation.

The improved USBL algorithm and transducers were tested in a dock near Newcastle with floating pontoons in a regular grid pattern. Figure T1.4.4 shows the position fixes obtained (50 in each location) relative to the USBL at coordinate (0, 0) with the X-Y, plane and the Y-Z planes displayed. Ground truth positions from the map are indicated by a red asterisk. The standard deviation (σ) of fixes (in 3 dimensions) was calculated in each case, indicating a value of about 1.5% of range (<1 degree in angle). As expected for a USBL system, this is dominated by the variance of azimuth and elevation angle rather than the ranging accuracy. For reference, results of parallel testing of the Tritech Micron USBL device are provided (an established commercially available product with much larger array baselines and hardware dimensions). Further optimisation of the USBL algorithms will continue, based on this data set and others, together with enhancements to the matching of transducer elements and analogue circuitry.

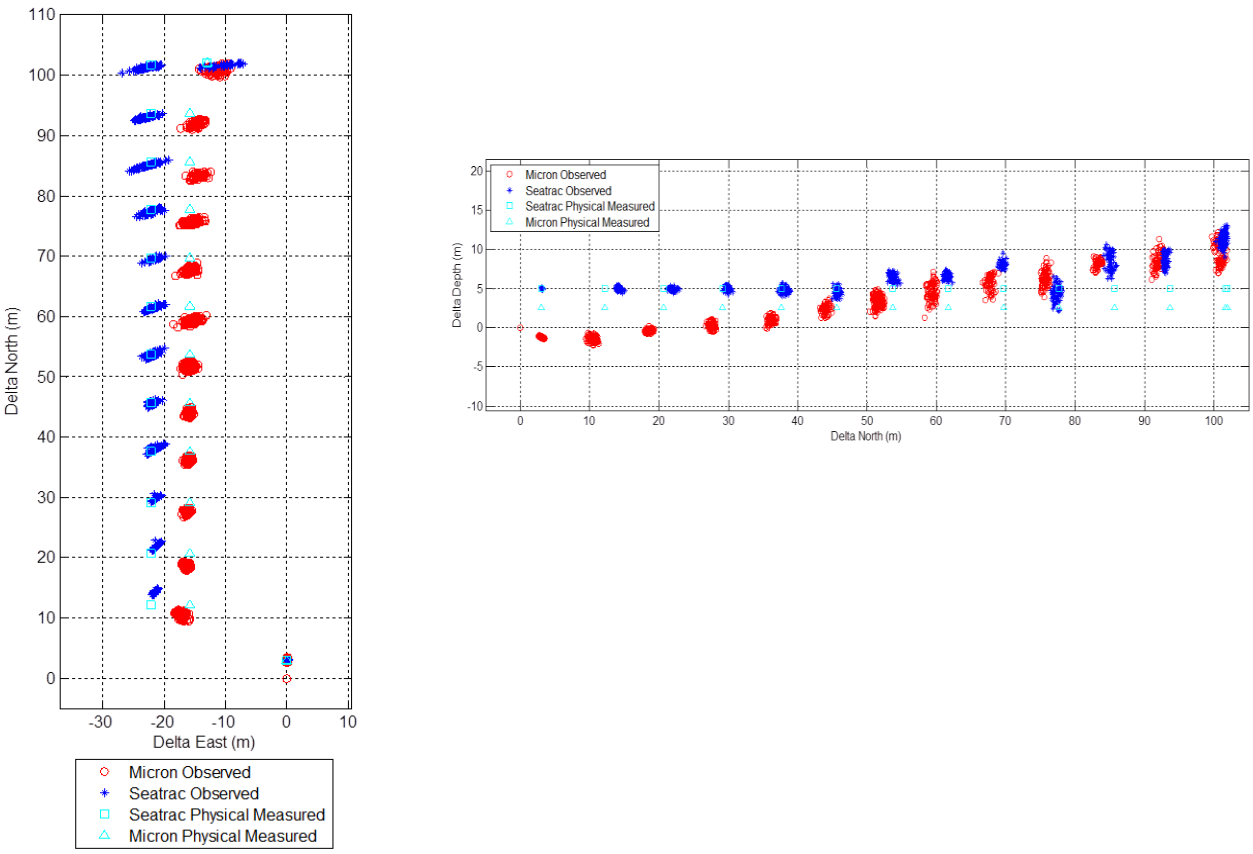


Figure 1.4.4. Results of dock testing of Seatrac USBL with regular pontoon layout

Medium data rate spread spectrum communication (UNEW)

In D1.2.1 the modulation and receiver structure for a medium bit rate acoustic communication link, based on the principles of direct sequence spread spectrum (DSSS), was described. Here a detailed description of the finalised modulation, encoding, packet formats and receiver algorithms is presented along with test results to assess the robustness of the transmission scheme in the presence of severe multipath, Doppler effects due to platform motion and noise. The emphasis of this design is to achieve high reliability using only a single receiver hydrophone whilst keeping the computational complexity of the receiver within the capability of the miniature, low cost Seatrac platform.

LFM chirp (frame synch)	255 chip QPSK training	(*N*,*K*) Reed Solomon encoded QPSK symbols, each spread by an *L*-chip portion of 8191 chip binary
50ms	31.9	1.02s (for L=8, f_{chip} = 8kHz,

Figure T1.4.5. Transmitted packet format for DSSS acoustic link

The structure of a transmitted data packet is shown in figure T1.4.5. Each packet starts with a 50ms long linear frequency modulated (LFM) chirp waveform for frame synchronisation. This is followed by a 255 chip QPSK modulated sequence, derived from a maximal length binary code (M-sequence), which is used to train the adaptive filter and Doppler correction structure in the receiver. Finally Reed Solomon (RS) encoded data is modulated as a series of QPSK symbols, each spread by an *L*-chip segment of a longer 8191 point binary M-sequence. As later results will show, although this spreading gain cannot on its own guarantee to remove inter-symbol interference (ISI), it is consistently able to reduce the mean ISI to a level where the error correction coding can eliminate remaining errors. By varying the values of *L* and the RS code rate (*K*), spread spectrum processing gain and coding gain can be easily tuned to balance data throughput against channel conditions. The transmitter and receiver structures are described in figures T1.4.6 and T1.4.7 respectively.

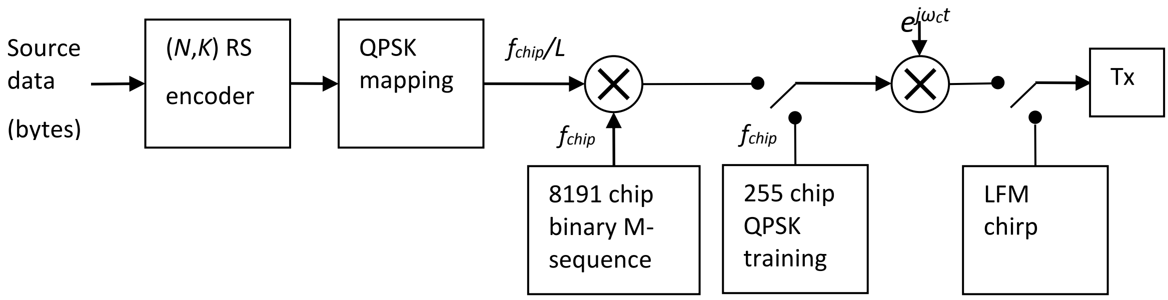


Figure 1.4.6. DSSS transmitter structure

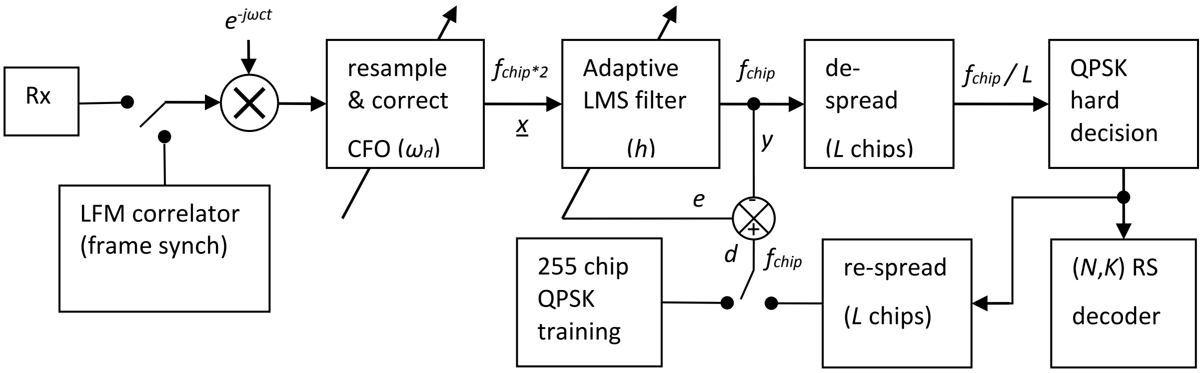


Figure 1.4.7 – DSSS receiver structure

The receiver first synchronises to the start of a transmitted packet by correlation for LFM frame synch waveform. The signal is then down-converted to a complex baseband signal and resampled by a factor *R*, using linear interpolation, to remove Doppler effects. This Doppler correction step also includes the removal of carrier frequency offset (CFO) estimated as ω_d. The estimation of both the resampling factor and carrier frequency offset is discussed later. The re-sampler outputs 2 samples per chip which are fed into a linear adaptive filter.

The output of the adaptive filter is calculated at one sample per chip according to equation (1). The purpose of this filter is twofold: primarily to maintain precise phase and chip synchronisation but also to provide equalisation, combining the energy from multipath arrivals to increase the achievable signal to interference and noise ratio (SINR). Whilst complex non-linear equaliser structures can be effective on quite long delay spreads up to perhaps 100 symbols, the intention here is that the DSSS processing gain will be able to attenuate multipath of almost limitless delay spread. Hence the adaptive filter is restricted to <40 taps to minimise computational load and maximise stability at low SNR. Nevertheless this does provide a useful gain through equalisation of short delay multipath arrivals. After the adaptive filter, the synchronised and equalised chip sequence is then de-spread to recover the estimated QPSK symbols, a hard decision is made and the data finally decoded.

The adaptive filter coefficients are updated at the chip rate to maximise tracking ability. The error signal is calculated as in equation (2), where d[i] is the transmitted chip value which is either taken from the a priori known training sequence or is estimated by re-spreading the QPSK hard decision output with the a priori known spreading sequence (decision directed mode). The adaptive filter coefficients are then updated as in equation (3), using the computationally simple least mean squares (LMS) algorithm, where μ is the adaptive step size.

$$y[i] = \underline{h}^T[i]\underline{x}[i] \tag{1}$$

$$e[i] = d[i] - y[i] \tag{2}$$

$$\underline{h}[i+1] = \underline{h}[i] + \mu e[i]\underline{x}^*[i] \tag{3}$$

The resampling factor, R, for Doppler correction must also be adapted. The phase error on the output symbols is calculated, as in equation (4), and this becomes our cost function for minimisation. A straightforward proportional feedback loop is then used to update the resampling factor as in (5), where k_p is the proportional tracking constant. Finally the CFO (ω_d) is proportional to the estimated resampling factor and calculated as in equation (6).

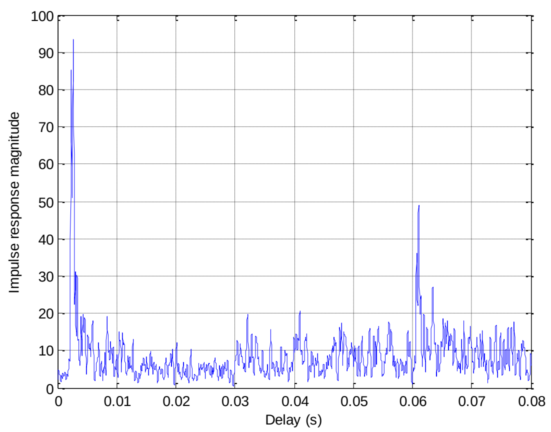
$$\theta_e[i] = \arg\left(y[i].d^*[i]\right) \tag{4}$$

$$R[i+1] = R[i] + k_p \theta_e[i] \tag{5}$$

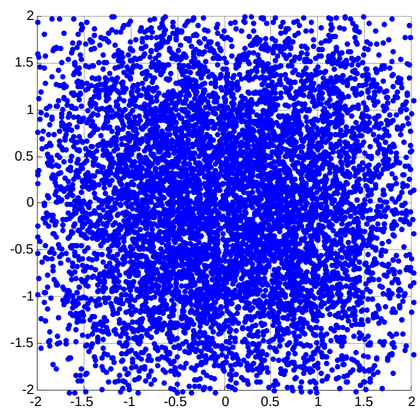
$$\omega_d = \omega_c\left(R[i]-1\right) \tag{6}$$

Parameter	***Symbol***	***Value***
Carrier frequency	f_c	12kHz
Acoustic frequency band	-	8-16kHz
Chip rate	f_{chip}	8000
Spreading ratio (chips/symbol)	L	8
RS code rate	(N,K)	(255,191)
Training sequence length	-	255 chips
Net data throughput	-	1.39 kbits/s
LFM chirp	-	8-16kHz, 50ms duration
Adaptive filter length	-	36 taps
Adaptive step size	μ	0.02 training, 0.005 for data
Doppler tracking constant	k_p	2×10^{-5} training, 5×10^{-6} for data

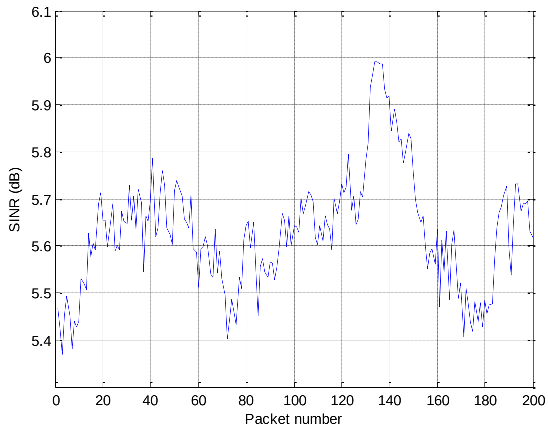
Table T1.4.8 – Parameters for DSSS experiments



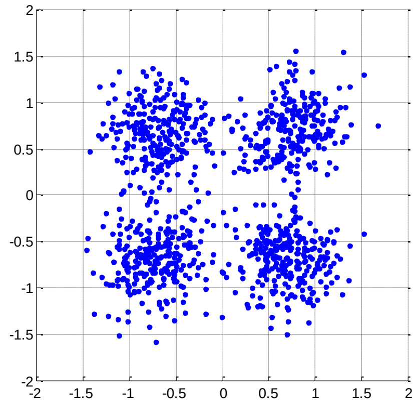
(a) Example channel impulse response



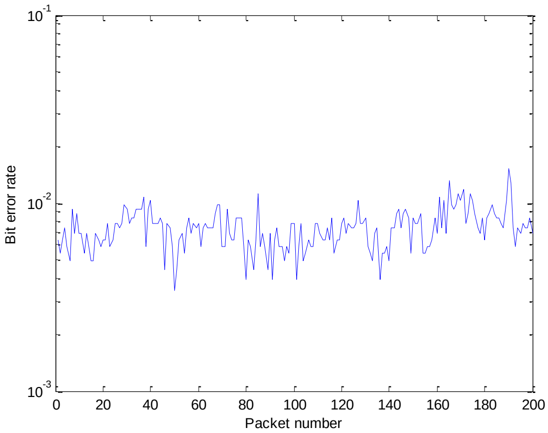
(d) Chip I-Q constellation



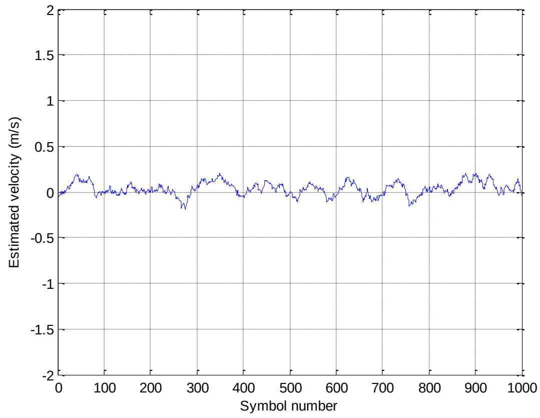
(b) SINR over 200 received packets



(e) Symbol I-Q constellation



(c) Bit error rate before decoding

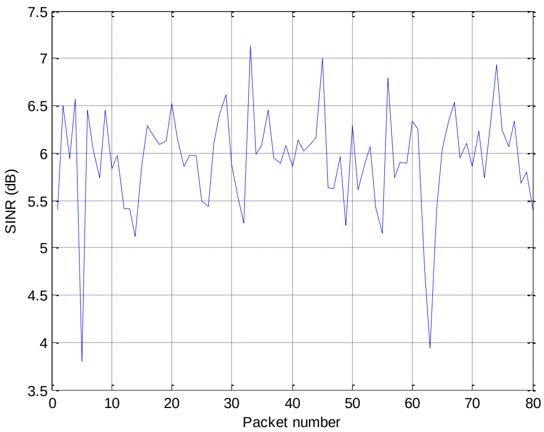


(f) Estimated velocity from Doppler tracking

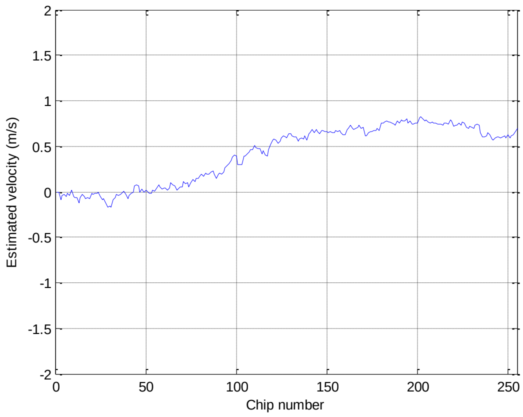
Figure 1.4.8. Results of 100m DSSS transmission experiment in highly reverberant dock environment

Initial test results of the basic DSSS scheme was presented in the D1.2.1 document and these were used to establish the best set of parameters for a system implementation. Further experiments were conducted during October 2014 to fully explore the performance of this scheme in extremely challenging multipath conditions, posed by an enclosed concrete lined dock, and with erratic source velocity and acceleration induced to simulate deployment on a diver or agile underwater vehicle. The parameters used in these experiments are listed in table T1.4.8.

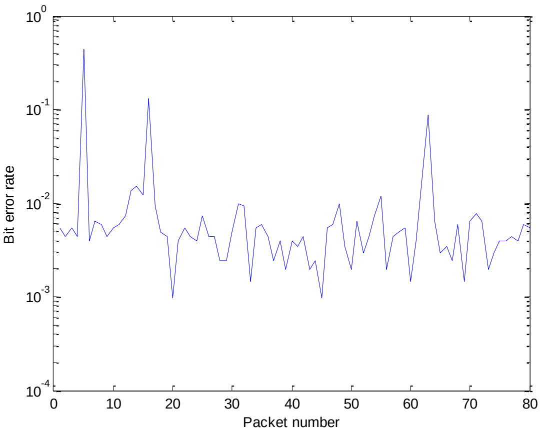
Figure T1.4.9 shows the results of a static test over 100m range, illustrating the high resilience to multipath effects of the DSSS scheme. Figure T1.4.10(a) shows the channel impulse response with significant signal arrivals spanning at least 80ms. Such a channel is extremely difficult to deal with by equalisation alone and would require many hundreds of filter taps. Figure 5.5(d) shows an example constellation plot for the estimated chips in one packet, indicating a completely closed eye. However the constellation of the symbol values, after de-spreading, shows a much improved result leading to acceptable SINR (figure T1.4.10(b)) and a sustained mean bit error rate of less than 10^{-2}. After RS decoding, all 200 of these packets are received error free achieving a sustained throughput of 1.39kbits/s.



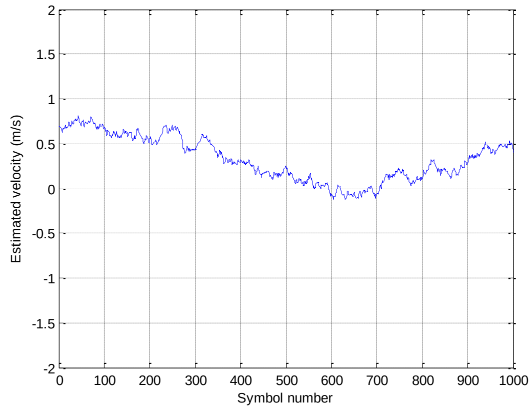
(a) *SINR over 80 received packets*



(c) *Estimated velocity during training*



(b) *Bit error rate before decoding*



(d) *Estimated velocity during data packet*

Figure 1.4.9. Results of DSSS transmission experiment with time varying Doppler effects

Figure 1.4.9 shows the results of a transmission experiment, in the same reverberant dock environment, while random motion was induced in the transmitting unit resulting in accelerations frequently exceeding 2 m/s^2. Figure 1.4.11 (a) and (b) show the SINR and bit error respectively over 80 transmitted packets, with 77/80 packets decoded error free. Figure 1.4.11 (c) shows the acquisition phase of the Doppler tracking algorithm during the training sequence and figure T1.4.11 (d) shows how the algorithm continues to track varying velocity during the reception of a data packet. This synchronisation method proves to be critical for the success of the DSSS system with only 22/80 of the same packets successfully decoded without it.

The medium rate DSSS transceiver design has proven extremely robust in a wide range of realistic test scenarios, whilst satisfying the low computational load requirements for implementation on the SEAtrac platform. The algorithm is now being ported onto the SEAtrac hardware to provide upgraded data rates for the next set of CADDY vehicle/diver trials.

Seatrac driver and message generation

Additional effort was invested in developing a modular driver and low-level simulator for the Seatrac USBL/Modem. The driver is implemented in a plug-in fashion, shown in figure 1.4.1, and separated into four concepts: core, communication, controller and listeners. The SeaTrac core loads necessary plug-ins, creates connections and assembles everything into a working unit. The plug-in approach was chosen to reduce the number of ROS nodes required for the USBL and allow use of polymorphic messages for simpler binary encoding and decoding of packets. Usage of ROS support for plug-ins allows partners to implement parts of the USBL infrastructure in separate ROS packets similar as is done with ROS nodes.

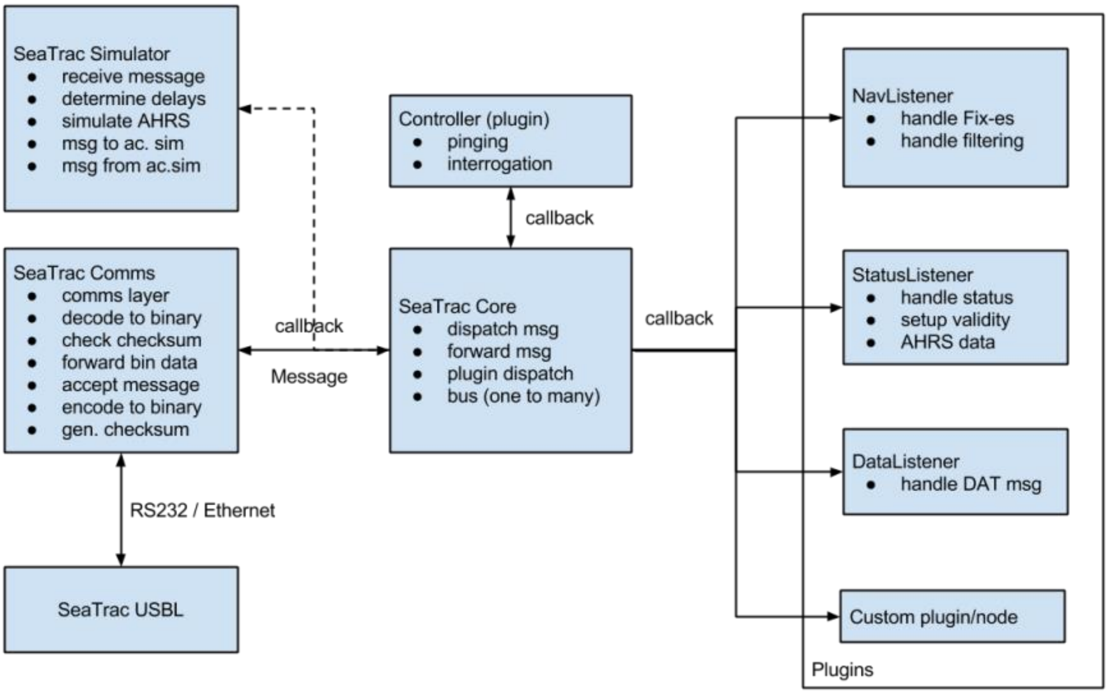


Figure 1.4.1 The layout of the ROS SeaTrac USBL/Modem driver

Communication plug-ins implement the low-level work of decoding/encoding binary messages into full objects that are then passed around inside the driver. Currently a RS232 communication protocol plug-in was developed. The USBL *simulation* is implemented on the communication level. This allows testing of custom plug-ins and easier operation with external hardware devices like the underwater tablet. Using the SeaTrac protocol simulator the underwater tablet can easily be connected as hardware in-the-loop to the overall system simulator. This allows divers use the tablet and interact with the simulated vehicles on land prior to diving. The approach is especially useful for training new divers how to use the underwater tablet.

Listeners are defined as plug-ins that can only receive message to which they subscribe. Arbitrary number of listeners can be loaded into the driver depending on the configuration files. They can interact with ROS same as all nodes. The only difference is that they receive the USBL data through a separate call-back function and that a SeaTrac message registration map has to be filled out on creation of the plug-in.

Controllers are defined as plug-ins that, in addition to listening to messages, are able to control the USBL/Modem device. Currently, only a single controller is allowed but extending to multiple controllers is possible. Based on the desired sub-task and application different controllers and listeners can be developed and combined to custom-tailor the USBL driver. Currently a PING USBL controller with data sending support and a passive modem controller are implemented. Interaction is achieved through two ROS message shown in table 1.4.1a and 1.4.1b.

Field name	Type	Description
header	std_msgs/Header	• message timestamp
action	int32	• the action the controller should do, options are: ○ RANGING – explicitly perform a ping ○ RANGING_DATA – ping with added data ○ SEND_DATA – send data only ○ SET_REPLY – add the message to a reply queue
payload	uint8[]	• data that should be sent (raw bytes)
nbits	int32	• number of bits in the message (ignored currently)
sender	int32	• the source node ID
receiver	int32	• the destination node ID

Table 1.4.1.a The suggested ROS message for controlling the USBL/Modem

The internal messaging system of the driver is based on the message protocol description provided by UNEW. The message protocol had to be implemented for ROS in C++ and for the underwater tablet in Java. The message protocol can change during improvements to the USBL/Modem hardware and different payload messages, requiring bitwise encodings, are expected for the data exchange between the diver and autonomous agents. Previous message serialization systems were therefore joined and extended to implement auto-generation of class and serialization methods for C++ and Java. The data type and message definitions are specified in a XML format mimicking the C++ class and type system, see listing 1.4.1. For Java equivalent storage types are defined.

Field name	Type	Description
header	std_msgs/Header	• message timestamp • frame_id
beacon	int32	• beacon ID to which the fix relates
type	int32	• fix type, can be: ○ RANGE_ONLY – when only ranging is done ○ AZIMUTH_ONLY – when only azimuth and elevation are valid ○ FULL_FIX – for a full 3D fix
relative_position	geometry_msgs/Point	• clean relative North-East-Down measurement
position	auv_msgs/NavSts	• absolute position, speed measurements
range	float32	• range measurement
bearing	float32	• azimuth angle measurement
elevation	float32	• elevation angle measurement
sound_speed	float32	• velocity of sound used for calculation

Table 1.4.1.b The suggested ROS message for reporting a USBL fix

The definitions implement only a minimal amount of concepts that are necessary for successful message generation; most language features are ignored or preset. Currently, the format allows for the following:

- specifying a public C++/Java structure
- single class inheritance
- conditional (de)serialization based on boolean flags (required by SeaTrac protocol)
- specifying member variables, methods, enumerators and type definitions
- specifying bit-fields with random bit sizes up to 64 bit in size

The bit-field encodings are currently limited to 64 bits for convenience of using a primitive data-type as the main storage variable. Future applications will show if there is a necessity to have larger bitwise encodings as most large payloads can easily be encoded as a series of bytes rather than bits.

SeaTrac commands and responses are implemented in a similar fashion as in listing 1.4.1 but inherit from a super class in order to limit the message passing call-backs to a single super-type that is automatically casted into its derived type when delivered to a listener or controller. Creation and serialization of messages is handled automatically by a factory class based on their *CID*.

```
<struct name="AcoFixBits" assert_size="1" bitfield="true">
   <var type="bool" name="RANGE_VALID" bits="1" />
   <var type="bool" name="USBL_VALID" bits="1" />
   <var type="bool" name="POSITION_VALID" bits="1" />
   <var type="bool" name="POSITION_ENHANCED" bits="1" />
   <var type="bool" name="POSITION_FLT_ERROR" bits="1" />
</struct>
```

Listing 1.4.1 Example definition of bit-field

Device and acoustics simulation

The USBL/Modem devices are simulated by a special communication plug-in that on one side connects into the Seatrac driver structure and on the other connects to ROS. The Seatrac driver side communication is done using the Seatrac protocol while the ROS side communication uses a custom ROS message defined in table 1.4.2.

Field name	Type	Description
header	std_msgs/Header	• message timestamp
message	uint8[]	• complete serialized message
duration	float64	• the hardware specific transmission duration
gain	float64	• acoustic signal level *(unused)*
sender	int32	• the source node ID
receiver	int32	• the destination node ID
snr	float64	• signal to noise level at the receiving modem *(unused)*
position	auv_msgs/NavSts	• position of the sender
range	float64	• range to the sender
azimuth	float64	• azimuth angle to the sender
elevation	float64	• elevation to the sender

listener_id	int32	• node ID that can hear the transmission
conflict	bool	• if a conflict occurred at the receiving node

Table 1.4.1.a The suggested ROS message for controlling the USBL/Modem

Each simulator connects with the simulated vehicle position topic in order to simulate the AHRS measurements. The simulator serializes a message to be transmitted and calculates the necessary transmission time. Currently, pinging and data messages are supported from the Seatrac protocol. Complex messages like the DEX, NAV can be added in future. This data is sent via the ROS topic to the acoustic medium simulation node. The simulator node registers to the acoustic medium node with basic data: node ID, position topic name, etc.

The acoustic simulation node subscribes to a common input topic for all modem simulators and publishes on a common output topic. Common topics improve scaling with multiple agents. The node keeps track of all simulated vehicle positions in order to estimate the transmission delay through the medium. The simulated message goes through several steps:

- distances to other nodes are calculated
- one ROS timer for each node is started with timeout depending on their distance
- when the timer timeouts the message "arrives" at the node
- a second timer is started based on the *duration* parameter that simulates the message reception
- when the second timer timeouts the message is forwarded to the actual USBL/Modem simulator through a ROS topic

The used timers are executed in parallel and allow for many-to-many transmission. Conflicts are detected if during the second phase multiple messages "arrive" at the receiving node. When this is the case both transmissions are interrupted and a conflict is reported. Since all information is published on a single topic the *listener_id* parameter is used to indicate which of the nodes the ROS message is intended to. Other USBL/Modem simulators will ignore the message if the *listener_id* does not match their acoustic node ID.

The simulator leaves room for easy implementation of message corruptions and acoustic medium noise modelling in the future. Message mangling in the acoustic medium due to multiple acoustic sources is also missing from the simulator. However, the message delay is modelled precisely in order to allow testing of control and navigation algorithms.

T1.5. Integration, experiments and performance evaluation (CNR, UNIZG-FER, UNEW, IST, JACOBS)

UNIZG-FER

During the field trials held in Biograd, Croatia from 04.05 - 15.05, all agents of the UNIZG-FER CADDY systems were experimentally tested at sea, individually and independently, as planned. Agents were also tested in pairs according to some envisioned scenarios of the initial validation trials. The role of diver was played by the ROV VideoRay using diver communication and localisation system. PlaDyPos, surface vehicle and BUDDY vehicle played their own roles in respect to their state of development. It is important to stress that coordination among agents were achieved using the acoustic communication and localisation hardware developed in the scope of task 1.4. which is common for all CADDY "fleet". Conversely, communication protocols and interrogation scheme still has to be harmonized between the partners and then modified and applied according agreed approach.

On top of communication and localisation but based on that data, some of developed control algorithms were tested. Namely, positioning of the surface vehicle in respect to underwater agents e.g. using range only measurement, see T3.4.

Performance evaluation of the tested subsystems were carried out in order to address possible issues prior the validation trials. Acoustic localisation worked at a satisfactory level even in very unfavourable shallow water environment with a lot of reflections and multipath signals. Lower localisation performance and increased level of outliers were noticed when agents are just above/under each other which can be explained by the beam shape of the acoustic transducer. It resulted in implementation of the outlier rejection algorithm whose results are shown in T3.4. Communication performance was satisfactory with acceptable rate of lost data packages.

WP2 Seeing the diver

T2.1. Development and integration of diver remote sensing framework

Refraction from the air-glass-water interface of any underwater camera housing changes vital parts of the camera geometry if no special care is taken. Jacobs has investigated when it is possible to approximate the in-water camera geometry with a pinhole model. Careful analysis has shown that the in-water geometry of a refracted camera never exactly exhibits a single focal point, the prerequisite for using a pinhole model. However, the analysis discovered that it is possible to approximate the geometry using a simple pinhole model under the condition that the physical camera is placed very close to the glass port. Basing on this, a novel camera modelling method was developed for underwater vision, requiring only in-air calibration parameters. Then, it is possible to calculate the in-water camera geometry (specifically including refractive effects) from housing parameters (glass thickness and material, water salinity) and the in-air calibration. This work resulted a high quality 3D underwater data (see also the section on T2.4).

We are working now on testing this method with different camera systems and under different water conditions (sweet and sea water) to show the generality of the method. We are in the process of preparing a journal submission reporting on results of this work.

T2.2. Motion compensation and fusion of passive sensors

Motion compensation methods have been developed by Jacobs to estimate sensor motion even when observing a dynamic scene. Specifically, the work focused on the dynamic aspects introduced by gesturing divers in front of a static background. These methods compute the motion of the sensor such that apparent motion of the static scene parts is eliminated, leaving only the motion of dynamic parts. This result can then be used to segment moving divers.

Spectral Registration with Multilayer Resampling (SRMR) developed at Jacobs is very robust to occlusions and dynamic changes. Please refer to Deliverable 2.2 for specific details of the experiments conducted.

Figure 2.2.1 shows a summary of the findings reported in D2.2. SRMR is very robust to dynamic aspects and noise. The highest level of noise (right column) represents a severe degradation in quality usually not seen in stereo range data, but it was included in the analysis for completion.

Subsequent processing will be facilitated by motion compensation methods. One example of further processing steps is change detection, a simple approach to detect the presence of and segment the rough shape of dynamic objects.

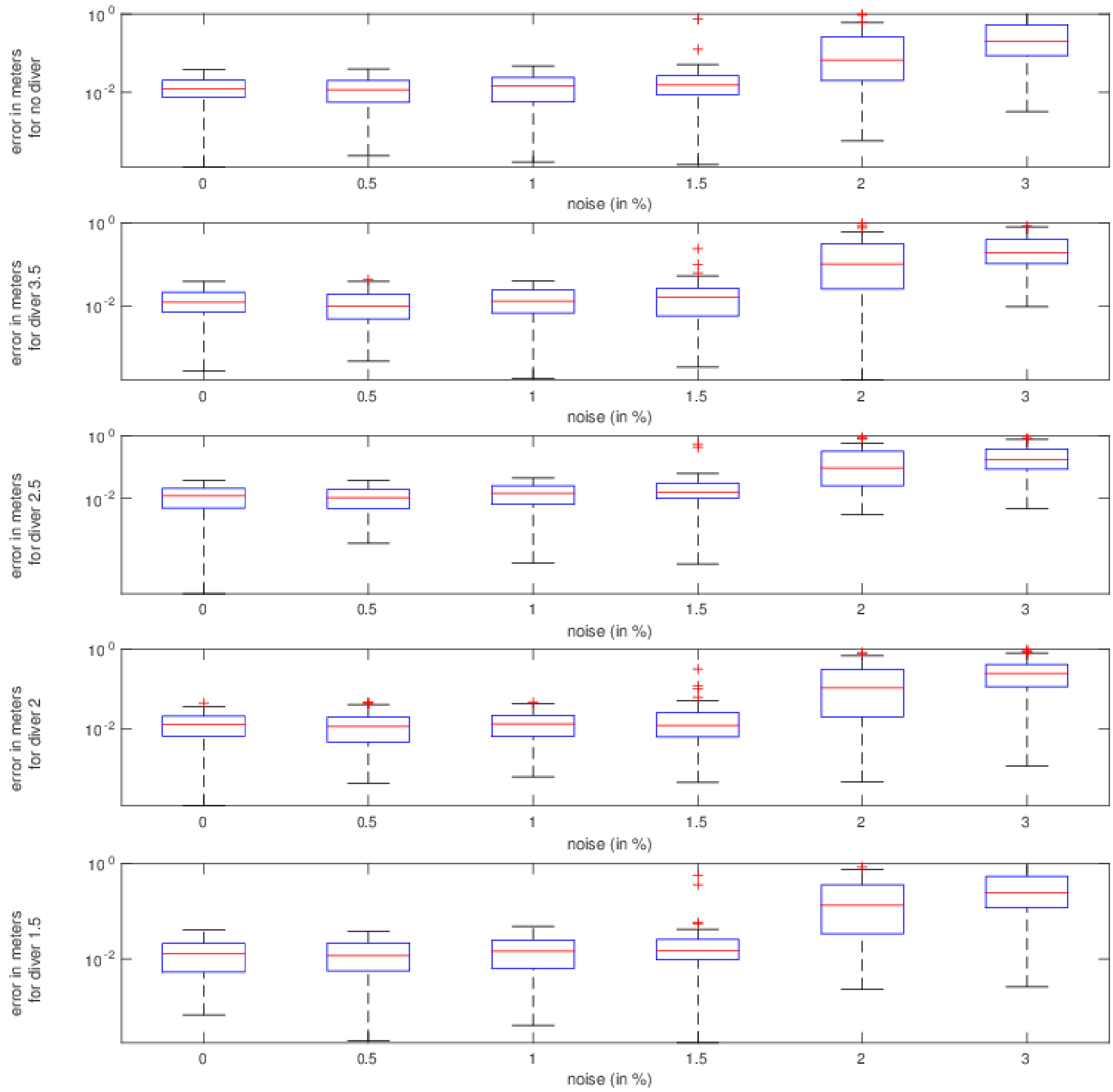


Figure 2.2.1: Estimation error (translation) using SRMR on data of varying noise (horizontal axis) and varying levels of dynamic content (vertical axis). Dynamic aspects do not influence the estimation quality significantly. The residual error even at zero noise and zero dynamic content is due to the quantization error as SRMR operates on voxel grids.

T2.3. DiverNet sensor and communication development

Several improvements have been made to the DiverNet data processing and visualization software. Most noticeably, a quaternion-based orientation filter developed by S. Madgwick has been implemented. This filter was chosen as it offers performance comparable to Kalman filter based solution, but is not as computationally expensive. This will be particularly important when the data processing will be moved to the DiverNet hub in the future.

A simple calibration method was developed and implemented to compensate for the misalignment of the sensors on diver's body. Divers are requested to do a pre-defined pose and the rotation offset from the expected orientation is calculated for each individual sensor.

Minor improvements have also been made to the virtual model of the diver. A permutation of the axis is performed to allow a more natural representation of the diver in case only part of the sensors are connected. Some alignment of the body parts was made to give a more human-like representation.

The existing commercially available breathing belt, previously interfaced to the DiverNet, has issues with reliability underwater since it was never intended for submersion. A specially adapted version of the piezoelectric breathing belt has been designed and constructed by UNEW for subsea operation. The piezoelectric element is encapsulated in high modulus silicone rubber and all electrical connections sealed as shown in figure T2.3.1. Performance in dry experiments appears identical to the previous device and UNIVIE are currently gathering data in underwater experiments with the new device.

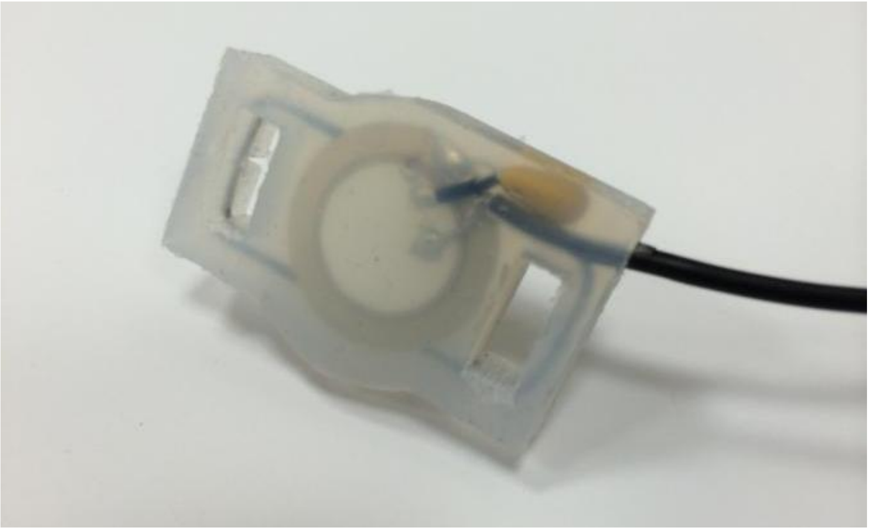


Figure 2.3.1. Subsea breathing sensor element for DiverNet

T2.4. Experimental data collection

The cloud server has been implemented and is running – we just were able to remove the 2 Gigabyte limit. OwnCloud online at https://caddy.univie.ac.at/caddycloud

It currently holds data from Video and DiverNet Data collected in Pag, Padua I and Padua II and the sonar and Sonar and Stereo Camera Data from Pag: May 2014. Also Lisbon Hand Gestures are online.

Behaviour Annotation of diver behaviour is a necessary prerequisite for behaviour recognition (see below), thus we developed a behaviour repertoire (n=38) for divers. Currently this repertoire is tested for reliability and will be used for coding Padua II and III data. (Pia Stephan, Anna Schaman)

Catalogue for diving behaviour coding

Track: **Upper limbs right**

Behaviour	**Definition**
hand signal	hand performs defined diving signal
manipulating own diving equipment	hand touches, grabs, moves or picks up object related to the diver's equipment
manipulating other diver's equipment	hand touches, grabs, moves or picks up object related to another diver's equipment
touching object	hand touches object (except equipment)
picking up object	hand grabs and picks up object (except equipment)
carrying object	upper limbs carry object
touching person	hand touches another person's body
touching own body	hand touches part of the own body
touching floor	hand touches floor
hanging on to something	hand hangs on to object, floor or person
still	upper limbs still without contact with equipment, object, person or own body parts
moving	upper limbs moving without contact with equipment, object, person or own body parts
none	

Track: **Upper limbs left**

Behaviour	**Definition**
hand signal	hand performs defined diving signal
manipulating own diving equipment	hand touches, grabs, moves or picks up object related to the diver's equipment
manipulating other diver's equipment	hand touches, grabs, moves or picks up object related to another diver's equipment
touching object	hand touches object (except equipment)
picking up object	hand grabs and picks up object (except equipment)
carrying object	upper limbs carry object
touching person	hand touches another person's body
touching own body	hand touches part of the own body
touching floor	hand touches floor
hanging on to something	hand hangs on to object, floor or person
still	upper limbs still without contact with equipment, object, person or own body parts
moving	upper limbs moving without contact with equipment, object, person or own body parts

none	

Track: **Lower limbs right**

Behaviour	**Definition**
still bent	lower limbs do not move, while they are located in open water (no contact with floor)
kneeling/touching floor	parts of the lower limbs (except the bottom of the foot) touch the floor
standing	body upright on the feet which touch the floor
paddling	lower limbs move smoothly, while angle between shank and thigh changes
none	

Track: **Lower limbs left**

Behaviour	**Definition**
still bent	lower limbs do not move, while they are located in open water (no contact with floor)
kneeling/touching floor	parts of the lower limbs (except the bottom of the foot) touch the floor
standing	body upright on the feet which touch the floor
paddling	lower limbs move smoothly, while angle between shank and thigh changes
none	

Track: **Breathing**

Behaviour	**Definition**
expiration	air bubbles visible near the diving regulator
none	

Table 2.4.1. Diver Behaviour Catalogue

The final codings can be accessed by our software and played by in real time

Two new dry experiments and one underwater experiment were conducted.

1. Physiological Measurements: Breathing, Heart Rate and Emotion (Katharina Oremus, Karl Grammer)

The experiment on emotional breathing done in spring 2014 was repeated with the goal to achieve a large enough sample size for the training of algorithms for detection of Emotion in breathing and heart rate data as well as to allow for more complex tools of data analysis that depend on larger samples. 91 participants were shown seven video stimuli chosen to elicit seven emotional states (anger, anxiety, disgust, happiness, neutral, sadness and surprise). In between clips, participants filled in a Pleasure-Arousal-Dominance Questionnaire and took a short task as a distraction between stimuli. Participants' heart rate, breathing patterns and facial muscle activity was measured. (For more detailed information, see Data collection in Spring 2014).

After cleaning and controlling for errors in the data, this dataset will be combined with the data collected in 2014, resulting in 2100 30 second clips. The clips will be used for machine learning and the development of TDNNs.

Fig. 2.4.1.Setup

2. Effects of Emotion on Motion Patterns, Breathing, Heart Rate (Anna Schaman. Dominic Reichl)

This experiment was intended to provide a large data set of motion data in combination with Pleasure-Arousal-Dominance Data. As the induction of strong emotions in divers increases their risk of health problems (heart attack, etc.), this experiment will also allow us to study the influence of strong emotions on motion patterns. The motion data will be used to train algorithms/use multivariate analysis methods to detect promising parameters of motion (such as motion rate, abruptness, expressiveness etc.) that can be used as indicators of emotion in divers. A second task was designed to measure the effect of the exercise of executive functions (used for impulse control, planned behaviour and willpower) on motion patterns.

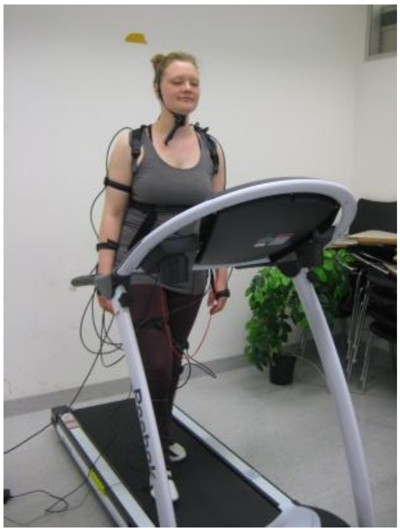


Fig. 2.4.2 Participant on the treadmill

Participants were equipped with the DiverNet Sensors, a breathing belt and a heart rate sensor. They were then asked to step onto a treadmill and choose a comfortable speed. Seven video stimuli (the same ones used in the experiments for physiological measurements Spring 2014 and 2015) were shown to the participants to elicit the emotions anger, anxiety, disgust, neutral, happiness, sadness and surprise. After each clip the participants filled in a Pleasure-Arousal-Dominance questionnaire and completed a short cognitive task that served as distraction.

Fig.2.4.3 Setup of video stimuli and equipment.

In addition, participants were given a willpower task, in which they had to avoid looking at an attractive video stimulus. By the end of June, 52 people had participated in the experiment.

We are planning to extend our sample to 80 participants in July. The data will be cleaned and analysed in August, by which time we expect to narrow down the list of potential parameters of motion to about 10 promising candidates which can then be tested for predictive power on the Motion-Emotion data set for divers.

<u>3. Motion Patterns, Heart Rate and Emotion in Divers</u> (Anna Schaman (Video data collection, annotation and synchronization); Dominic Reichl, Katharina Oremus (DiverNet data collection, equipping the divers

The goal of this experiment was twofold: To replicate the experimental data collection in Padova (Feb. 2015) in order to test the remodelled underwater breathing belt and to increase the sample size for data on divers' motion patterns during typical tasks, which will then be analysed for effects of emotions.

As women were underrepresented in the DiverNet Motion sample, this data collection was also used for balancing the sex ratio. In addition, the data collection will allow a comparison in breathing data between two measurement devices: The breathing belt presently included in the DiverNet and a breathing device provided by DAN.

Data was collected during the 29th and 30th of June 2015 in the Y-40 Pool in Padova. Seventeen women (aged 16 years to 60 years) and four men (aged 42 years – 64 years).

DAN Europe collected the Certificates and Consent Forms. Divers were briefed with the help of printed instructions by Guy Thomas (DAN Europe).

Fig. 2.4.4. Diver with DiverNet

Divers were equipped with the DiverNet sensors and the underwater breathing belt. On the 30th, the Divers were using an additional device to measure breathing provided by DAN. Communication with the Divers during the experiment was effected via underwater headphones provided by DAN Europe. Video material was collected using a glass window looking into the pool. Video and DiverNet data were synchronized by means of a time server. The videos were annotated in real time based on the tasks the divers were performing.

Fig.2.4.5. Diver swimming slowly

Divers were asked to perform ten tasks (breathing with and without regulator, taking off the mask and the regulator, controlling buoyancy, moving up and down between 2 targets, moving in the horizontal plane at a slow pace and swimming quickly, displacing an object and a free behaviour task). Between two tasks, the divers had to perform a t-posture for calibration and segmentation of the motion data. In addition, divers filled in a Pleasure-Arousal-Dominance-Questionnaire after each task. (For more detailed information, see Data collection in February 2015).

After cleaning and controlling for errors in data, the results of this experiment will be merged with the data collected in February and will be analysed in July and August. This will give us a large enough sample to perform more specific analyses and will allow a better estimation of natural variance both in the perception and the execution of the tasks.

JACOBS

On June 16th, stereo data of underwater gestures was collected in Lisbon. Jacobs and CNR teams met and, with the help of IST, collected data of a diver performing gestures belonging to CADDIAN language in a pool. The diver used gloves with markers, provided by CNR, that will enable easier and more robust gesture detection and recognition (see the section on T2.6). Data was recorded with the Jacobs Bumblebee XB3 stereo camera system, which allows delivering high quality dense stereo point clouds. It also allows using two stereo pairs – with wide and short baseline. The short baseline covers more volume close to the cameras, while the wide baseline best covers structure further away.

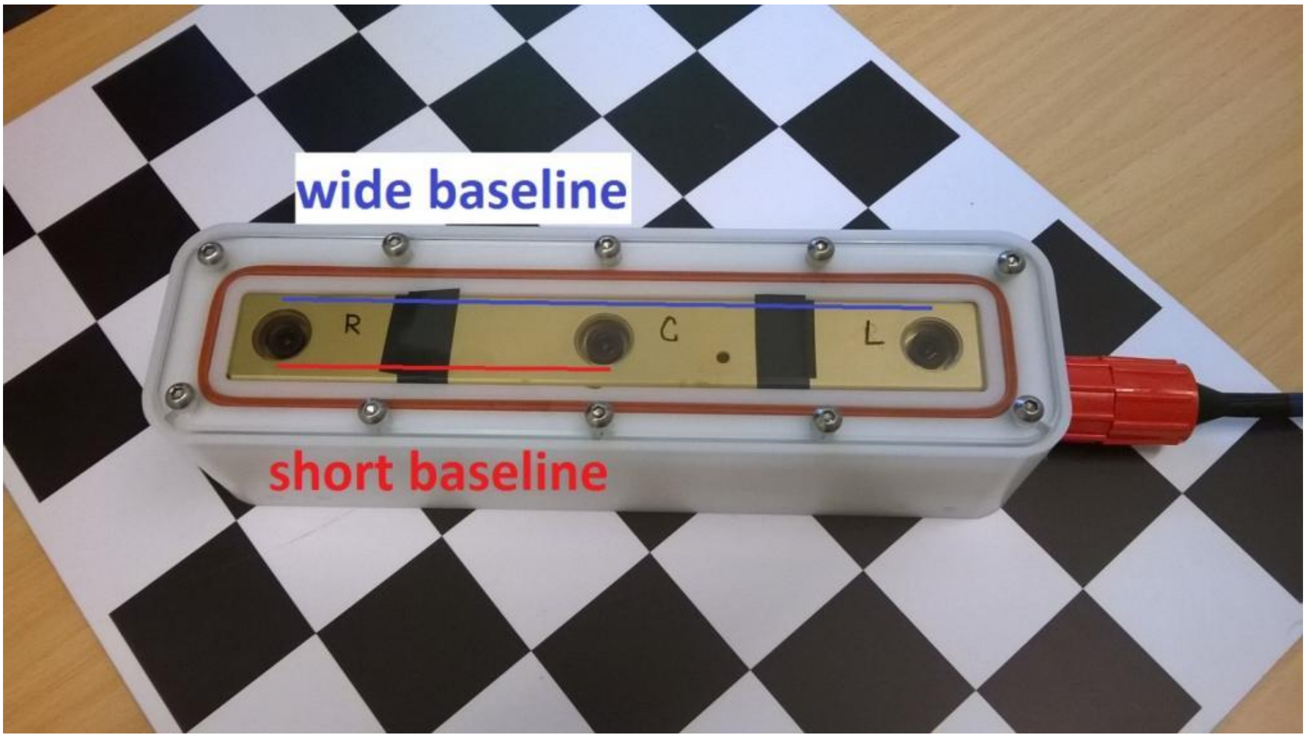


Fig. 2.4.6: Bumblebee XB3 stereo camera with marked baselines

The recorded data covered a variety of gestures belonging to the CADDIAN language – both static and dynamic. A range of conditions was also tested: different distances to the camera, viewing angles etc. The recorded data was then processed to produce 3D point clouds.

This early-stage processing gave very promising results and no difficulties are predicted on the data acquisition level in future work.

Figure 2.4.7: Impressions from the data collection

Figure 2.4.8: 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. This will be mitigated by a fused approach: A classifier will label diver pixels, and estimates will be filled in to the range image accordingly.

T2.5. Diver pose estimation

Recognizing diver in sonar images (UNIZG-FER)

A lot of sonar data was recorded on data gathering in Padua in February 2015. SoundMetrics ARIS 3000 multi-beam sonar was mounted on the side of the pool and was continuously recording divers who were performing pre-defined tasks with the DiverNet. This data, together with one recorded on Pag trial in 2014, is now being used for developing diver detection and tracking algorithms from sonar imagery.

Several approaches have been tested to see what classic computer vision algorithms work on the sonar images. First, the calculation of optical flow in the sonar image was implemented, with the idea of detecting activity regions in the image. This attempt was unsuccessful, as the sonar image proved to be too noisy and erratic for accurate feature detection and tracking.

The second classic approach was the use of background subtraction algorithms. This resulted in fairly accurate detection of moving regions in the image (in our case usually the part of the image where the diver was moving). Having this type of data could be very useful for finding regions of interest in the image. However, unlike optical flow which could be used even when the sonar is moving, background subtraction only works if the sonar is still. This greatly reduces the potential use of such an algorithm since the sonar will be mounted on the moving vehicle in the future.

The final approach was relying on thresholding the sonar image and detecting the contours which are a result of diver presence. First, the image is blurred to smooth the sonar noise. After that OpenCV's adaptive threshold function is used to create a binary image, setting high-value regions to white. Since the Cartesian space sonar image is used, which has a sector shape, and all the image processing algorithms work on rectangular images, the outside of the useful sonar image is coloured in neutral grey to avoid artefacts on the edge region. The detected contours are later processed to find the ones that might represent the diver.

On the previously collected data from Pag, where the sonar was placed almost horizontally and was not recording the sea bottom, the diver is much clearer than in the Padua data, where there were a lot of reflection from walls and floor, and the floor and walls were highly visible.

The following set of images in Fig. 2.5.1. shows contour-based detection on Pag data. The left pair of images shows the detection of diver's silhouette, while in the right pair bubbles created by exhaling are detected.

Images in Fig. 2.5.2. show the contour detection on a difficult case of Padua data. In the next steps clustering algorithms and location estimators will be used to allow better tracking even on such data with a lot of background noise and reflection. However, it is unlikely that real situations at sea will result in such noisy data.

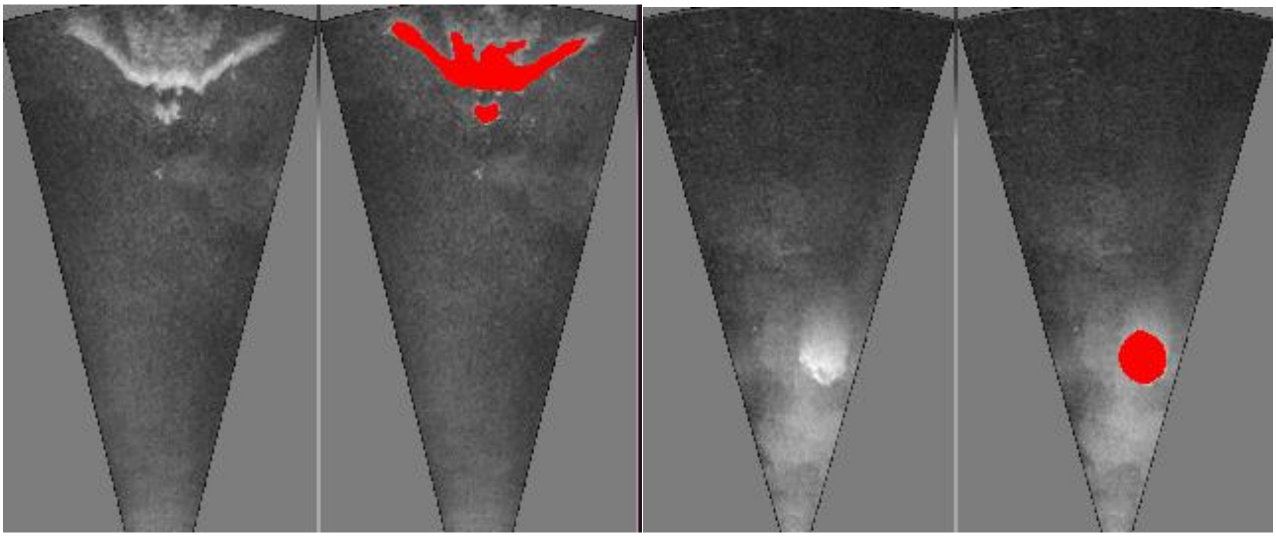


Fig. 2.5.1. Detecting diver silhouette (left) and exhale bubbles (right) in sonar images from Pag data

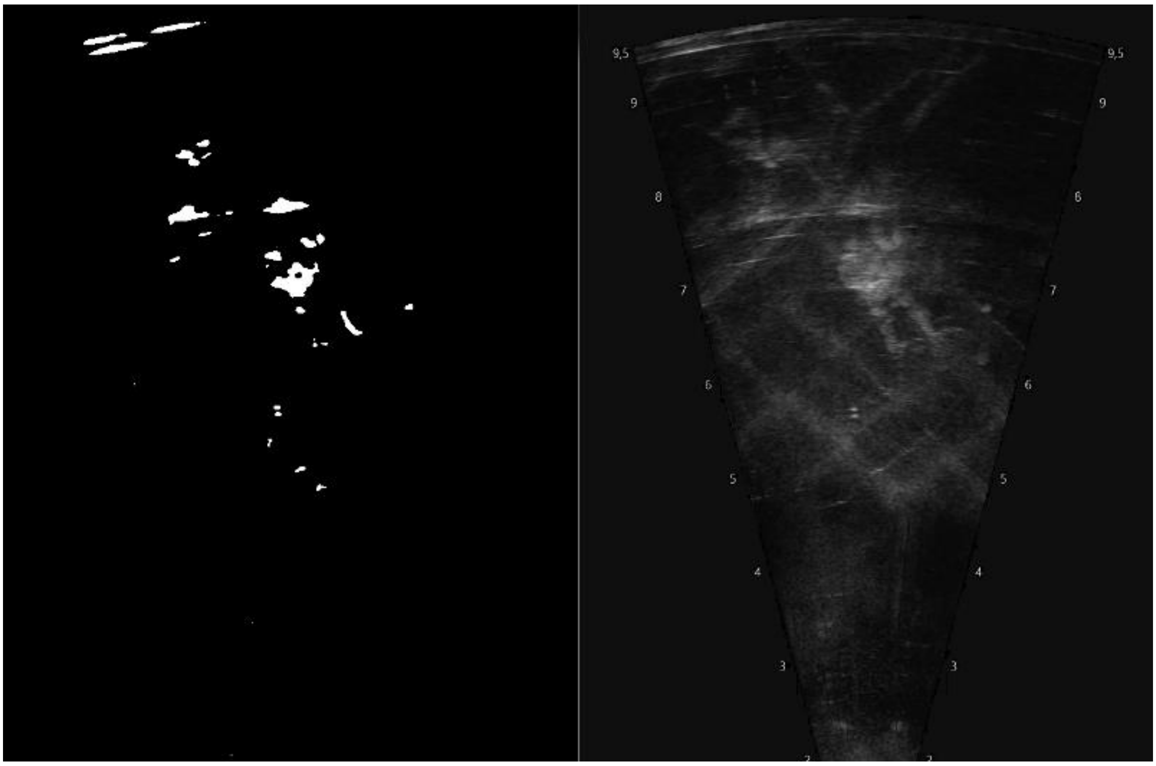


Fig. 2.5.2. Detected contours and sonar image from Padua data

__Diver tracking with ARIS multi-beam sonar (UNIZG-FER)__

- **Image and sonar data acquisition**

A ROS-based driver developed at University of Girona is used for sonar image reading. It publishes three ROS messages:

- Polar image - image of *nbeams* width and *nsamples* height; native image for sonar

- Cartesian image - polar image remapped into a human-intuitive geometry
- Sonar info - information about the sonar (range, resolution, orientation…)

All three messages are timestamped together, so the processing begins only when the image - sonar info pair is received. That way it is ensured that the sonar info data is corresponding to the image. Cartesian image is used in the diver tracking.

- **Image processing**

The image processing is split into several stages. First, blurring and adaptive thresholding is performed on the grayscale image. After that contour detection is performed, followed by contour clustering.

Blurring and thresholding

Sonar image is typically very noisy. To remove the noise, Gaussian blurring is performed in the first step. Before the thresholding step, background is filled with neutral grey (127) to remove artefacts on the image borders. This process is shown in Fig. 2.5.3.

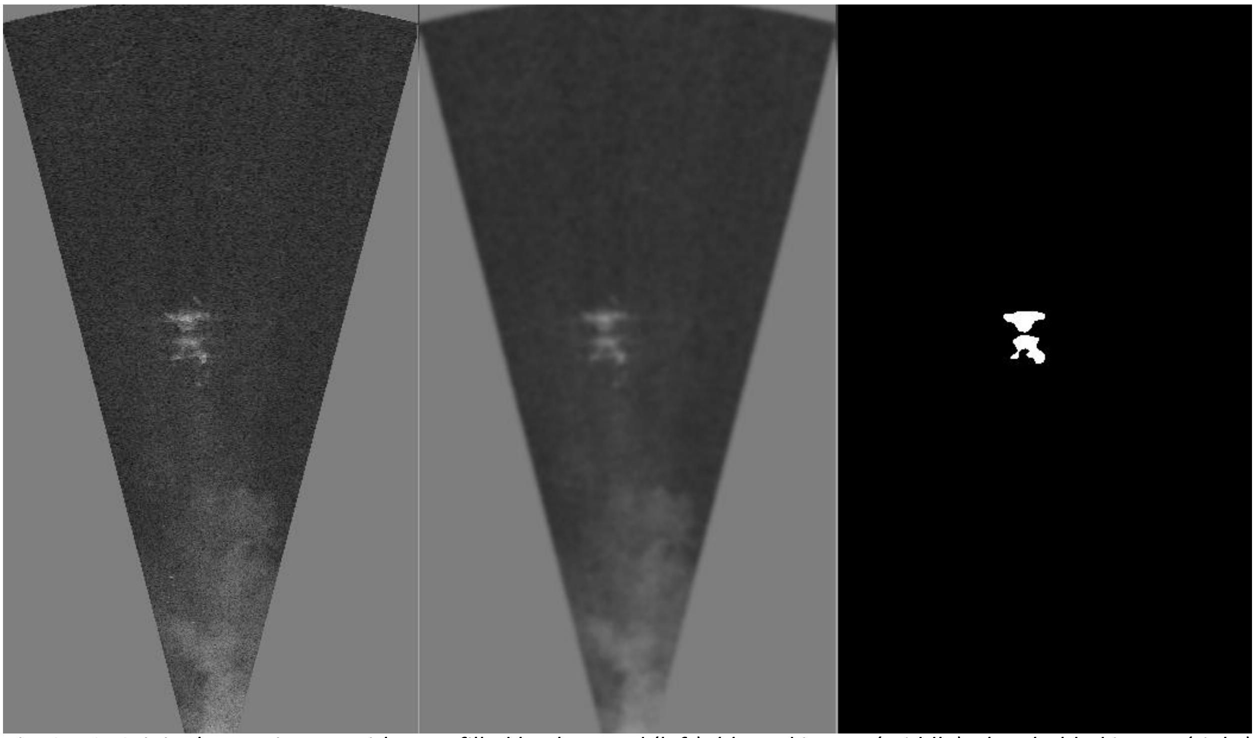


Fig. 2.5.3. Original sonar image with grey-filled background (left); blurred image (middle); thresholded image (right)

Finding and clustering contours

In the resulting image of the previous step, which is a binary thresholded image, is used for contour detection. Given that the object in the sonar image is more often than not fragmented, a clustering algorithm is used on the detected contours. Predefined parameter - minimum separate contour distance - is used to denote which is the smallest distance between contours that will not result in clustering. To achieve the clustering, a union find data structure is used. Weighted quick union with path compression is used for almost linear time.

The effect of the contour clustering is shown in Fig. 2.5.4., where on the right image the contours that are closer than 500mm from each other are clustered together.

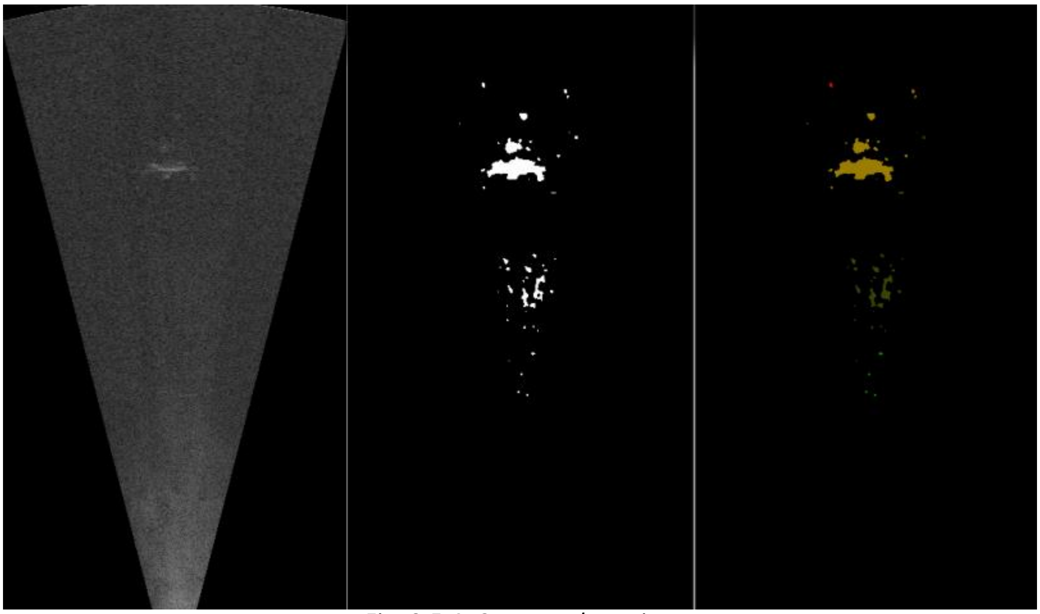


Fig. 2.5.4. Contour clustering

- **Motion estimation**

An Extended Kalman filter with kinematic model is used to estimate diver's motion. The prediction of the model is used to extract a region of interest (ROI) in the image so that only the measurements (contours) inside the ROI are considered. The centre of the ROI is equal to the prediction location, while the *x* and *y* size of the ROI rectangle are tied to the model's covariance matrix, making the ROI larger as the uncertainty of the model grows and vice versa.

The variance of the measurement is adapted based on the "quality" of the current measurement. An expected reference area (e.g. around $2m^2$ for the human diver) is provided, with the measurement quality being calculated based on the difference from the expected area. If the measurement is around the same size as the reference, the measurement variance is set to a low value. For a measurement with area much smaller or larger than expected, variance is higher. Variance function calculated based on the measured area is shown in Fig. 2.5.5., where the reference size is $2m^2$. The curve shape is a negative Gaussian.

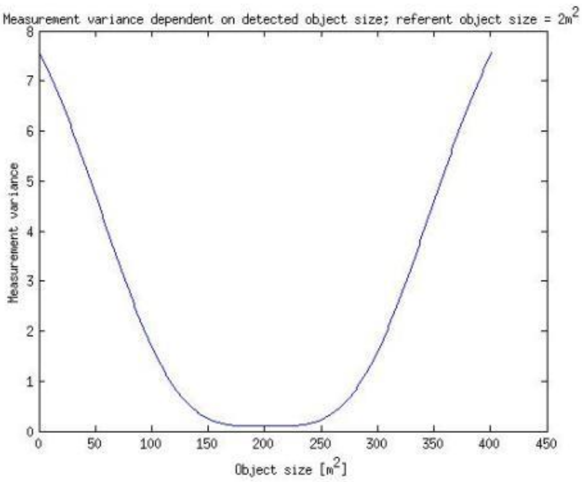


Fig. 2.5.5. Measurement variance for the EKF based on reference object size and detected contour size

Benefit from having a motion estimator and ROI based on it can be viewed in Fig. 2.5.6., where the dominant contour in the image is a large bubbly area behind the diver. However, due to the estimate moving forward, the bubbles are ignored and the smaller contours representing the diver are chosen.

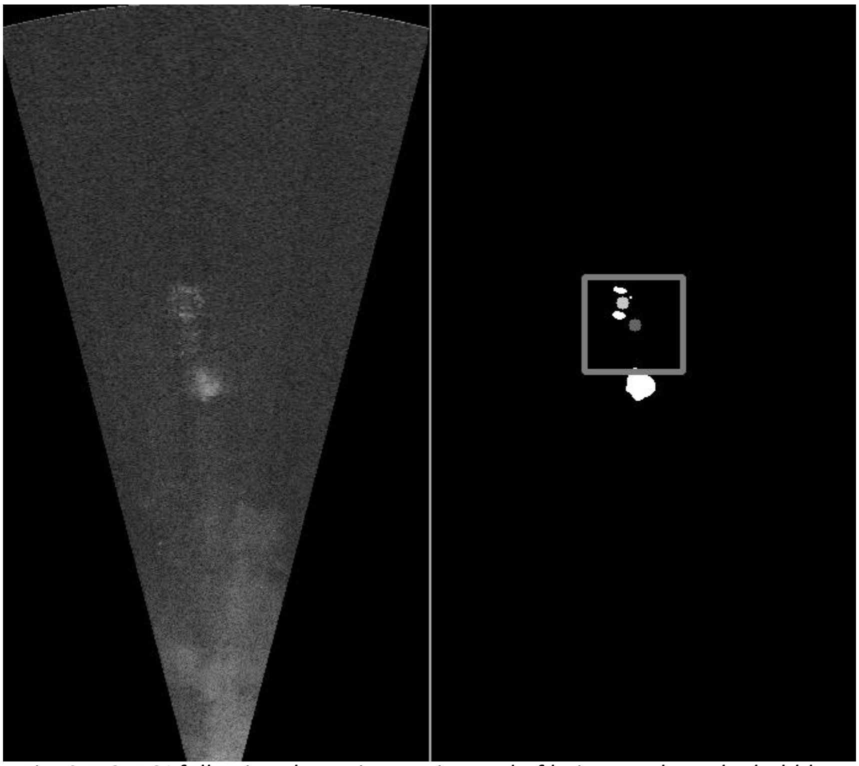


Fig. 2.5.6. ROI following the estimator instead of being stuck on the bubbles

Tracking of other objects (ROVs, AUVs etc.)

The whole tracking process uses no distinctive characteristic of human body and can work for tracking any object. The only thing that is required is approximate area that the object covers. It was tested with a small VideoRay ROV (whose dimensions are approximately 50x30cm).

Automatic range setting

Based on the located position of the tracked, range can be automatically adjusted. For example, if the diver is located 2 meters straight away from the sonar and starts swimming outwards, both starting point and ending point will automatically be adjusted to capture the area around the diver. Also, the frequency used by the sonar (low or high mode) is automatically adjusted based on the distance from the object of interest.

T2.6. Recognition of hand gestures

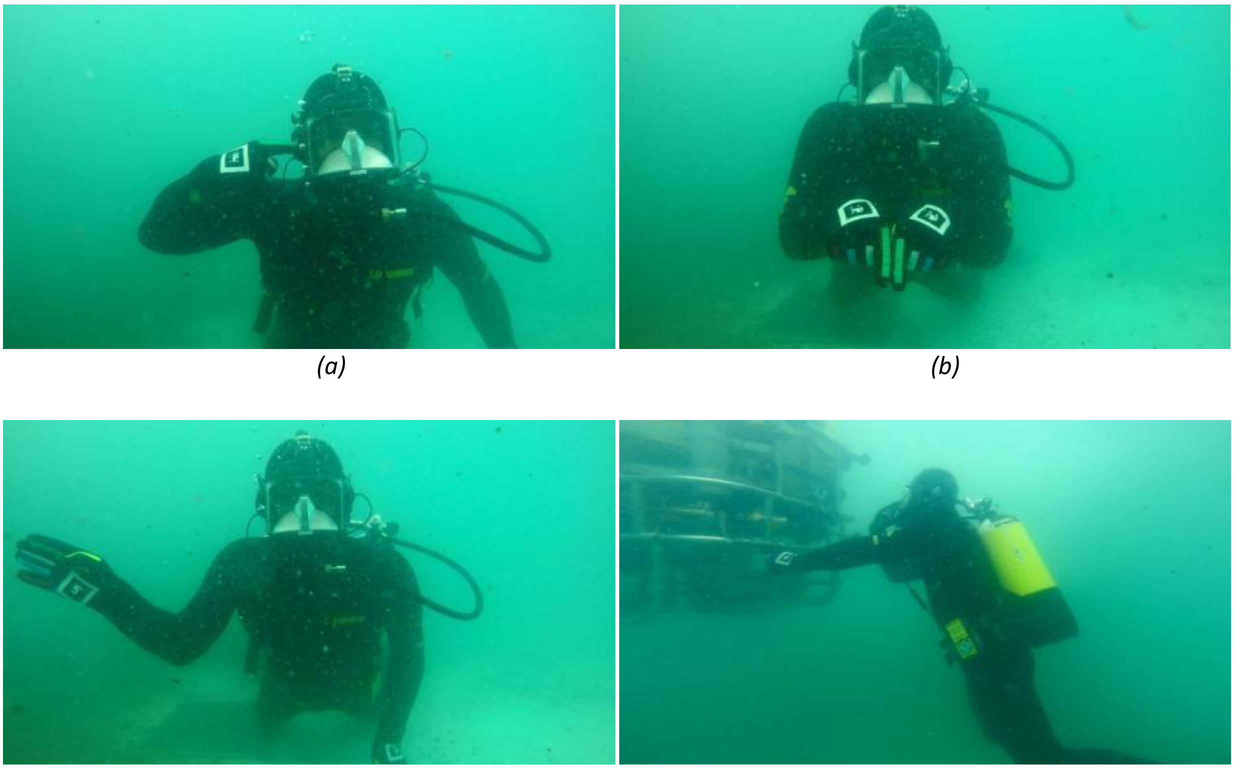
Recognition from mono camera (CNR)

A two-day campaign has been carried out for image data gathering at the Genova-Albaro swimming pool in date 30-31 March 2015. The aim of these trials was to collect further images with a diver performing gestures in front of the underwater robot.

In particular, different aspects have been put into test during these trials:

- gestures executed by professional diver;
- different light conditions;
- different water clearness levels;
- employment of marked gloves.

The light and water conditions can be appreciated as shown in Fig. 2.6.1.



(a) *(b)*

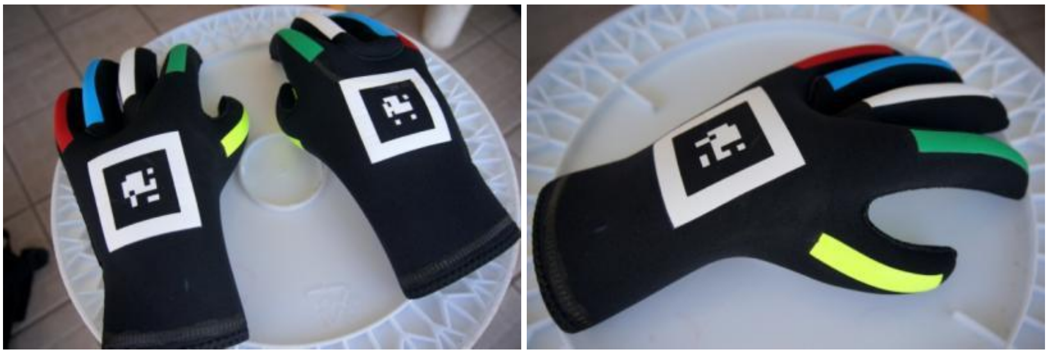
(c) *(d)*

Fig. 2.6.1. Gesture execution during swimming pool trials

An important aspect is the test of the artificially marked gloves. With the aim of making easier and more reliable the process of the automatic hand gesture recognition, the diver gloves have been modified adding:

- quad-markers on both the palm and the backside of the glove;
- colour bands on each finger (with a different colour for each finger).

The modified gloves are shown in Fig. 2.6.2.



(a) *(b)*

Fig. 2.6.2. Marked gloves

The analysis and preliminary computations on the gathered images are currently ongoing.
The expectation is that the presence of the quad-markers can be used to determine the orientation of the hand and to discriminate if the palm or the backside is facing the camera. Moreover, tracking the marker over the time would make possible to detect the motion of the hand thus easily allowing the recognition of dynamic gestures.
With the same concept, the colour bands applied to each fingers would help the detection of which fingers are currently extended or folded (knowing in advance the matching between colours and fingers).

<u>Recognition from sonar image (UNIZG-FER)</u>

Hand gesture recognition system is divided into two steps: hand detection and gesture classification. Hand detection is implemented using a cascade classifier and the gesture recognition is based on two approaches: convex hull method and support vector machine algorithm.

- **Hand detection**

Hand detection is performed using a cascade of boosted classifiers based on Haar-like features proposed by Viola and Jones. For this purpose classifier is trained to detect five hand gestures containing different number of visible fingers. After applying trained classifier on sonar image, hand is marked as shown in Fig. 2.6.3.

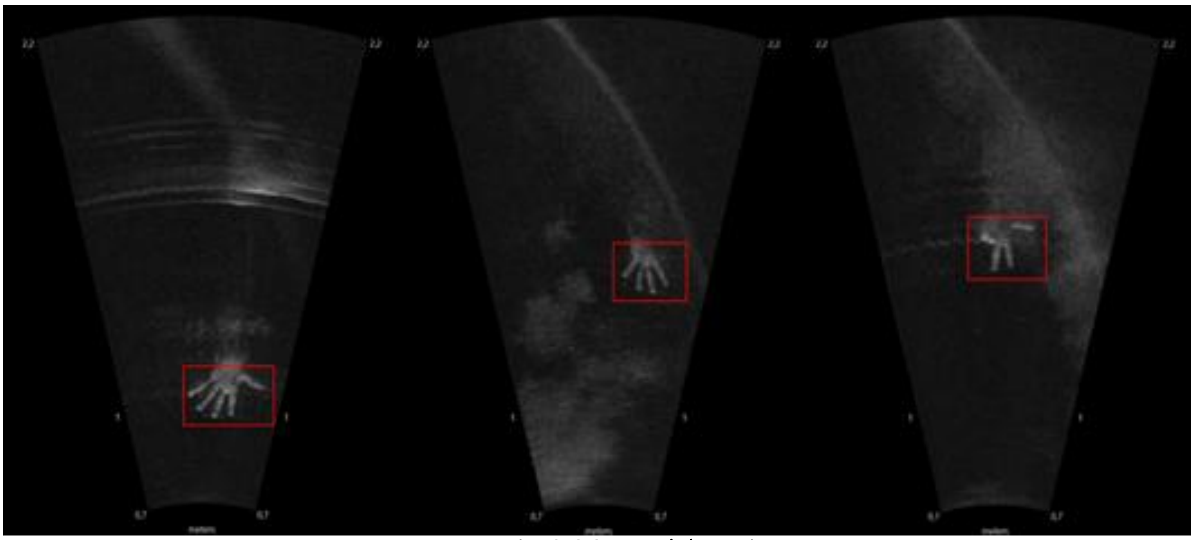


Fig. 2.6.3. Hand detection

- **Gesture recognition**

After hand detection step, area marked by cascade classifier is used for further processing and gesture recognition.

Image pre-processing

First, Gaussian blurring and adaptive threshold are performed in order to get binary image. After that, morphological operations of erosion and dilation are performed to additionally smooth image and reduce noise. Process is shown if Fig. 2.6.4.

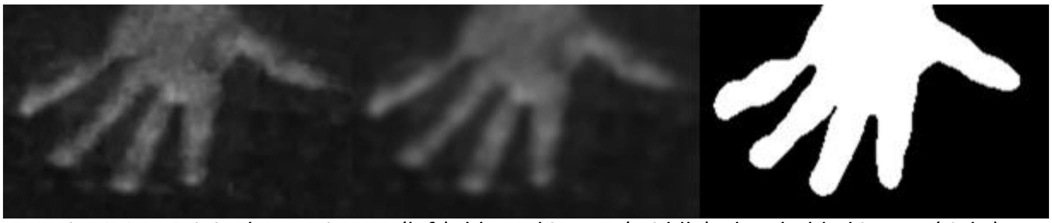


Fig. 2.6.4. Original sonar image (left); blurred image (middle); thresholded image (right)

Method 1: Convex hull method

Previously binary thresholded image is used for contour extraction and convex hull calculation. Convexity defects are then determined based on contour and convex hull (marked as red dots on Fig. 2.6.5.). Redundant convexity defects are filtered by depth and angle between the lines going from the defect to the neighbouring convex polygon vertices. Finally, fingertips are marked on the original image (Fig. 2.6.6.).

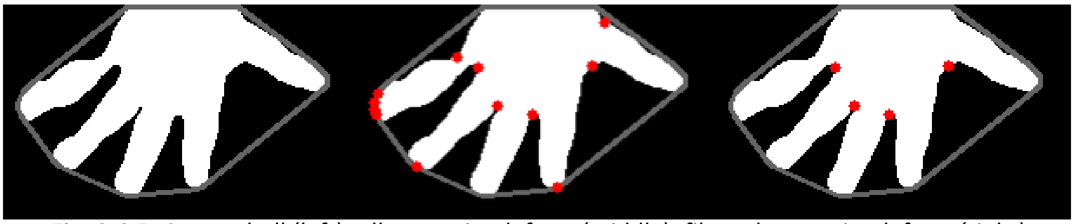


Fig. 2.6.5. Convex hull (left); all convexity defects (middle); filtered convexity defects (right)

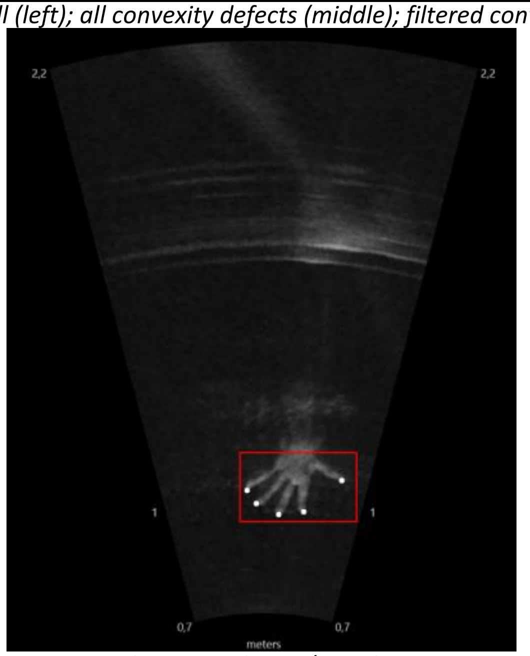


Fig. 2.6.6. Finger detection

Method 2: Support vector machine

Another method implemented for gesture recognition is machine learning algorithm- multiclass support vector machine. Goal is to classify five different gestures shown in Fig. 2.6.7.

Fig. 2.6.7. Hand gestures

Features selected for classification are seven Hu invariant moments. These feature are proven to be good shape descriptors, while providing translation, scale and rotation invariance. For each class a set of image is prepared and Hu moments are calculated from binary images. Features are scaled to the range [0, 1] and used for training. Applying the trained model to test images gives the class number corresponding to number of visible fingers.

WP3 Understanding the diver

T3.1. Adaptive interpretation of diver behaviour

We also developing of a DiverNet player with synchronized video. This will allow us to test different algorithms for data manipulation and machine learning. Currently we can play back a rosbag file from DiverNet synchronized with a video recording of the diver in real time. Annotations are in a list and highlighted during playback.

Starting with our first dry experiments we developed basic procedures for data manipulation and analysis. From DiverNet we get three channels: breath, heart (not yet implemented in DiverNet, but in the player) and motion. The algorithms which are implemented at the moment are noise reduction with a Gaussian smoother, this gave the best results. In a second step we use event detection, with an algorithm which uses the detection of minima and maxima. Thus we also can calculate rates of change in all channels and turbulence detection. The player also allows down sampling - this might be useful for the determination of optimal sensor sampling rates.

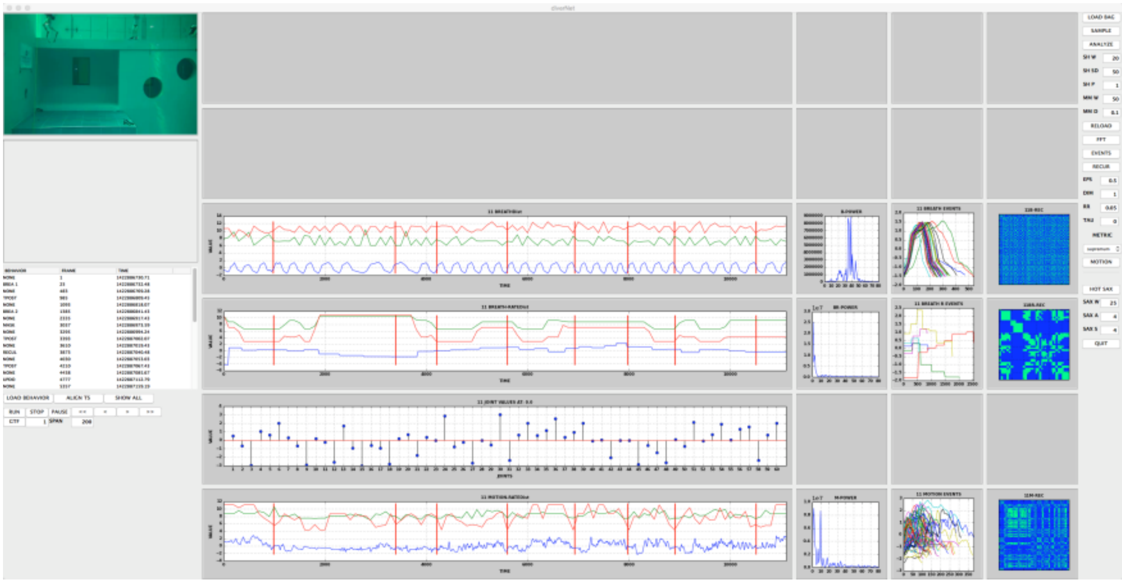


Fig. 3.1.1. Screenshot of the DiverNet player.

In addition we started with the task of anomaly detection. We implemented a symbolic aggregation approximation algorithm (Keogh et al. 2005[2]) which allows us to detect anomalies and motifs in real time. The procedure consist of three simple steps: calculate the z-scores of the time series, use a piecewise aggregate approximation and then translate this into symbols of an alphabet. For the detection the resulting string is divided into words and the Euclidian distance is calculated between words. The following graph shows the results. On the x –axis are the video

[2] Keogh, E., Lin, J and Fu, A. (2005): HOT SAX: Efficiently Finding the most unusual time series subsequence. Proceedings of the Fifth IEEE International Conference on Data Mining (ICDM'05) 1550-4786.

frames, the blue line is the motion rate the green line is the simple distance and the red line represents the Euclidian distance of a word to all other words in the window. As you can see the t-postures from the behaviour file which are presented as vertical red lines all fall on depressions in the similarity. Thus it seems to be possible to identify certain behaviours and anomalies with this method from motion rate alone. The plan is to extend this on all 60 channels of DiverNet.

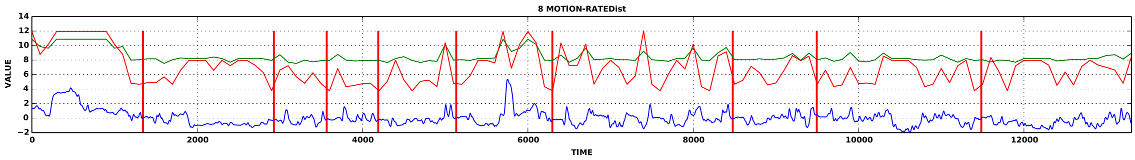


Fig. 3.1.2. Similarity of words of motion rates for anomaly detection.

T3.2. Symbolic language interpreter

CNR, during this period, has finalized a new version of CADDIAN (version 1.2), adding new commands, revising old ones, producing a dictionary for the language and a more precise list of the CADDIAN slang gestures. The new version has been created following the reviewers' suggestions for a simpler language or better for a language which has a simpler minimal set of gestures recognizable by all divers all over the world.

New commands/messages have been added to communicate the status of the cylinder of diver ("low on air" and "On reserve") and to allow the diver/robot to ask questions. A command to turn the robot of 180° degrees has been added, too. The previous version of CADDIAN has been subjected to a review because divers, for their part, have made it clear that acceptance of the language would be better if a subset of the messages would have made using gestures already used normally for diving. In this regard, a subset of gestures has been therefore identified and added to the language. Many of the slang gestures can be found under the new production <slang>: some of the identified gestures remain outside of it but they can be performed anyway because syntax allowed them also in the previous version (i.e. one of them is the gesture for "OK"). Here follows a comprehensive list of the messages considered slang:

CADDY SLANG

I = I, me	**K = cramp**
Y = you	**V = vertigo**
Const = stay at this level	**B_2 = to be out of air**
+ = up	**const= stay at this depth**
- = down	**U = don't understand**
Ok = ok	**B = boat**
No = no	**ƀ = Something is wrong [on me]**
B_3 = breath	**low = low on air**
C_1 = cold	**Reserve = on reserve (50 bar left)**
P_g = generic problem (danger)	**Turn = Turn of 180° degrees**
E = ear	

The syntax has been revised, accordingly to all the above changes.

The dictionary created contains a very detailed description of each gesture used for the language. Each dictionary entry (see Fig. 3.2.1) is made up of the following fields (a short description is given):

Title
The name of the command
CADDIAN written form
The CADDIAN symbol used to write the command on documents
Type
It can be static or dynamic: in case of a dynamic gesture, the images showed below have to be seen as a sequence
Hands
It describes which hand is involved in the gesture
Palm/back
It describes if the hand shows the palm or the back to the camera
Fingers
Fingers extended; the number identifies the finger while the letter the hand. For example 1R is the thumb of the right hand.
Notes
Self-explaining
Images
List of Sample Image representing the gesture

End of communication

CADDIAN written form (symbol): ∀
Semantics: end of communication
Type: static gesture
Hands: R
Palm/back: back to camera
Fingers: 2R
Notes: none

Fig. 3.2.1 An example of the dictionary entry

The dictionary has been created with the aim to be useful for the project partners, but also to be a future dissemination material for all people who want to learn CADDIAN.
The new version of CADDIAN also contains a sequence table (i.e. “Table of possible sequences”) where the whole language is represented. The table has been created to be useful for the classifier, given the fact it shows which gesture can follow a given one. For example in Fig 3.2.2 it can be seen that after the “C” gesture only “P” or “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).

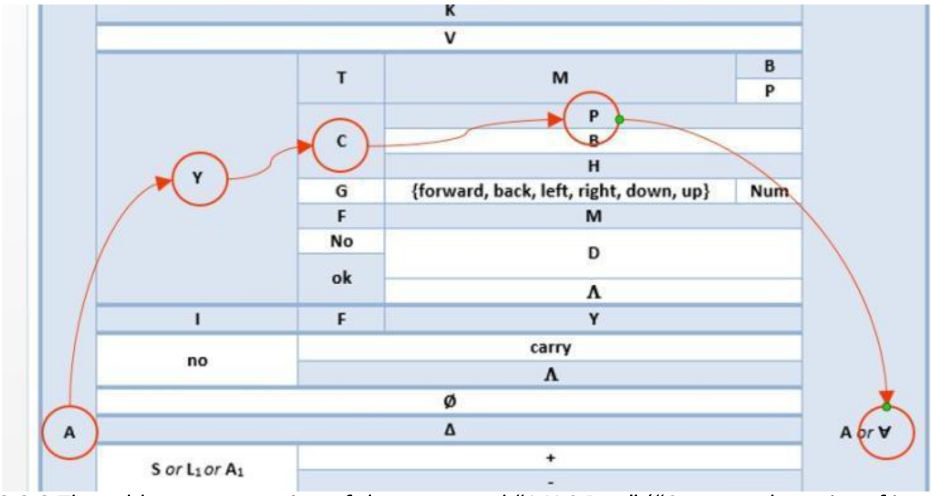


Fig. 3.2.2 The table representation of the command "A Y C P ∀" ("Come to the point of interest")

In this same period, few tests in swimming pool have been made (see Fig. 3.2.3 and Fig. 3.2.4).


Fig. 3.2.3 Gestures trials on the ground before dive


Fig. 3.2.4 Gesture trials in the water

In May 2015, an article of scientific dissemination about the previous version of CADDIAN (i.e. the one before the addition of the slang part) has been presented at MTS/IEEE OCEANS'15 Genova conference.

T3.3. Cognition-based mission (re)planner

T3.4. Performance evaluation

WP4 Diver-robot cooperation and control

T4.1. Compliant diver buddy tasks

The aim of providing a compliant behaviour of the overall robotic system, with respect to the operations undertaken by the diver, is made available through the development of an automatic selection system for the execution of the proper autonomous robotic tasks.

First of all, the basic CADDY functionalities has to be mapped into subsets of tasks that can be provided by the robotic platforms. In order to define the primitives-tasks matching, an additional high-level task set has to be defined as cross-interface between the primitives and robotic task sets.

A preliminary definition of the three sets is reported in Fig. 4.1.1, where:

- functional primitives represent the macro-actions that the robotic platform has to carry out in order to support the diver operation and that are strictly related to the current functional mode (slave, guide, observer);
- high-level logical tasks are the interface between the primitives and the operative task provided by robot. This logical task set is common in the overall architecture and will provide the required functionalities activating the proper low-level tasks that are currently made available by the employed robotic platform;
- low-level robotic tasks are the actual implemented autonomous functionalities on the target robot, e.g. speed regulators, heading and depth controller, etc. Depending on the low-level task availability, the CADDY compliant mission control system will properly select which high-level functionalities can be activated allowing, in turn, the enabling of the required primitives to fulfil the mission operations.

For the automatic selection, activation and inter-task conflict management, a Petri net based execution control system, inherited from the CNR-ISSIA robotic framework, is under current development. The system is configured by means of a set of configuration files that specify, on one side, the capabilities of the robot in terms of autonomous tasks and, on the other side, the set of high level functionalities that the CADDY system has to provide for the diver support. A real-time Petri net engine models the logical interconnections among the tasks and primitives and, depending on the specific actions commanded by the diver, automatically handle the activation/deactivation of the proper task sets.

As an example, Fig. 4.1.2 reports the case of activation of the "Follow me" primitive; such a primitive requires the system to turn on the following functionalities: "go_to_depth" to reach and maintain a desired depth (i.e. the same of the diver); "go_to_2D_point_fa" is the procedure to track a 2D point (the diver position) for fully-actuated (fa) platforms, that generates proper horizontal velocities for point tracking; "turn_towards" enabling the auto-heading capability to always look towards the diver.
In turn, each of the high-level task has to be linked with one or more low-level tasks in order to physically execute the required actions:
- "go_to_depth" requires the activation of a depth_controller;
- "go_to_2D_point_fa" requires the activation of surge and sway velocity regulators;

-"turn_towards" enables the auto-heading controller.

The logical links between the high- and low-level layers are set on the basis of the input/output variables: the output generated by a high-level task is the input for one or more low-level tasks, e.g. "go_to_2D_point_fa" generates the *u* and *v* speed reference signals that feed the low-level speed controllers.

If, as a second exemplificative case, an under-actuated platform is employed, it implies in turn that the "sway_speed" controller is not available (due to the under-actuation, e.g. of a rudder based vehicle). The unavailability of this latter low-level task reflects on the inhibition of the "go_to_2D_point_fa". Anyway to fulfil the "follow me" primitive requirements, the system can automatically switch to the "go_to_2D_point_ua" that can drive the robotic platform towards the desired point generating proper surge velocity and heading signals. The activation of the "go_to_2D_point_ua" task goes in conflict with the "turn_towards" one, given the generation of the ψ reference signals by both the tasks. Detecting this logical conflict, as depicted in Fig. 4.1.3, the system deactivates the execution of the "turn_towards" (that, by user definition, has a lower priority with respect to the "go_to_2D_point_ua" in relation to the "follow me" primitive).

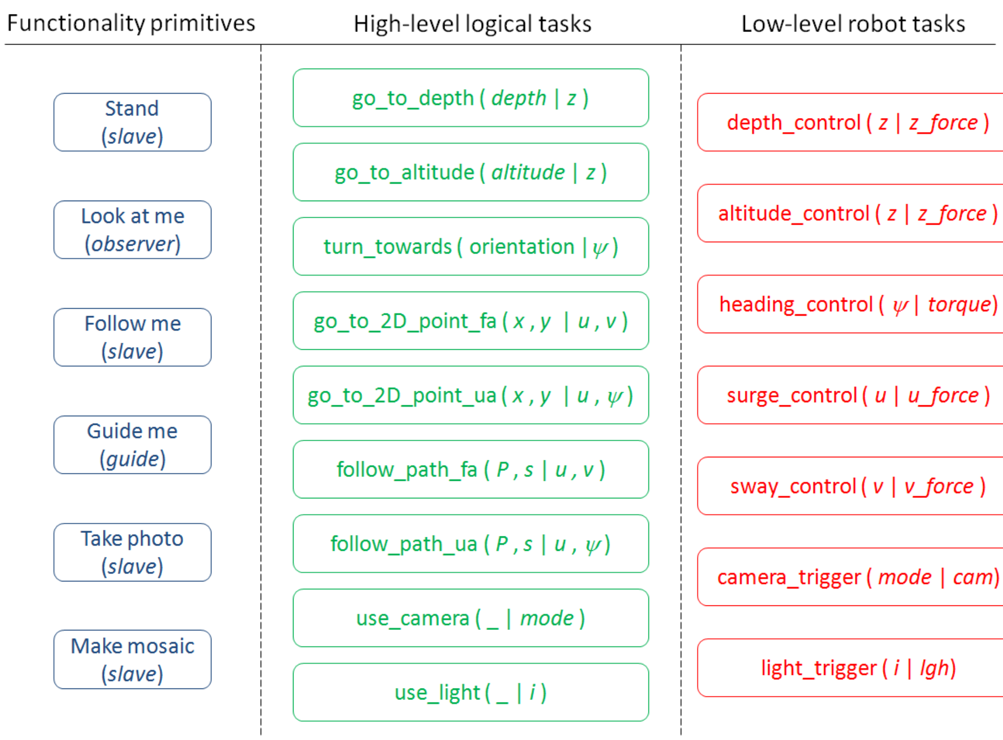


Fig. 4.1.1. Primitives and tasks definition

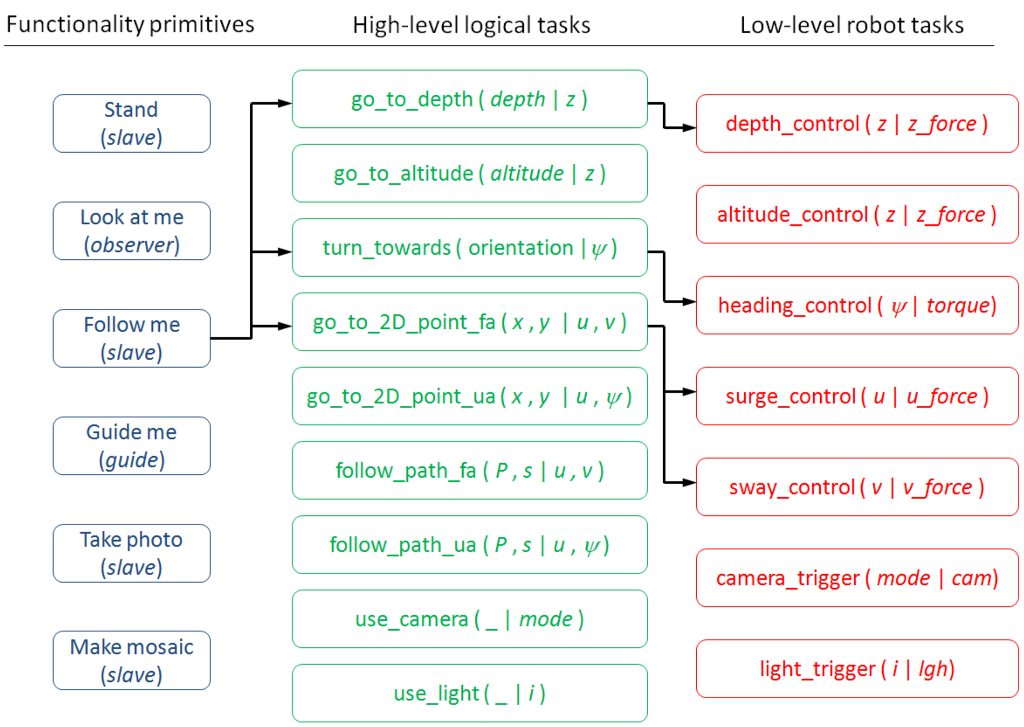


Fig. 4.1.2. Example of "follow me" primitive activation for fully-actuated robot

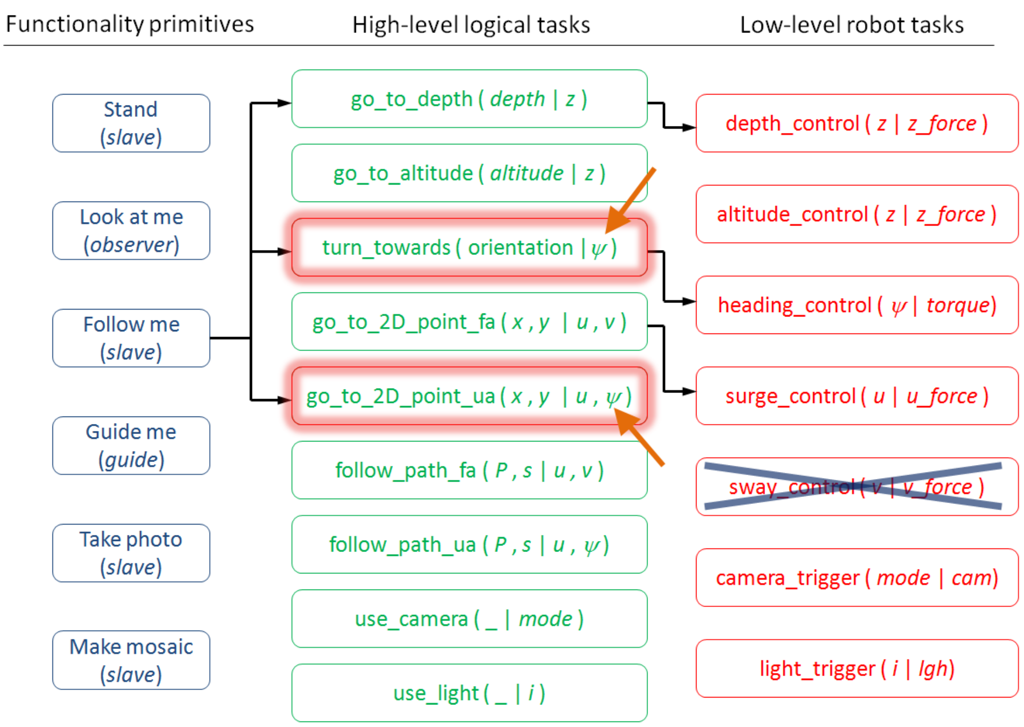


Fig. 4.1.3. Example of "follow me" primitive activation for under-actuated robot and inter-task conflict management

Jacobs is further working on improving the implementation of the “Make Mosaic” task, namely the module that will perform the simultaneous localization and mapping. Specifically, the work has recently focused on the map representation. A coloured occupancy map implemented with the octomap (https://octomap.github.io/) library was developed, including a corresponding visualization in RViz. Further work will identify a suitable forward sensor noise model for underwater stereo cameras, allowing much better probabilistic estimation of the environment structure in 3D.

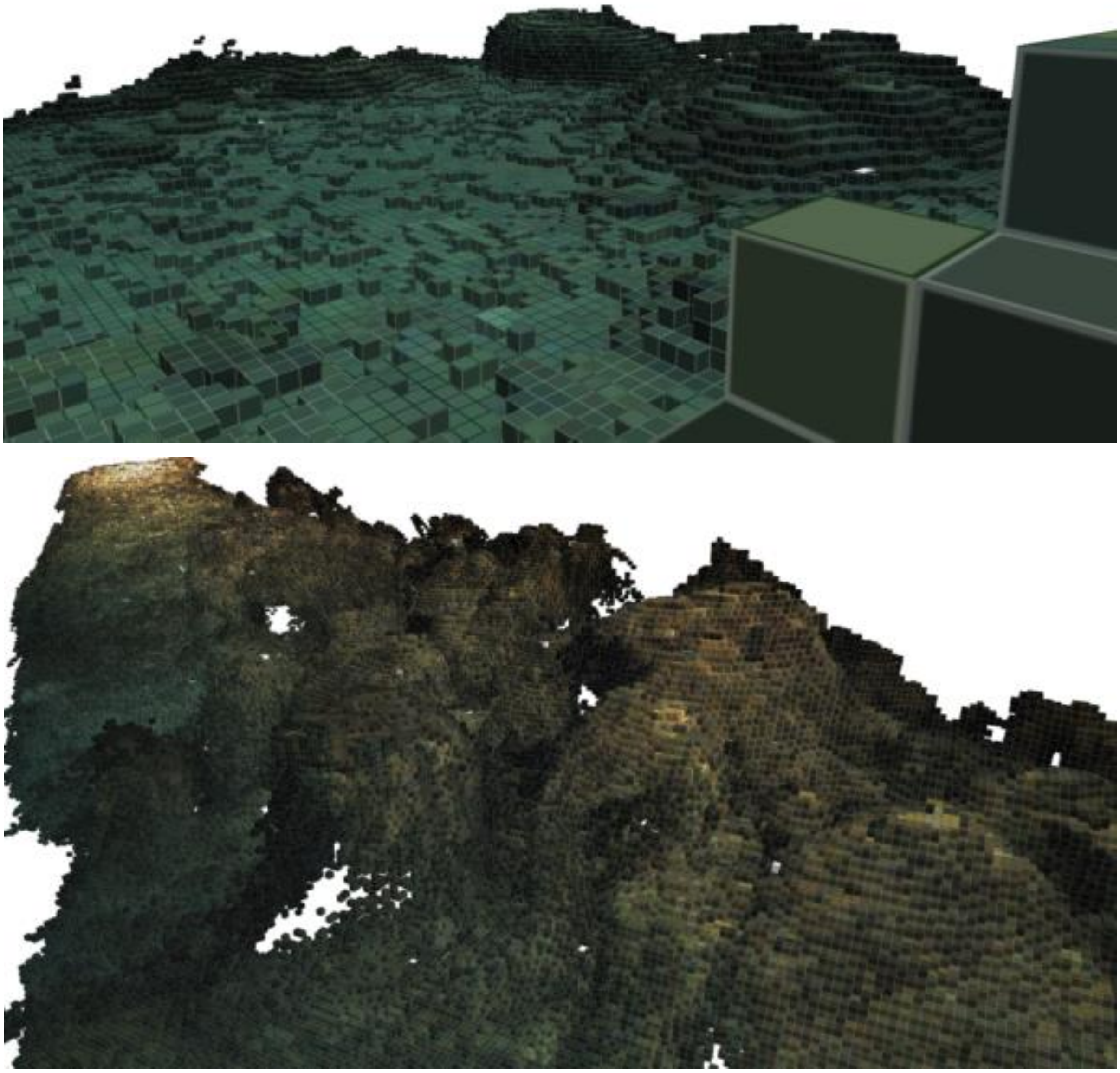


Fig. 4.1.4: Two views of a sample 3D occupancy grid of stereo data collected at BTS in 2014

T4.2. Cooperative control and optimal formation keeping

Virtual target path following and pointer experiment

The pointer experiment, shown in figure 4.2.1, requires Buddy to position relative to the driver on a circular path. Movements must be executed on a safety circular path to avoid unplanned entry into the diver private space. The virtual target path following control method offers a simple controller structure for implementing this behaviour. The problem can be extended to incorporate positioning on the path in case of the fully-actuated Buddy vehicle.

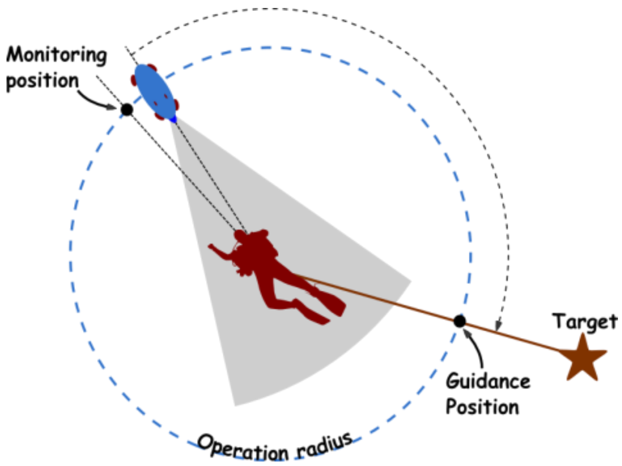


Figure 4.2.1 Pointer experiment layout

Deriving the controller requires defining three working frames, shown in Figure 4.2.2. The {N}-frame is defined as the local tangent plane or North-East-Down frame. The vehicles and diver navigate inside of this frame. {B}-frames are the body fixed frames connected to a vehicle or a diver. A Seret-Frenet, {SF}-frame, is introduced which axis are defined by a tangent unit vector (T) and the normal unit vector (N) at some point ''s'' of the defined path. The main goal is to have Buddy converge to the origin of the {SF}-frame, thus ensuring that Buddy is on the safety path (circle) around the diver. The secondary goal is to have Buddy converge on a certain point of the path "s_D" and take a desired heading.

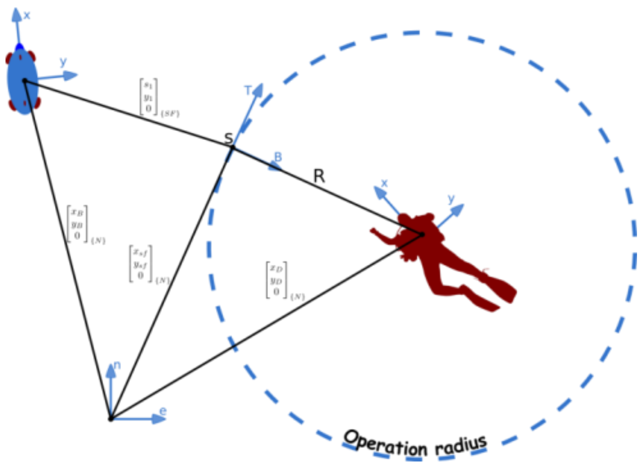


Figure 4.2.2 Pointer experiment

The theoretical kinematic controller can be derived by using a Lyapunov based controller design. The following Lyapunov function fulfils both the primary and secondary objectives:

$$V = \frac{1}{2}s_1^2 + \frac{1}{2}y_1^2 + \frac{1}{2}\left(\frac{\tilde{s}}{k_{\tilde{s}}}\right)^2$$

where ψ_r and $s^\sim = (s_D - s)$ are the desired heading and the position error on the path; s_D is the desired position on the path. Other parameters are shown on Figure 4.2.2. By requesting the function to converge to zero we request that all goal are fulfilled. Notice that having s_1 and y_1 converge to zero in essence means that Buddy converged to the {SF}-frame origin and hence on the path. The heading control part has been skipped since it represents a trivial control where the desired heading is always towards the diver.

The kinematic model in {SF}-frame is derived as:

$$\begin{aligned}
\dot{s}_1 &= (\dot{x} + \dot{x}_c - \dot{x}_D)\cos\psi_f + (\dot{y} + \dot{y}_c - \dot{y}_D)\sin\psi_f - \dot{s}(1 - c_c y_1) \\
\dot{y}_1 &= -(\dot{x} + \dot{x}_c - \dot{x}_D)\sin\psi_f + (\dot{y} + \dot{y}_c - \dot{y}_D)\cos\psi_f - c_c\dot{s}s_1
\end{aligned}$$

where position derivatives of the diver and current (x_c, y_c) have been included; (x,y) derivative represent the Buddy speed. The diver speed has to be included since the path travels with the diver, rather than standing still. The Lyapunov gradient can be derived as follows:

$$\begin{aligned}
\dot{V} &= ((\dot{x} + \dot{x}_c - \dot{x}_D)\cos\psi_f + (\dot{y} + \dot{y}_c - \dot{y}_D)\sin\psi_f - \dot{s}(1 - c_c y_1))\, s_1 + \\
&\quad (-(\dot{x} + \dot{x}_c - \dot{x}_D)\sin\psi_f + (\dot{y} + \dot{y}_c - \dot{y}_D)\cos\psi_f - c_c\dot{s}s_1)\, y_1 - s_1\dot{s} + \frac{\tilde{s}\dot{\tilde{s}}}{k_{\tilde{s}}^2} \\
&= (s_1\cos\psi_f - y_1\sin\psi_f)(\dot{x} + \dot{x}_c - \dot{x}_D) + \\
&\quad (s_1\sin\psi_f + y_1\cos\psi_f)(\dot{y} + \dot{y}_c - \dot{y}_D) - s_1\dot{s} + \frac{\tilde{s}(\dot{s}_D - \dot{s})}{k_{\tilde{s}}^2}
\end{aligned}$$

The (x, y, s) derivatives can be commanded and selected in such a fashion as to ensure that the gradient is at least negative semi-definite. The following commands can be chosen:

$$\begin{aligned}
\dot{x}^* &= -k_x(s_1\cos\psi_f - y_1\sin\psi_f) - \dot{x}_c + \dot{x}_D + \dot{s}_D\cos\psi_f \\
\dot{y}^* &= -k_y(s_1\sin\psi_f + y_1\cos\psi_f) - \dot{y}_c + \dot{y}_D + \dot{s}_D\sin\psi_f \\
\dot{s}^* &= k_s\left(s_1 + \frac{\tilde{s}}{k_{\tilde{s}}}\right) + \dot{s}_D
\end{aligned}$$

where the speed of change of the desired position on the path is feed-forwarded as well. This theoretically ensures that during diver movement the control remains stable. However, in real-life scenarios the diver will move slowly and keep his heading mostly constant. The gains k_x, k_y, k_s, $k_{s\sim}$ can be selected appropriately to shape the response transient.

Notice that the draw-back of the approach is that the diver position and orientation need to be known with good precision in order to assure a stable monitoring position. While the position can be acquired with some precision from the sonar, the USBL position, due to noise, will not be enough to assure good tracking. The diver orientation and orientation rate of change will have to be estimated from the USBL data and potentially from the sonar image processing.

Leader tracking system

In what follows, we summarize the results of practical experiments that illustrate the performance of the LTS (Leader Tracking System) in a scenario where an ASV is the leader and an AUV is the follower. The core results of this experiment were reported previously but are included here to clearly show how a problem that was detected (deterioration of performance when the leader enters a piece of arc) was solved.

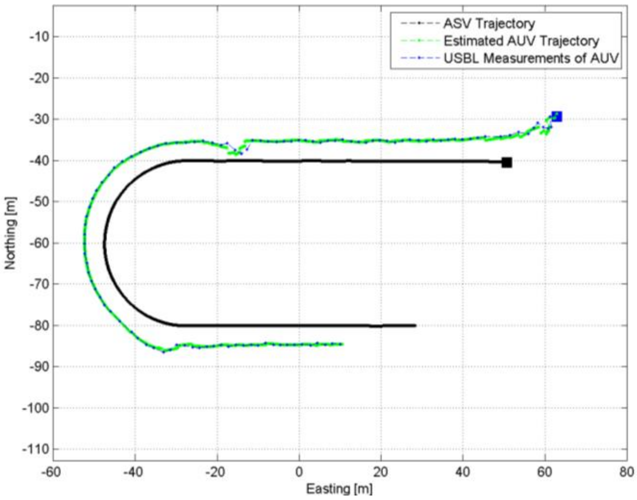


Fig. 4.2.3. Leader Tracking System with ASV as leader: ASV and AUV trajectories.

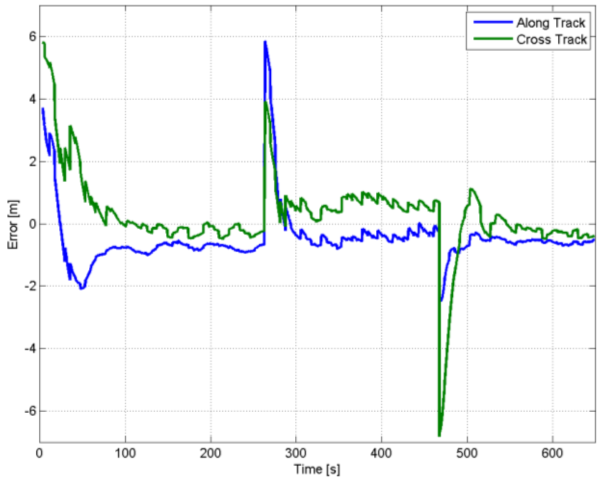


Fig. 4.2.4. Tracking error of the AUV

Fig. 4.2.3 shows the trajectories of both vehicles, and Fig. 4.2.4 shows the position error (with respect to the virtual target that should be tracked). The performance of the Leader Tracking System illustrated by these figures is visibly good. The deterioration in performance that occurs when the ASV enters or leaves the circular part of the manoeuvre is simply due to the fact that the along- and cross track position specification for the virtual vehicle (to be tracked by the ASV) are done considering that the circular part of the path is extended backward as a circumference (upon detection that the ASV actually entered the circular path). This was done at the time when these tests were conducted to simplify the implementation of the Leader Tracking system. Meanwhile, this problem has been overcome by extending back the path taken by the AUV taking into consideration the actual path traversed, stored in memory. This is illustrated in the results shown in the next paragraph, which no longer exhibit this problem.

The second scenario is illustrated in Fig. 4.2.5 with results obtained with one AUV playing the role of leader, performing path-following on the same pre-defined U-shaped mission, and one ASV playing the role of follower.

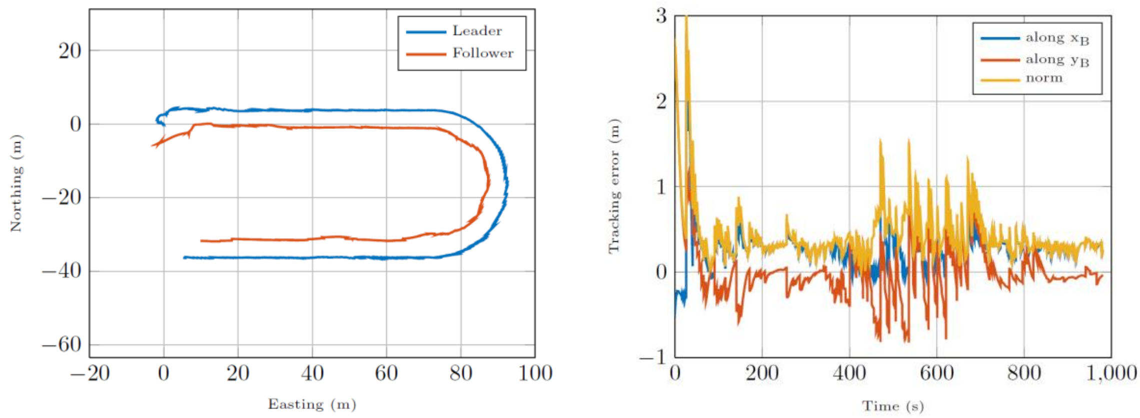


Fig. 4.2.5. Leader Tracking System with AUV as leader. Left: Trajectories of AUV and ASV. Right Tracking error of the follower (ASV)

Again, the results are visibly good, with the tracking error of the follower (ASV) generally below 1 meter. The issue identified in the previous section when the leader vehicle enters or exits the turn has been effectively addressed and the performance no longer exhibits considerable deterioration in this situation, as happened in the previous scenario.

T4.3. Cooperative distributed navigation and localization

Extremum seeking (UNIZG-FER)

Good underwater localization is of utmost importance for successful execution of all CADDY scenarios and therefore USBL systems are used to achieve that. Cheaper alternative is to use range only measurements. In such case unmanned surface vehicle (USV) is trying to execute trajectories informative enough in order to enhance observability of an underwater object, e.g. AUV or diver, which navigates itself by using only range measurements acquired by acoustic modems. We investigate the possibility of using extremum seeking (ES) scheme for online determining of informative enough beacon trajectories with lower computational effort. ES scheme is usually deployed when system model is not known very well or even completely unknown and its use for navigating autonomous vehicles towards an unknown source using measurements that indicate field intensity in certain point in environments without GPS signal is a common research.

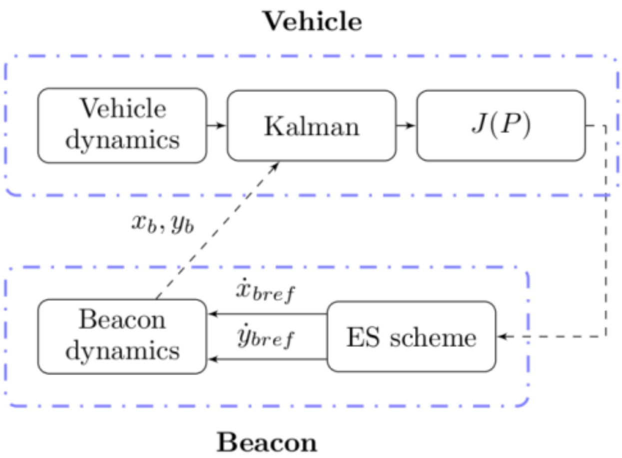
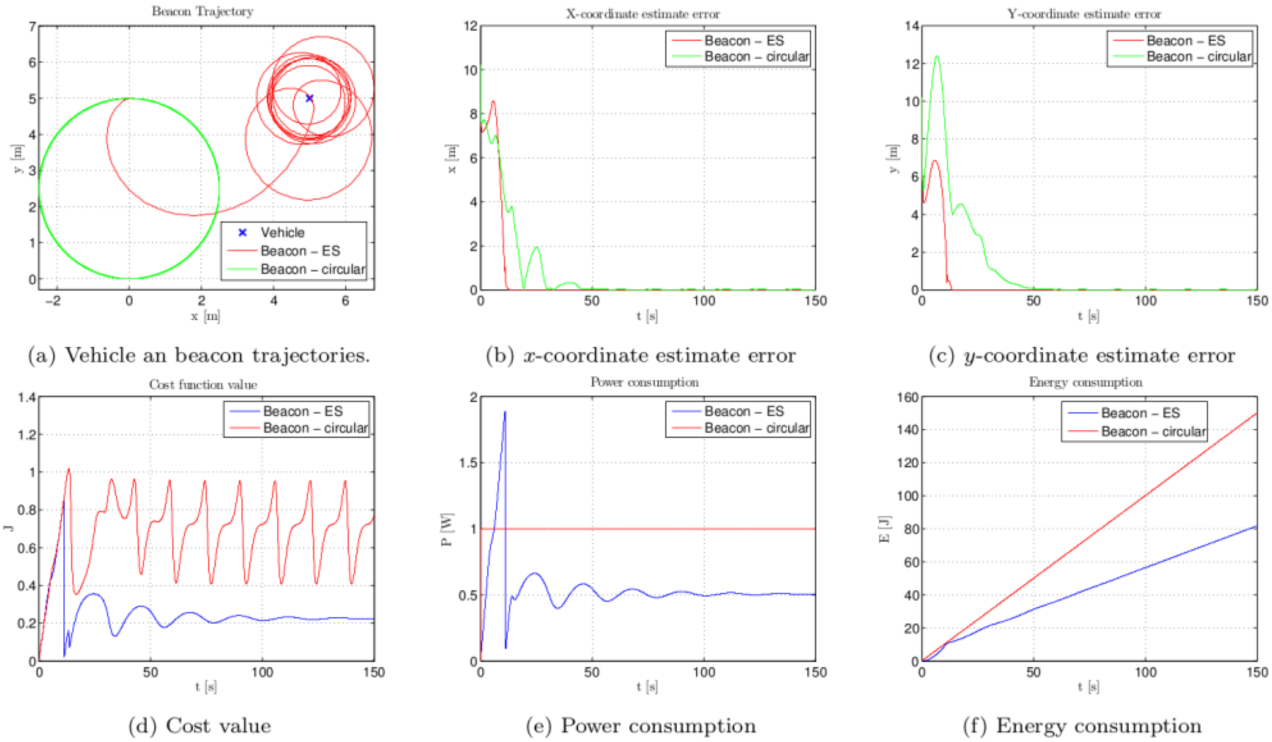


Figure 4.3.1.Extremum seeking scheme

As it has been noted, in order to estimate its position using single range measurements, the vehicle has to travel sufficiently informative trajectories. This can disable the vehicle from doing other useful activities which require trajectories that are not informative enough. In order to avoid that, an approach with two vehicles, where one of them is a beacon, can be used. In that case, a mobile beacon, which knows its position accurately (from GPS), is responsible for travelling trajectories which will provide informative range measurements for the vehicle's navigation filter. Figure 1 depicts the main idea which enables better vehicle position estimation by using single beacon measurements. Mobile beacon sends its position (xb , yb) to the vehicle's Kalman filter used for navigation. Information generated in the navigation filter is then used to calculate cost function value J which gives a measure of observability. Current cost value is then sent to mobile beacon which tries to minimize it online by using extremum seeking scheme which steers the mobile beacon towards the minimum of cost function. The beacon again sends its position to the vehicle, thus closing the control loop. Range measurement used for determining vehicle's position is acquired during the communication cycle.



(a) Vehicle an beacon trajectories. (b) x-coordinate estimate error (c) y-coordinate estimate error

(d) Cost value (e) Power consumption (f) Energy consumption

Figure 4.3.2.Simulation results for the static vehicle scenario

The proposed algorithm was simulated for two different scenarios: stationary vehicle and mobile vehicle assuming curved trajectory. For both scenarios, we compared the basic case where mobile beacon executes constant speed circle trajectory which ensures system's observability, and the case where the mobile beacon is assuming the trajectory generated by the extremum seeking algorithm. Fig. 4.3.2. and Fig 4.3.3. represent simulation results for a static vehicle and moving vehicle scenario, respectively.

Proposed mobile beacon trajectory generation method is particularly interesting for underwater application because of limited bandwidth of acoustic communication. In the extremum seeking scheme, the only data that needs to be transmitted over the acoustic link is the cost function value which is sent from the vehicle to the beacon, and the beacon position data needs to be sent to the vehicle. Extremum seeking is not a model based approach so it can be easily deployed on different types of vehicles. That can be particularly interesting in cases when model is difficult or impossible to obtain, i.e. in the case when the vehicle is replaced with a human diver. Another great advantage of extremum seeking is the fact that constant disturbances acting on vehicle, i.e. gravity, buoyancy or currents, are automatically compensated by the extremum seeking control loop. Furthermore, the proposed algorithm does not require knowledge of the vehicle's trajectory in advance. That can be particularly useful in real–life conditions when planned trajectories are known but currents that affect the vehicle and the mobile beacon change its desired trajectory and decrease optimality of solution.

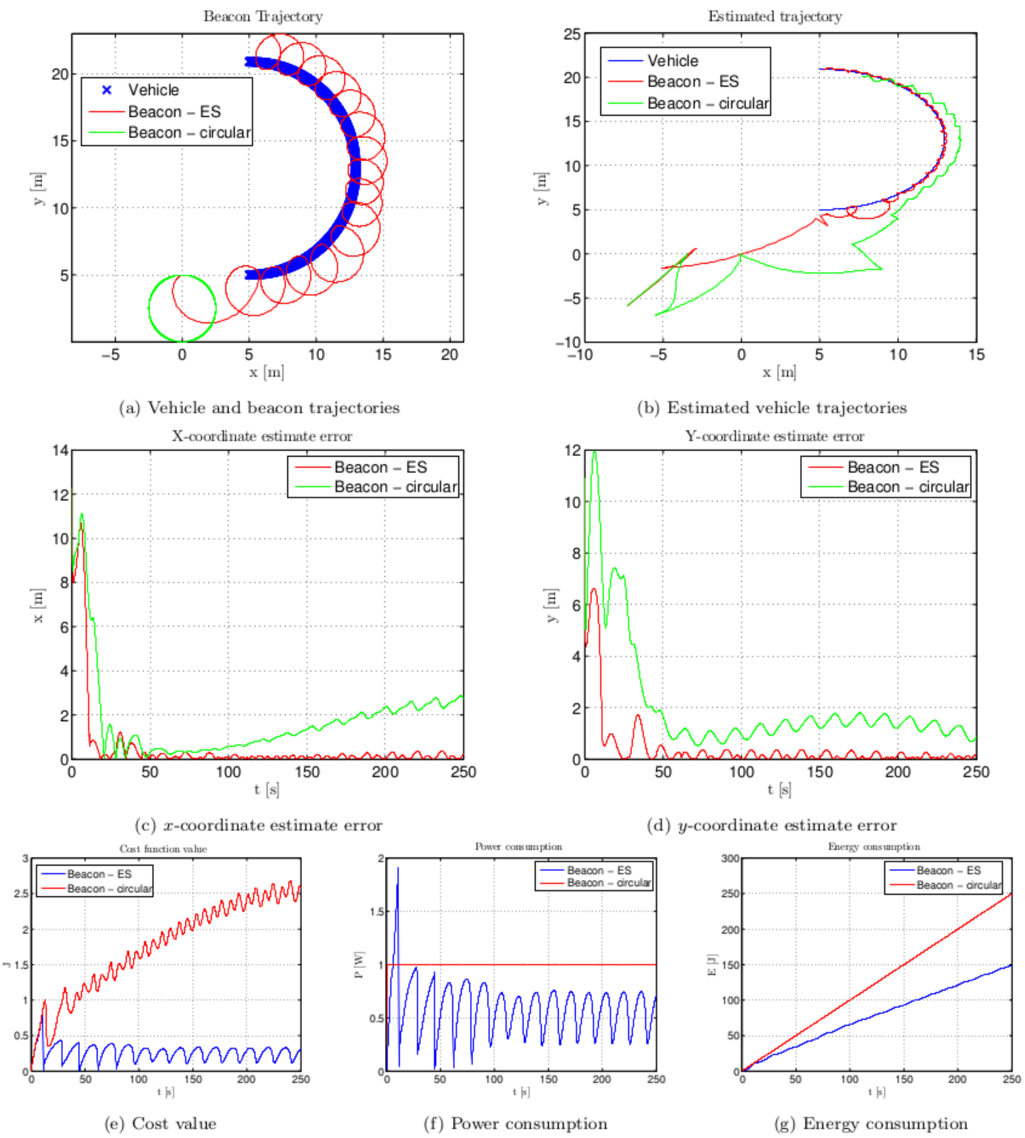
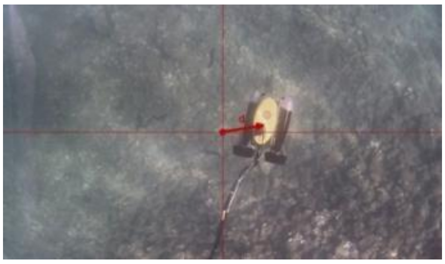


Figure 4.3.3.Simulation results for the moving vehicle scenario

T4.4. Experiments and performance evaluation

Extremum seeking tracking tests (UNIZG-FER)

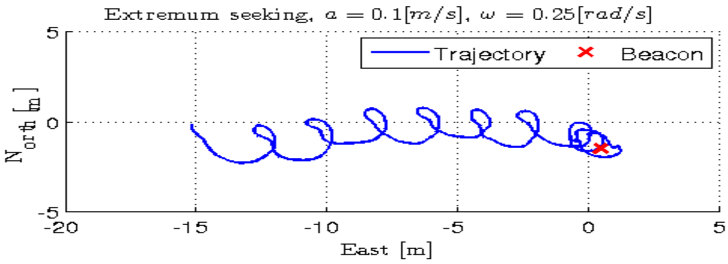
In order to validate simulation results of extremum seeking tracking, during field trials, which took place in Biograd na Moru, Croatia in June 2015, algorithms for diver tracking using range-only measurements from an autonomous surface vehicle were tested. By using only range measurements surface vehicle was able to localize underwater target, i.e. diver, and stay on top of its position. That was achieved using three different extremum seeking algorithms. Test setup, shown in Figure 4.4.1., consisted of PlaDyPos platform with USBL modem which provided range measurements from VideoRay ROV which simulated diver



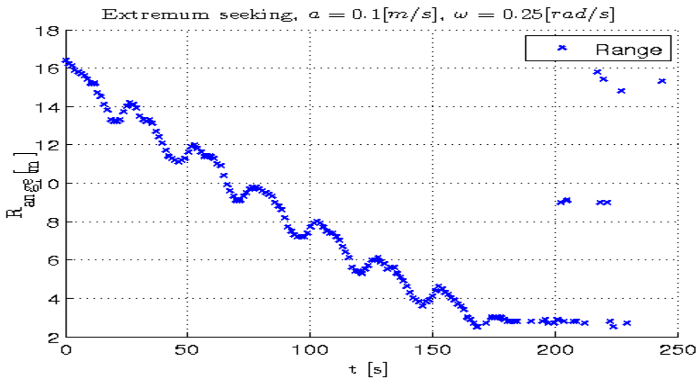
PlaDyPos *VideoRay ROV* *USBL with custom built cage*

Figure 4.4.1. Systems used during extremum seeking experiments

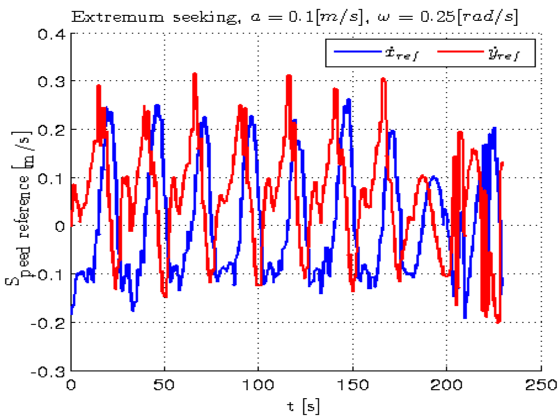
The basic idea of extremum seeking control is to find control input u∗ which generates output y ∗, where y ∗ is minimum steady-state system output of unknown map y = F (u). Optimal control input u∗ is found by performing online gradient estimation. So in order to track the diver we want that the range between diver and surface vehicle is as low as possible.

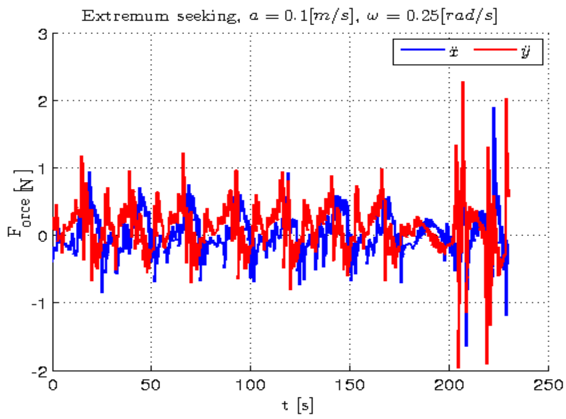


Trajectory



Range





Speed *Force*

Figure 4.4.2. Extremum seeking experimental results

Basic extremum seeking algorithm successfully localized underwater target, but alternative versions with EKF based gradient estimation showed better results due to the better speed of convergence. Some results are shown in Figure 4.4.2. As it can be seen from Figure 4.4.2, range measurements are sometimes affected by outliers caused by reflections from the underwater obstacles. Therefore, implementation of outlier rejection due to possible outliers is necessary.

Great advantage of extremum seeking is the fact that constant disturbances acting on vehicle, i.e. gravity, buoyancy, currents are automatically compensated by extremum seeking control loop which was supported by experimental data. Although range measurements are delayed, and there was very strong influence of wind, PlaDyPos successfully located underwater target position. Over 40 tests using extremum seeking algorithms were successfully conducted in changing conditions which shows robustness of approach.

OUTLIER REJECTION TEST

Since measurements provided by USBL are integral for many localization and navigation problems USBL unit was tested. Testing of USBL unit was conducted inside outdoor pool area. In such environment outliers in range measurements are quite possible. Therefore, online outlier rejection algorithm was tested. Some results are shown in Figure 4.4.3. In general, from conducted trials it was shown that range measurements are very accurate and have a small deviation therefore implementation of underwater localization and navigation algorithms is feasible.

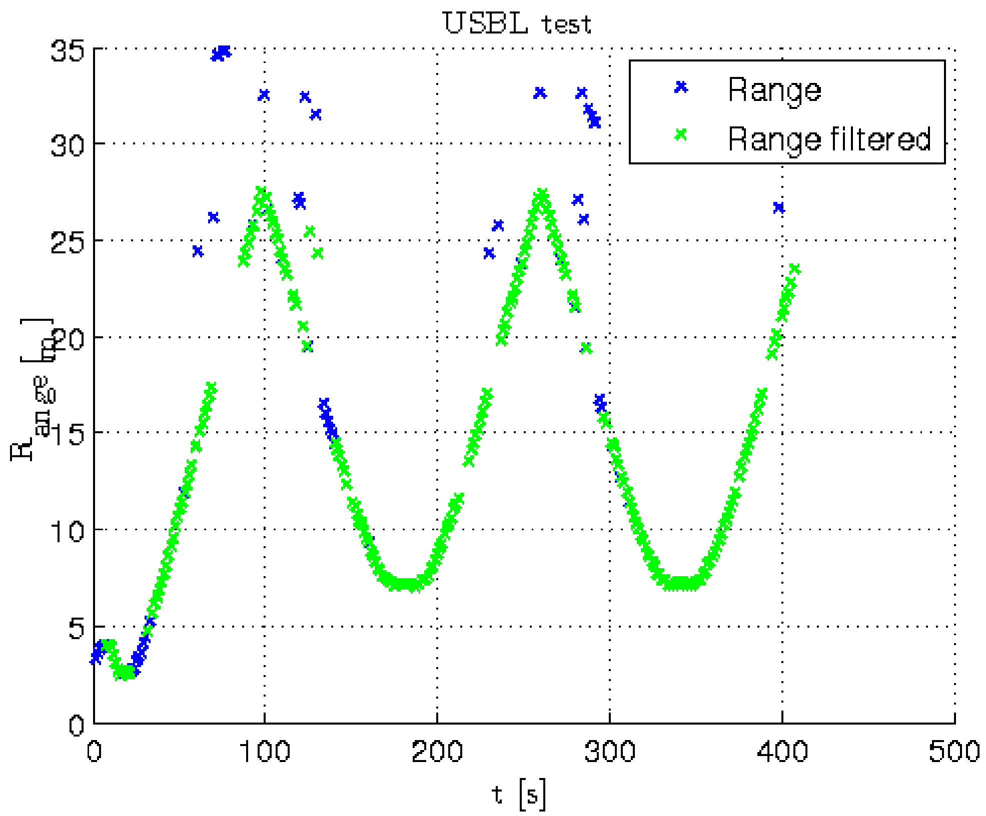


Figure 4.4.3. Outlier rejection

WP5 Integration and validation

T5.1. System integration

T5.2. Task A: Search and rescue (S&R) mission validation task

T5.3. Task B: Underwater archaeology mission

T5.4. Validation tasks assessment

WP6 Diver safety and regulation issues

T6.1. Rules for development and evaluation of safe technology

For the vehicles side, the risk assessment is performed based on the quantification described at deliverable 6.1.1 page 12 using the hazards of man-machine interaction described in the section 2.2 of the deliverable 6.1.1. the results are documented in the Deliverable D.6.1.2. For the divers' side, the improvements on safety is planned and achieved by changes in:

- Design
- Procedures
- Training

And are documented in the deliverable D.6.1.2. The new procedures were tested during the Y40 dives with success: 19 CADDY dives have been carried out with a total bottom time of 351 min without any incident (February 2015). That was followed by another series of 21 CADDY dives at Y40 on the 29 and 30th of June 2015. The latest dives had a cumulative bottom time of 548 min and are described in details the appendix.

Fig 6.1.1. Newly designed equipment to increase the diving safety

T6.2. Regulatory and professional acceptance road-map

The regulatory and professional acceptance road map deliverable 6.2.1 is finalised. The document includes the market segmentation as the first step. For each society (Medical, recreational and occupational) a three step acceptance roadmap was drawn: Induction, dissemination and consensus. The induction step is the dialogue with these societies and explaining the project; the second step is to share the initial results and the third step is to establish the standards and good practices for diver – AUV interactions. The details are found in the Deliverable 6.2.1.

T6.3. Automatic diver status report generation system

The goal of project task T6.3. is to develop a system that allows consumers to build an application to select data that needs to be included in the report, specify how alarms are generated and even to automatically alert the desired authorities should an emergency arise.

Every entity in the system will be accessible to the consumer through different widgets that allows acquisition, processing or manipulation of data. All widgets will be implemented as Robot Operating System (ROS) rqt plugins which can be connected together into different perspectives which are deployed depending on application and consumers preferences.

The collection of gadgets will include data acquisition gadgets which acquire data from diver's tablet, AUV, USV, generation of table reports, data reports (plots, charts), and logic widgets which enable specification, detection and reaction to specific user defined conditions.

First step towards such widget based graphical user interface (GUI) is shown in Fig. 6.3.1 It shows navigational information about deployed vehicles to ground operator. It enables plotting of custom data, and alerts ground station about important events.

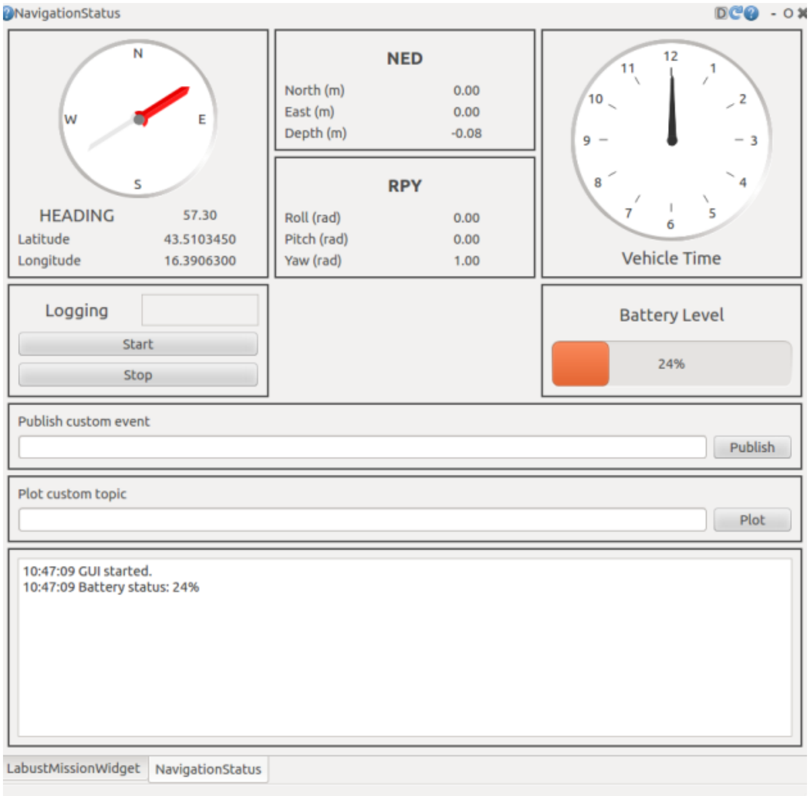


Figure 6.3.1.

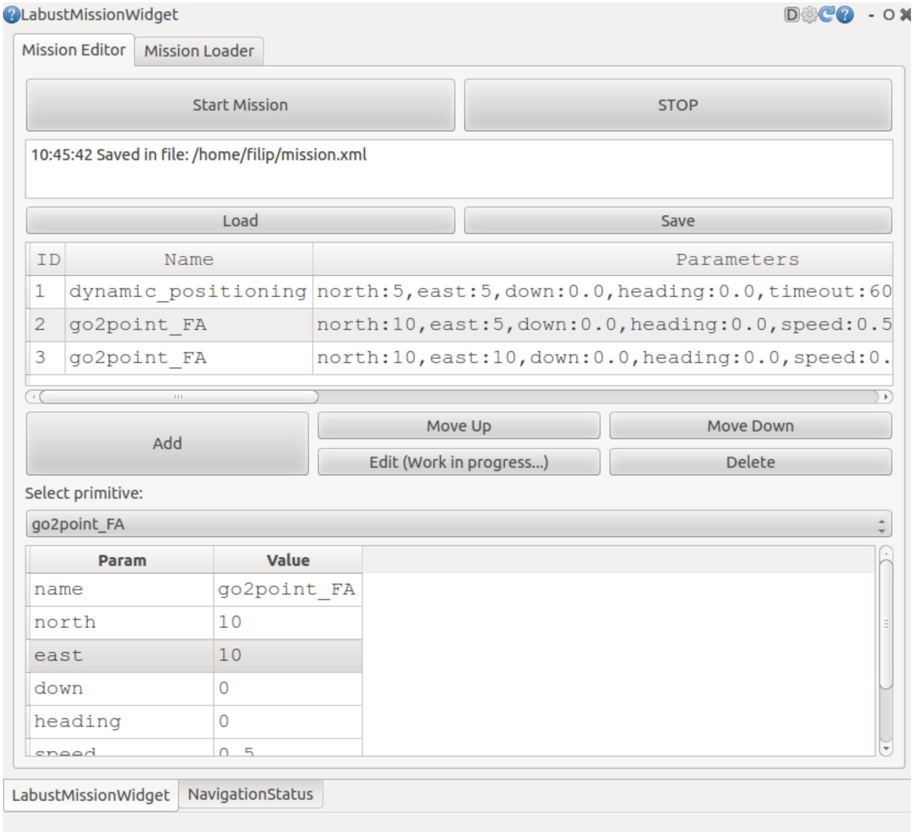


Figure 6.3.2.

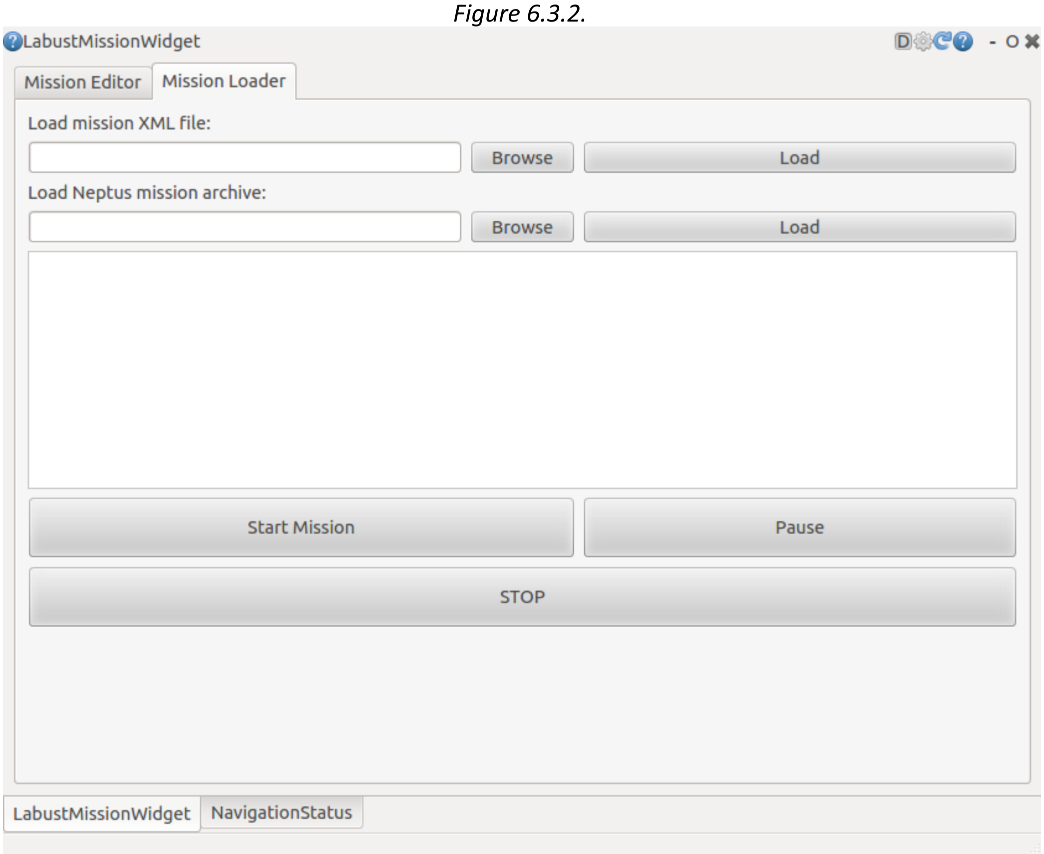


Figure 6.3.3.

On the other side, there exists a unified diver exposure database called DSL used by DAN Europe for 15 years. The database contains the depth profile in addition to pre and post dive health status of the divers with occasional measurements on the leading physiological indicators of a decompression stress such as urine density, Doppler, haematocrit etc. This database has a standard called DL7 (See appendix). The DL7 standards are communicated to the rest of the project team in order to align the status reporting system to with the existing database.

WP7 Dissemination and exploitation

Task 7.1 Reporting and outreach

Main activities
One of the main activities is continuous update of the official Caddy web-site (www.caddy-fp7.eu) with recent news, developments and results of Caddy project, project deliverables, published papers, press releases, events etc.

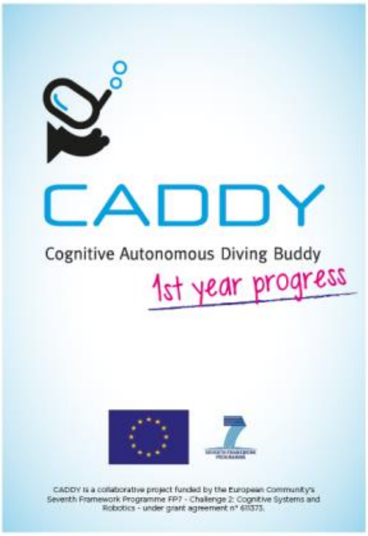
Social media accounts are updated on regular basis:
Facebook page https://www.facebook.com/caddyproject
YouTube channel http://www.youtube.com/user/caddyproject

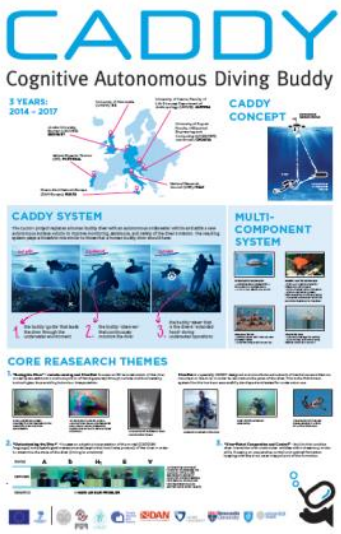
Along with the project web-site and social media accounts, partners' Universities and organizations web-site deliver recent information regarding the project and thus provide a broader reach to possible project's end-users.

In order to achieve best communication between project partners and collaborators Google Drive, Google Calendar and Google Plus are filled with recent information regarding Caddy project.

After the first year of the project and in the last six months materials that describe the meaning and significance of the project and the first year progress and results were made:

- **CADDY 1st year progress video** launched via YouTube and Facebook Caddy accounts
- Printed materials for distribution at conferences, workshops, seminars etc.: "CADDY 1st year progress" brochure, CADDY infographic and posters. All materials are also available online





<u>TV/newspaper appearance of CADDY</u>

<u>Press releases and interviews were given and distributed by the partners:</u>

Publisher	Partner	Country	Date	link
ANSA.it	CNR	Italia	16/05/2015	http://www.ansa.it/mare/notizie/rubriche/uominiemare/2015/05/13/mare-oceans-15-700-ricercatori-fra-scienza-e-tecnologia-_7a8eaec1-c5c7-4a57-8369-46cba727b437.html
ANSA.it	CNR	Italia	21/05/2015	http://www.ansa.it/mare/notizie/rubriche/uominiemare/2015/05/19/mare-per-lavorare-negli-abissi-arrivano-robot-amici-uomo-_291e00a7-1200-4448-a4b9-742eb2c8c351.html?idPhoto=2

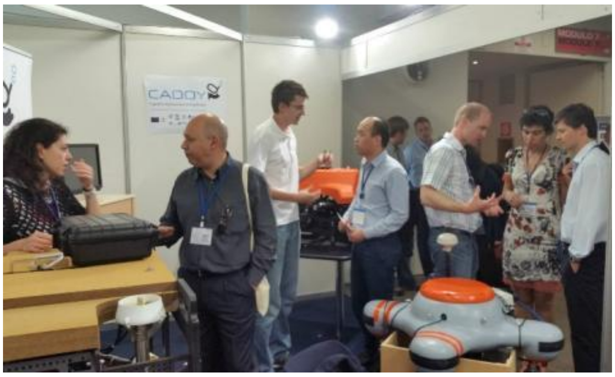
<u>Outreach</u>

1. CADDY project featured in the Times Higher Education supplement in a feature on the impact of Newcastle University's research
2. **<u>CADDY booth and lectures at OCEANS'15 Genova Conference & Exhibit</u>**

The MTS/IEEE **<u>OCEANS'15 Genova Conference & Exhibit</u>** was held from 18 - 21 May 2015 in Genova, Italy. Technological innovation is a key element of sustainable use of ocean resources, provision of ecosystem services, as well as long term economic growth. The MTS/IEEE Oceans series of Conferences promotes awareness, understanding, advancement, application and implication of marine technology.

The MTS/IEEE Oceans'15 exhibit was held in parallel to the conference sessions and it was open to all the registered conference participants. The Exhibit is a showcase opportunity for Companies and Manufactures, to promote their latest developments and to receive feed-back from the scientific end-users, but also for scientists and researchers, to disseminate to the end-users community the results or the work-in-progress of their latest research engagements.

CADDY project was presented at CADDY project's booth in the exhibition space which offered a high international visibility and showcase to promote the project.



CADDY project was also presented through lectures at conference part of OCEANS’15. Representatives of all partners were present at the conference and exhibition.

Task 7.2 Scientific dissemination

Conferences attended

All partners attended the Workshop on EU-funded Marine Robotics and Applications - EMRA´2015, Lisbon, Portugal; 18-19 June 2015.

1. Paris Diveshow and Human Underwater Society Meeting: CADDY Project presentations (9-11 January 2015)
2. Underwater Intervention (UI 2015)), AUV-ASV technologies track: AUV for Monitoring Divers CADDY Project (SM Egi), (11.02.2015
3. European Robotics Forum 2015, Vienna, Austria (11-13 March 2015)
4. 10th IEEE Sensors Applications Symposium (IEEE SAS 2015), Zadar, Croatia, (13 – 15 April 2015)
5. IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV’2015), Girona, Spain (28 - 30 April 2015)
6. **6.** OCEANS'15 Genova Conference & Exhibit, Genova, Italy (18 - 21 May 2015)

7. MIPRO'15 - 38th international convention on information and communication technology, electronics and microelectronics, Opatija, Croatia (28 May 2015)

Special sessions

1. FP7 CADDY Project Workshop Dissemination special session at OCEANS'15, Genova, Italy

List of scientific publications

1. Egi SM, Balestra C, Pieri M, Cialoni D, Thomas G, Marroni A. **Cognitive Autonomous Diving Buddy (CADDY)- Operational Safety and Preliminary Results**. CAISSON. March 2015;30(1):6-13
2. Mišković, Nikola; Pascoal, Antonio; Bibuli, Marco; Caccia, Massimo; Neasham, Jeffrey A.; Birk, Andreas; Egi, Murat; Grammer, Karl; Marroni, Alessandro; Vasilijević, Antonio; Vukić, Zoran. **Overview of the FP7 project "CADDY - Cognitive Autonomous Diving Buddy"** // Proceedings of MTS/IEEE OCEANS'15 Conference.
3. Stilinović, Nikola; Nađ, Đula; Mišković, Nikola. **AUV for Diver Assistance and Safety - Design and Implementation** // Proceedings of MTS/IEEE OCEANS'15 Conference.
4. Mišković, Nikola; Pascoal, Antonio; Bibuli, Marco; Caccia, Massimo; Neasham, Jeffrey A.; Birk, Andreas; Egi, Murat; Grammer, Karl; Marroni, Alessandro; Vasilijević, Antonio; Vukić, Zoran. **CADDY Project, Year 1: Overview of Technological Developments and Cooperative Behaviours** // Proceedings of 4th IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV'2015).
5. Goodfellow, Geraint M.; Neasham, Jeffrey A.; Rendulić, Ivor; Nađ, Đula; Mišković, Nikola. **DiverNet - a Network of Inertial Sensors for Real Time Diver Visualization** // Proceedings of IEEE Sensors Applications Symposium (SAS) 2015. IEEE, 2015. 1-6
6. Mandić, Filip; Mišković, Nikola. **Tracking Underwater Target Using Extremum Seeking** // Proceedings of the 4th IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV'2015).
7. Rendulić, Ivor; Bibulić, Aleksandar; Mišković, Nikola. **Estimating diver orientation from video using body markers** // Proceedings of MIPRO 2015 Conference / Petar Biljanović (ur.). Rijeka : Croatian Society for Information and Communication Technology, Electronics and Microelectronics - MIPRO, 2015. 1257-1263
8. Gomez Chavez, Arturo; Pfingsthorn, Max; Birk, Andreas; Rendulić, Ivor; Mišković, Nikola. **Visual Diver Detection using Multi-Descriptor Nearest- Class-Mean Random Forests in the Context of Underwater Human Robot Interaction (HRI)** // Proceedings of MTS/IEEE OCEANS'15 Conference
9. Ivaylo Enchev, Max Pfingsthorn, Tomasz Luczynski, Andreas Birk, Daniel Tietjen. **Underwater Place Recognition in Noisy Stereo Data using Fab-Map with a Multimodal Vocabulary from 2D Texture and 3D Surface Descriptors.** Proceedings of Oceans'15 IEEE/MTS Genova, May 2015
10. Neasham J.A, Goodfellow G, Sharphouse R, **Development of the "Seatrac" miniature acoustic modem and USBL positioning units for subsea robotics and diver applications**, Proceedings of MTS/IEEE OCEANS 2015, Genoa
11. B. Bayat, N. Crasta, A. Aguiar, A. Pascoal, "**Range-Based Underwater Vehicle Localization in the Presence of Unknown Ocean Currents: Theory and Experiments**," accepted for publication in the IEEE Transactions on Control Systems Technology, March 2015.

12. B. Bayat, N. Crasta, A. Aguiar, A. Pascoal, "**Observability Analysis of 3D AUV Trimming Trajectories in the Presence of Ocean Currents using Range and Depth Measurements**," submitted to the IFAC Annual Reviews in Control, Special Issue on Marine Systems, 2015.
13. M. Pedro, D. Moreno Salinas, N. Crasta, A. Pascoal, "**Underwater Single-Beacon Localization: Optimal Trajectory Planning and Minimum-Energy Estimation**," Proc. IFAC Workshop on Navigation, Guidance, and Control of Underwater Vehicles (NGCUV´2015), Girona, Spain, 28-30 April, 2015
14. P. Abreu, B. Bayat, J. Botelho, P. Góis, A. Pascoal, J. Ribeiro, M. Ribeiro, M. Rufino, L. Sebastião, H. Silva, "**Cooperative Control and Navigation in the Scope of the EC CADDY Project**", Proc. OCEANS´15 MTS/IEEE Genova, Italy, 18-21 May, 2015
15. J. Ferreira, A. Pascoal, "**Nonlinear System Identification with Applications to the MEDUSA Autonomous Marine Vehicles**," Internal Report IR/IST/IMedusa/2015, Instituto Superior Técnico (IST), Lisbon, Portugal, June 2015.

Invited lectures (containing materials prepared in the scope of the CADDY project)

1. Invited talk on CADDY project at European Robotics Forum 2015 (ERF'15) by Nikola Miskovic, Vienna, Austria
2. Invited talk on *Developments in robust acoustic positioning and communications* at Workshop on EU-funded Marine Robotics and Applications 2015 (EMRA'15) by Jeff Neasham and Robin Sharphouse, Lisbon, Portugal
3. Invited talk on CADDY project at Workshop on EU-funded Marine Robotics and Applications 2015 (EMRA'15) by Nikola Miskovic, Lisbon, Portugal
4. Presentation of CADDY Project - UNESCO UNITWIN Training on Underwater Cultural Heritage, 16-25 May 2015
5. Antonio Pascoal, "**Cooperative Motion Planning, Navigation, and Control of Multiple Autonomous Marine Vehicles: Robots and Humans in the Loop**," Keynote Lecture, International Conference on Vehicle Technology and Intelligent Transport Systems, VEHITS 2015, Lisbon, Portugal, May 25, 2014.
6. Antonio Pascoal, "**Exploring the Frontier of Cooperative Marine Robotics: Navigation and Control of Networked Autonomous Vehicles**, " Invited Talk, National Institute of Ocean Technology (NIOT), Pallikaranai, Chennai, India, 22 January, 2015
7. Antonio Pascoal, "**Navigation and Control of Networked Autonomous Vehicles**, "Invited Talk, Indian Institute of Technology (IIT), Chennai, India, 21 January, 2015
8. Antonio Pascoal, "**Cooperative Navigation and Motion Control of Autonomous Marine Robots**," Invited Talk, National Institute of Technology (NIT), Goa, India, February 2, 2015.

Courses (containing materials prepared in the scope of the CADDY project)

António Pascoal, co-organization of "**A Course on Marine Robotic Systems: From Theory to Practice**," National Institute of Oceanography, Goa, India, 27-31 January, 2015. The course targeted an audience of app. 50 graduate students and research engineers from across India and covered a large spectrum of issues pertaining to single and multiple vehicle navigation, guidance, and control of marine robots including humans in the loop. The course counted with the participation of Prof. Giovanni Indiveri (Univ. Salento, Lecce, Italy), Prof. John Hauser (Univ. Colorado at Boulder, USA), Prof. Prathyush Menon, (Univ. Exeter, UK), and Dr. Pedro Afonso (Institute of Marine Research, Horta, Faial Island, Azores, Portugal).

Task 7.3 Exploitation

After the segmentation of the diving industry described in previous reports, two specific targets were addressed in the period of M15-18.

The first one is the least regulated part of the diving industry namely: Public Safety Diving (PSD). An initial attempt to understand the market size of the public safety diving in Germany, Italy and Netherlands is made despite the difficulties in identifying the relevant body responsible for Public Safety Diving: Red Cross, Fire Brigade, Police, Armed forces. A feedback from the Italian police stating the number of 55 divers do not describe the whole PSD in Italy and answers from other parties are expected. Efforts to get information about the German sector failed. On the other hand, Netherlands seemed to have a very structured large team of PSD. In fact, the Dutch Fire brigade has 809 PSD and 200 Instructors. The key persons were identified for getting feedback on medium affordability CADDY that can be used in S&R missions.

As a second target, a meeting at the headquarters of Technip (the largest commercial diving company in off shore oil and gas industry) was made in France at the Research and Innovation centre of Technip in June 2015. CADDY project was presented to the R&I managers of Technip. Being a large scale company their participation to the project as a user board member depends on the final corporate decision.

New board members

Commercialisation

Task 7.4 Education and training

2nd CADDY workshop: EMRA '15

2nd CADDY workshop is organized as a part of the **EMRA'15 - Workshop on EU-funded Marine Robotics and Applications** and it was held from **18 till 19 June 2015 in Lisbon, Portugal**. Founders of this new workshop are coordinators of four FP7 projects related to marine robotics: CADDY, MORPH, ARROWS and PANDORA.

EMRA'15

Date: 18 - 19 June 2015

Location: IST, Lisbon, Portugal

Website: http://dsor.isr.ist.utl.pt/emra2015/

Download the **programme** here.

EMRA’15 is attended by researchers and end-users of marine robotics technology. The workshop summarized current EU FP7 and H2020 projects on marine robotics and provided a platform for marine stakeholders to share and discuss current technological challenges and achievements.
To researchers, EMRA’15 offered the opportunity to disseminate current work and highlight new application areas that warrant further R&D effort. **To marine stakeholders**, EMRA’15 allowed for the cross-fertilization of ideas and offer novel approaches to meet future challenges in ocean exploration and exploitation.
The workshop **aims to contribute to building bridges** in marine robotics research, fostering cross fertilization of ideas between marine science and technology and commercial applications, and giving new momentum to outreach activities.

There is tight coupling between individual FP7 and H2020 projects and their intended applications audience, yet the technologies developed are applicable well beyond the original motivating problems. Currently, in order for marine technology stakeholders to fully digest the results of EU marine research requires that they attend too many overly technical, and often overly specific individual workshops. As a contribution to overcoming this situation, EMRA’15 condensed an exciting range of cutting edge research developments into a single, all encompassing, manageable event.

EMRA'15 PROGRAM

EC Projects Presentations

- ROBOACADEMY
- NOPTILUS
- euRathlon
- PANDORA
- WiMUST
- MORPH
- CADDY
- DexROV
- Marine UAS
- ARROWS
- subCULTron

Invited Talks

- **Dana Yoerger**, WHOI, USA – Mapping the seafloor in rough terrain with AUVs: mission planning versus real-time responses
- **Jorge Relvas** and **Fernando Barriga**, FCUL, Lisbon, PT – Challenges of seabed mining in a sustainable world: let's do it right!
- **Francisco Almeida**, TEKEVER, Lisbon, PT – UAVs for Marine Applications
- **Henrique Duarte**, GEOSURVEYS, Aveiro, PT – The future of autonomous marine vehicles in Ultra High Resolution Seismic reflection surveys (UHRS)
- **Konstantin Kebkal**, EVOLOGICS, DE – Easily deployable autonomous hydro-acoustic assets for highly mobile and flexible arrangements (underwater sensor networks, testbeds, and integrated USV and AUV robotic components)
- **Pedro Afonso** and **Jorge Fontes**, UAzores, IMAR/DOP, Horta, Faial, PT – Marine Megafauna Telemetry Systems
- **David Lane**, Edinburgh Centre for Robotics and Ocean Systems Laboratory, Heriot-Watt University (EURobotics Board Member 2013 – 15) – SPARC: Report from the EURobotics Board, Future Possibilities in H2020 Robotics PPP
- **António Sarmento**, WAVEC, Lisbon, Portugal – Marine Technology Challenges and Opportunities in relation to Marine Renewable Energy
- **Robin Sharphouse**, Blueprint, Ulverston, UK – Developments in robust acoustic positioning and communications
- **Ricardo Martins**, Oceanscan, Porto, PT – The Light Autonomous Underwater Vehicle – Past, Present & Future
- **Pere Ridao**, Univ. Girona, Girona, ES – Intervention AUVs: Experiences and Challenges
- **Alessio Turetta**, Graal Tech, Genova, IT – AUV Technology: from concept to commercialization
- **Rui Caldeira**, CIIMAR, Porto, PT –Measuring small island-induced processes: Tech-savvy approaches

References:

3.4 Deliverables and milestones tables

TABLE 1. DELIVERABLES										
Del. no.	**Deliverable name**	**Version**	**WP no.**	**Lead beneficiary**	***Nature***	**Dissemination level**	**Delivery date from Annex I (proj month)**	**Actual / Forecast delivery date Dd/mm/yyyy**	**Status No submitted/ Submitted**	**Comments**
7.1	WEB page	1	7	UNIZG-FER	Other	PU	1	1/1/2014	submitted	
6.1.1	Safety rules for the development of diver assistance system components	1	6	DAN Europe	Report	PU	1	28/2/2014	submitted	
7.2	Dissemination plan	1	7	UNIZG-FER	Other	PU	3	31/3/2014	submitted	
5.1	Scenario description and validation procedure for the validation trials	1	5	UNIZG-FER	Report	PU	3	31/3/2014	submitted	
7.3.1	Exploitation plan	1	7	DAN Europe	Report	PP	3	31/3/2014	submitted	
2.1	Diver remote sensing in the underwater	1	2	UNIZG-FER	Report	PU	5	31/5/2014	submitted	
7.4.1	Proceedings of the 1st CADDY Workshop	1	7	CNR	Report	PU	6	30/6/2014	submitted	
8.3.1	Six-month project report	1	8	UNIZG-FER	Report	PU	6	30/6/2014	submitted	
1.1	Technical and performance characteristics of the robotic diver	1	1	UNIZG-FER	Report	PU	11	30/11/2014	submitted	

	assistance system consisting of three agents									
1.2.1	Initial communication transceiver units, protocols and software	1	1	UNEW	Report	PU	11	30/11/2014	submitted	
3.1	Initial list of gestures and syntax	1	3	CNR	Report	PU	11	30/11/2014	submitted	
8.1.1	Minutes of the meetings	1	8	UNIZG-FER	Report	CO	12	10/02/2015	submitted	delayed to include review meeting
6.2.1	Regulatory and professional acceptance road-map – draft	1	6	DAN Europe	Report	PU	13	30/01/2015	submitted	
6.1.2	Evaluation of safe technology	1	6	DAN Europe	Report	PU	13	30/01/2015	submitted	
4.1	Cooperative control and navigation with diver in the loop – HIL simulation results	1	4	CNR	Report	PU	13	20/03/2015	submitted	
1.2.2	Enhanced communication transceiver units, protocols and software.	1	6	UNEW	Other	PU	14	17/03/2015	submitted	
2.3	DiverNet local sensor network integration on diver	1	2	UNEW	Report	PU	17	30/05/2015	submitted	
1.3	Report on integration of the robotic assist. system – experim. and performance	1	1	CNR	Report	PU	17			delayed
2.2	Motion compensation algorithms	1	2	JACOBS	Report	PU	18	30/06/2015	submitted	
2.4	An online repos. of diver datasets obtained from remote and local (DiverNet) sensing	1	2	UNIVIE	Other	PU	18	30/06/2015	submitted	

7.4.2	Proceedings of the 2nd CADDY Workshop	1	7	IST	Report	PU	18	30/6/2014		delayed
8.3.2	Six-month project report	1	8	UNIZG-FER	Report	PU	18	30/6/2014	submitted	

Table 2. Milestones							
Milestone no.	**Milestone name**	**Work package no**	**Lead beneficiary**	**Delivery date from Annex I dd/mm/yyyy**	**Achieved Yes/No**	**Actual / Forecast achievement date dd/mm/yyyy**	**Comments**
1	Integrated diver assistance systems	1	UNIZG-FER	30/11/2014	Yes	30/11/2014	

3.5 Project management

In the following part, we give a short overview of the meetings that took place during M13 – M18 of the project. All the meeting minutes and agendas are available in the Google Drive.

1. **<u>05/02/2015 :: 1st Review meeting</u>**

The first review meeting took place in Y-40 World's Deepest Pool (http://www.y-40.com/en/) in Montegrotto-TERME, Italy (http://www.millepini.it/en/information/how-to-reach-us.htm). The goals of the meeting were to:

- familiarize the reviewers with CADDY activities
- acknowledge reviewers' comments

The meeting was successful and was followed by reviewers' comments on how to proceed with the project.

2. **<u>06/02/2015 :: SB & EB meeting after the review meeting</u>**

This meeting was held the day after the review meeting. The goals of the meeting were to:

- Discuss reviewers' comments
- Establish a detailed workplan and deliverable list for the following 12 mths of the project
- Make arrangements for OCEANS'15 exhibition and EMRA'15
- Make arrangements for first validation trials

3. **<u>15/03/2015 :: technical meeting Skype</u>**

The meeting was held via Skype and organized by UNIVIE (Anna Schamann). The topic of the meeting was setting up the online diver data repository.

4. **<u>15/06/2015 :: SB & EB meeting, Lisbon, Portugal</u>**

This meeting was held prior to 2nd CADDY workshop (EMRA workshop) at IST. The goals of the meeting were to:

- Discuss reviewers' comments
- Establish a detailed workplan and deliverable list for the following 12 mths of the project
- Make detailed arrangements for first validation trials

3.6 Explanation of the use of the resources and financial statements

3.6.1 Justification of major cost items and resources

UNIZG-FER

Personnel:
- Antonio Vasilijević is working approx. 50% of his time on the project. From M19 he will be fully committed to the project
- Filip Mandić and Ivor Rendulić are hired 100% on the project. Salary of Filip Mandić is covered by the Croatian Science Foundation
- Nikola Mišković (Coordinator), Zoran Vukić and Đula Nađ have been working approx. 40% of their time on the project. Đula Nađ will from M19 be fully committed to the project

Major equipment:
No major purchase went in period M13 – M18. Mid-high purchases were
- construction of floating block: approx. 2.000 EUR

Travel:
For travel we spent around 16.000 EUR. This includes all meetings, workshops, conferences and field trials for UNIZG-FER staff and Advisory Board members.

UNIVIE:

Travel costs:

The data collection and review meeting in February was attended by Karl Grammer, Julia Ramesmayr and Anna Schaman,

The OCEANS 15 workshop was attended by Anna Schaman, the CADDY Workshop in Lisabon was attended by Karl Grammer

The data collection in June was attended by Katharina Oremus, Dominic Reichl and Anna Schaman.

Personnel costs:

- Karl Grammer is working 100% on the project
- Anna Schaman is working 75% of her time on the project
- Dominic Reichl is working approx. 40% of her time on the project in the months April to June.
- Katharina Oremus worked approx. 30% of her time on the project in the months April to June.
- Pia Stephan worked for approx. 10% of her time on the project for 3 months.
- Deborah Rolka, Claudia Neubert and Martin Dockner work approx. 5% of their time on the project

Deviations:

- We will consume more Person Months than anticipated, but this will not affect the personnel costs.
- UNIVIE bought a treadmill to collect a large sample of motion and emotion data. As the DiverNet was not yet wireless, having the participants walk around in an area was unfeasible, as the long cable is both heavy and would necessitate a second person walking behind the participant during the experiment, which in turn would inhibit natural motion and behaviour in general. To gather data on dry land is essential for estimating individual variance in motion, for the determination of useful parameters of breathing, heart rate and motion that can then be tested in the diver sample and for inferring the effect of strong emotions as well as high cognitive load, that for safety reasons cannot be induced in divers, on motion patterns. In addition, several small purchases were made for data collections (A second breathing belt to be adapted for underwater, Velcro bands for mounting the DiverNet, monitors for presentation of stimuli). Including these purchases our Materials budget is still well below the limit (presently approx. 8,382 Euros of the budgeted 10,000 Euros).
-

3.6.2 Budgeted versus Actual Costs

TABLE 4: COST/BUDGET FOLLOW-UP TABLE

Contract N°: | Acronym: | Date:

Beneficiaries	TYPE of EXPENDITURE (as defined by participants)	BUDGET Whole project	ACTUAL COSTS (EUR) Period 1	Period 2	Period 3	Period 4	Total	% spent Year 1	Year 2	Year 3	Total	Remaining Budget (EUR)
		e	*a1*	*b1*	*c1*	*d1*	*e1*	*a1/e*	*a1+b1/e*	*a1+b1+c1/*	*a1+b1+c1+d*	*e-e1*
UNIZG-FER	**Person-months**	**120**	39.3	20.94			**60.24**	33%	50%	0%	50%	**59.76**
	Personnel costs	**318,900**	82,558	47,247			**129,805**	26%	41%	0%	41%	**189,095**
	Subcontracting	**19,500**	2,469	1,524			**3,993**	13%	20%	0%	20%	**15,507**
	Equipment/ consumables	**120,000**	117,022				**117,022**	98%	0%	0%	98%	**2,978**
	Travel	**96,900**	24,728				**24,728**	26%	0%	0%	26%	**72,172**
	Other direct costs	**36,000**	11,891	24,143			**36,034**	33%	100%	0%	100%	**-34**
	Indirect costs	**343,080**	141,718	42,850			**184,568**	41%	54%	0%	54%	**158,512**
	Total Costs	**934,380**	**380,386**	**115,764**	**0**	**0**	**496149.8**	**41%**	**53%**	**0%**	**53%**	**438,230**
CNR	**Person-months**	**94**	33.1	15.75			**48.85**	35%	52%	0%	52%	**45.15**
	Personnel costs	**376,000**	136,677	60,804			**197,481**	36%	53%	0%	53%	**178,519**
	Subcontracting	**2,400**	0				**0**	0%	0%	0%	0%	**2,400**
	Equipment/ consumables	**20,700**	0				**0**	0%	0%	0%	0%	**20,700**
	Travel	**49,200**	18,924				**18,924**	38%	0%	0%	38%	**30,276**
	Other direct costs	**30,000**	7,241	4,813			**12,054**	24%	40%	0%	40%	**17,946**
	Indirect costs	**262,824**	89,114	39,097			**128,211**	34%	49%	0%	49%	**134,613**
	Total Costs	**741,124**	**251,956**	**104,714**	**0**	**0**	**356670**	**34%**	**48%**	**0%**	**48%**	**384,454**
IST	**Person-months**	**76**	25.6	10			**35.6**	34%	47%	0%	47%	**40.4**
	Personnel costs	**394,000**	155,607	59,358			**214,965**	39%	55%	0%	55%	**179,035**
	Subcontracting	**2,500**	0				**0**	0%	0%	0%	0%	**2,500**
	Equipment/ consumables	**40,000**	41				**41**	0%	0%	0%	0%	**39,959**
	Travel	**47,000**	7,165				**7,165**	15%	0%	0%	15%	**39,835**
	Other direct costs	**27,500**	0	18,321			**18,321**	0%	67%	0%	67%	**9,179**
	Indirect costs	**346,200**	104,341	40,671			**145,012**	30%	42%	0%	42%	**201,188**
	Total Costs	**857,200**	**267,154**	**118,350**	**0**	**0**	**385504**	**31%**	**45%**	**0%**	**45%**	**471,696**
JACOBS	**Person-months**	**63**	13.08	15.25			**28.33**	21%	45%	0%	45%	**34.67**
	Personnel costs	**308,800**	50,078	64,316			**114,394**	16%	37%	0%	37%	**194,406**
	Subcontracting	**2,500**	0				**0**	0%	0%	0%	0%	**2,500**
	Equipment/ consumables	**31,000**	0				**0**	0%	0%	0%	0%	**31,000**
	Travel	**34,000**	5,198				**5,198**	15%	0%	0%	15%	**28,802**
	Other direct costs	**14,000**	0	10,396			**10,396**	0%	74%	0%	74%	**3,604**
	Indirect costs	**232,680**	33,165	44,827			**77,992**	14%	34%	0%	34%	**154,688**
	Total Costs	**622,980**	**88,441**	**119,540**	**0**	**0**	**207980.5**	**14%**	**33%**	**0%**	**33%**	**414,999**
UNIVIE	**Person-months**	**70**	33.82	14.6			**48.42**	48%	69%	0%	69%	**21.58**
	Personnel costs	**384,762**	132,043	63,542			**195,585**	34%	51%	0%	51%	**189,177**
	Subcontracting	**2,500**	0				**0**	0%	0%	0%	0%	**2,500**
	Equipment/ consumables	**10,000**	4,313				**4,313**	43%	0%	0%	43%	**5,687**
	Travel	**32,000**	4,473				**4,473**	14%	0%	0%	14%	**27,527**
	Other direct costs	**10,000**	0	4,500			**4,500**	0%	45%	0%	45%	**5,500**
	Indirect costs	**262,057**	84,497	30,000			**114,497**	32%	44%	0%	44%	**147,560**
	Total Costs	**701,319**	**225,326**	**98,042**	**0**	**0**	**323368**	**32%**	**46%**	**0%**	**46%**	**377,951**
UNEW	**Person-months**	**49**	17	12			**29**	35%	59%	0%	59%	**20**
	Personnel costs	**222,700**	70,610	50,478			**121,088**	32%	54%	0%	54%	**101,612**
	Subcontracting	**0**	0				**0**	0%	0%	0%	0%	**0**
	Equipment/ consumables	**27,000**	15,816				**15,816**	59%	0%	0%	59%	**11,184**
	Travel	**26,300**	4,985				**4,985**	19%	0%	0%	19%	**21,315**
	Other direct costs	**30,000**	0	4,847			**4,847**	0%	16%	0%	16%	**25,153**
	Indirect costs	**183,600**	54,845	33,195			**88,040**	30%	48%	0%	48%	**95,560**
	Total Costs	**489,600**	**146,256**	**88,520**	**0**	**0**	**234776**	**30%**	**48%**	**0%**	**48%**	**254,824**
DAN	**Person-months**	**52**	12.5	10.26			**22.76**	24%	44%	0%	44%	**29.24**
	Personnel costs	**259,000**	72,813	59,544			**132,357**	28%	51%	0%	51%	**126,643**
	Subcontracting	**2,500**	0				**0**	0%	0%	0%	0%	**2,500**
	Equipment/ consumables	**40,000**	11,525				**11,525**	29%	0%	0%	29%	**28,475**
	Travel	**23,500**	8,797				**8,797**	37%	0%	0%	37%	**14,703**
	Other direct costs	**10,000**	112	10,100			**10,212**	1%	102%	0%	102%	**-212**
	Indirect costs	**199,500**	55,951	41,249			**97,200**	28%	49%	0%	49%	**102,300**
	Total Costs	**534,500**	**149,198**	**110,893**	**0**	**0**	**260091**	**28%**	**49%**	**0%**	**49%**	**274,409**
TOTAL	**Sum Person-months**	524	174.4	98.8			**273.2**	33%	52%	0%	52%	**250.8**
	Sum Personnel costs	**2,264,162**	**700,386**	**405,290**			**1,105,676**	31%	49%	0%	49%	**1,158,486**
	Sum Subcontracting	**31,900**	**2,469**	**1,524**			**3,993**	8%	13%	0%	13%	**27,907**
	Sum Equip / consumables	**288,700**	**148,717**	**0**			**148,717**	52%	0%	0%	52%	**139,983**
	Sum Travel	**308,900**	**74,270**	**0**			**74,270**	24%	0%	0%	24%	**234,630**
	Other direct costs	**157,500**	**19,244**	**77,120**			**96,364**	12%	61%	0%	61%	**61,137**
	Sum Indirect costs	**1,829,941**	**563,631**	**271,889**			**835,520**	31%	46%	0%	46%	**994,421**
	Total Costs	**4,881,103**	**1,508,717**	**755,823**	**0**	**0**	**2264539**	**31%**	**46%**	**0%**	**46%**	**2,616,564**

3.6.3 Planned versus Actual effort

The following table gives distribution of PMs per WP per partner for the period M1 – M12.

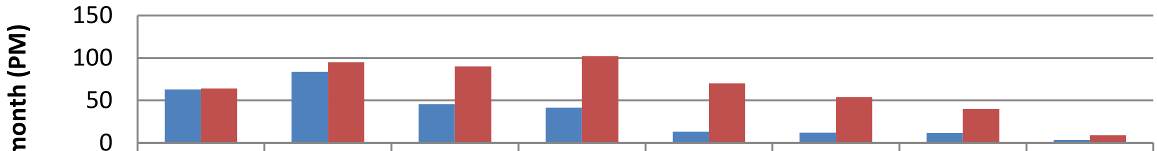
TABLE 5. PERSON-MONTH STATUS TABLE

GRANT AGREEMENT NO: 611373
ACRONYM: CADDY
PERIOD: 2 => 01/01/15 - 30/06/2015

Partner - Person-months per Workpackage

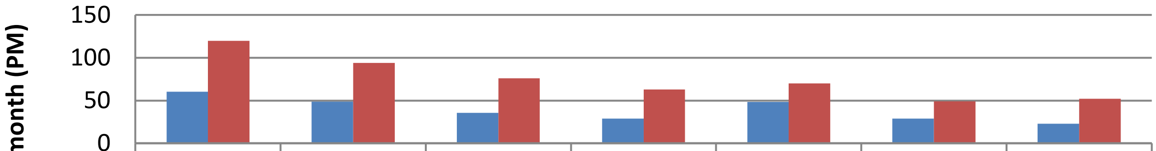
Workpackage	Title		UNIZG-FER	CNR	IST	JACOBS	UNIVIE	UNEW	DAN	TOTALS
Workpackage 1:	Robotic diver assistance system	Actual WP total:	3.03	3	1.5	2	0	4.2	0	*13.7*
		Planned WP total:	15	16	12	9	0	12	0	*64*
Workpackage 2:	Seeing the diver	Actual WP total:	8.41	1.75	1	10	0.4	6.6	1.6	*29.8*
		Planned WP total:	20	6	4	24	13	24	4	*95*
Workpackage 3:	Understanding the diver	Actual WP total:	0	2.4	1	2	13.5	0	2.7	*21.6*
		Planned WP total:	0	27	6	10	35	0	12	*90*
Workpackage 4:	Diver-robot cooperation and control	Actual WP total:	6.39	7	4	0	0	0	0.14	*17.5*
		Planned WP total:	29	26	34	5	5	2	1	*102*
Workpackage 5:	Integration and validation	Actual WP total:	1.79	0	1.8	1.25	0	0	0	*4.84*
		Planned WP total:	19	12	13	10	8	4	4	*70*
Workpackage 6:	Diver safty and regulations issues	Actual WP total:	0.12	0	0	0	0.5	0	4.96	*5.58*
		Planned WP total:	24	0	0	0	4	0	26	*54*
Workpackage 7:	Dissemination and exploitation	Actual WP total:	0.88	1.5	0.55	0	0.2	1.2	0.7	*5.03*
		Planned WP total:	10	6	6	4	4	6	4	*40*
Workpackage 8:	Managemet	Actual WP total:	0.32	0.1	0.15	0	0	0	0.16	*0.73*
		Planned WP total:	3	1	1	1	1	1	1	*9*
Total Project Person-months		Actual total:	**20.94**	**15.75**	**10**	**15.25**	**14.6**	**12**	**10.26**	***98.8***
		Planned total:	**120**	**94**	**76**	**63**	**70**	**49**	**52**	***524***

Project PM distribution



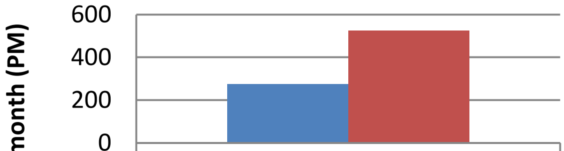
	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8
Actual	63	83,505	45,46	41,35	13,4	12,15	11,53	3,53
Planned	64	95	90	102	70	54	40	9

Total PM distribution per partner



	UNIZG-FER	CNR	IST	JACOBS	UNIVIE	UNEW	DAN
Actual	60,24	48,85	35,6	29,025	48,42	29	22,8
Planned	120	94	76	63	70	49	52

Total PM distribution



	TOTAL
Actual	273,925
Planned	524