COOPERATION

Grant Agreement No. 611373

CADDY

Cognitive Autonomous Diving Buddy

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D5.2. Report of first validation trials

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Dissemination level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

1 Introduction

First validation trials were performed from 03.10.2015 to 18.10.2015. in Biograd na moru, Croatia. Trials are according to the project timeline scheduled close to the end of the second year of the project when not all components and functionalities of the system were developed. Therefore, the first validation trial assessed specific sub-functionalities and sub-tasks, validating the state of the project progress, trends and accomplishments, rectifying the significant issues and providing the guideline for the future work. From functionality point of view, first validation assessment provide evidence that developed system is capable to perform some of: dive buddy *"observer",* dive buddy *"slave",* and dive buddy *"guide".* roles.

Figure 1.1. CADDY validation trials team in Biograd na Moru

The basis for defining validation activities was Validation Plan presented in D.5.1. As it was stressed in D.5.1., validation plan was not to be considered as a final document, but validation procedures and criteria could be modified to incorporate e.g. recent and upcoming research results, new vehicle design and/or new knowledge. As an example, we discarded slave functionality "illuminate a site" from the initial validation plan which we found very similar to the functionality "take a photo of the site". Instead, we included new slave functionality "move following my command" which is potentially more helpful for diver. If diver does not feel comfortable in the close proximity of the BUDDY, diver can command BUDDY to move away or if diver is not able to read from BUDDYs tablet screen, diver can command BUDDY to come closer.

This document covers validation activities elaborated in chapters "Safety validation" and "First validation trial" of the validation plan D.5.1. The safety validation ensures diver safety when interacting with autonomous underwater vehicle, meaning that developed system agents for diver assistance are safe to be used. The safety validation of the BUDDY vehicle interacting with diver is recorded in ANNEX A presented in section 7 of this document, confirming that all safety aspect are properly addresses if all answers in the Safety validation questioner are positive. The validation of system functionalities i.e. quality of validation tasks based on key performance indices is recorded in ANNEX B of the section 7.

Sections 2 to 6 elaborate validation experiments in details, present results which corroborate conclusions summarized in ANNEX B and provide comprehensive to-do list for future activities.

2 Experiment 1: Integration experiment

2.1 Description of experiment

The first experiment is envisioned as an integration experiment where all partners have to integrate their communication schemes, control algorithms, and ensure reliable exchange of data between different segments.

Main task of the experiment:

Command using CADDIAN language to perform a mosaic of the area of dimensions *m* x *n* from the current point. This command is issued from the surface, and gestures are identified from the surface (see Fig. 2.1.). The command is then transmitted to the vehicles (Fig. 2.2.). Two vehicles are involved in the execution of this task (Fig. 2.3): 1) underwater vehicle that executes the mosaicking mission by performing a lawn mower pattern close to seabed while collecting data using a stereo camera, and 2) surface vehicle that tracks the underwater vehicle and aids its navigation by transmitting position measurements via acoustic link.

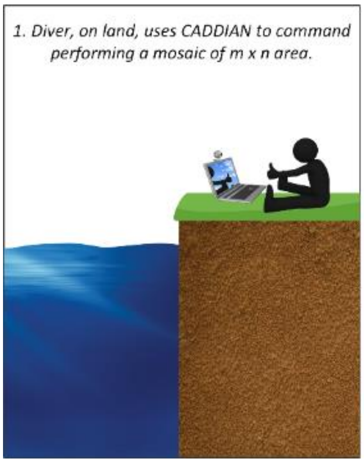


Fig. 2.1. Gesture recognition from dry land.

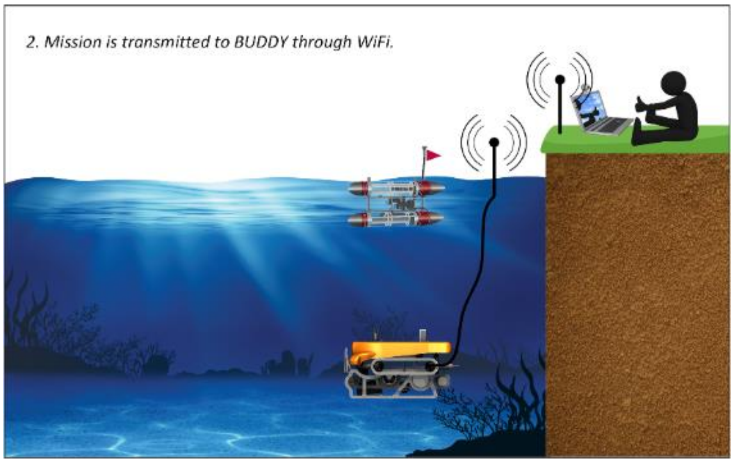


Fig. 2.2. Transmitting the mission to vehicles.

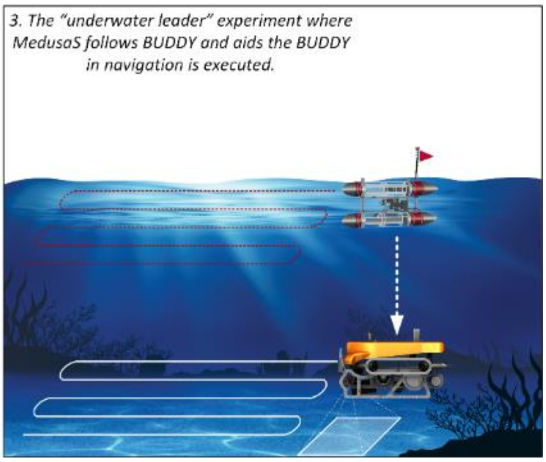


Fig. 2.3. Mission execution.

Vehicles:

In the first step, MedusaS serves as the surface vehicle and MedusaD as the underwater vehicle. In the second step, BUDDY replaces MedusaD. Both underwater vehicles are equipped with a stereo camera.

Experiment subtasks:

- **Integration of interrogation scheme a) over the internet and b) using the real vehicles**

The developed interrogation scheme includes agents pinging each other in order to exchange information required for proper navigation. The agents are surface vehicle, underwater vehicle and the diver tablet. Since the clocks on agents are not synchronized, a complex asynchronous interrogation scheme is implemented.

- **Setting up USBLs**

USBLs developed by UNEW have to be integrated with the vehicles and quality of their performance must be investigated.

- **Underwater leader experiment**

This task includes underwater vehicle performing the mosaic above the seabed while the surface vehicle tracks it. Acoustic link is used to exchange navigation information. In the first step MedusaD is used as the underwater vehicle, while ultimately BUDDY replaces MedusaD.

- **Complex gesture recognition on dry land**

By complex gesture here we mean a gesture that consists of a number of symbols, i.e. “perform mosaic”, number m, number n, together with all gesture communication delimiters, as described with the CADDIAN syntax.

- **Creating the mosaic**

In order to validate the quality of mosaicking, georeferenced markers have to be placed on seabed.

2.2 Validation procedure

2.2.1 *Integration of interrogation scheme over the internet*

The developed interrogation scheme is tested using simulated agents. Further on, all experiments that are to be executed during the two weeks of trials will be simulated. The goal is to validate the interrogation scheme and simulate the scenarios.

Validation procedure:	Validation output:	Result:
1.1. all three items exchange all possible data	percentage of package losses	PARTIALLY COMPLETED
1.2. tablet becomes unavailable, BUDDY and Medusa continue interrogation cycle	percentage of package losses	COMPLETED
1.3. simulation of complete Experiment 1 – "surface leader" with MedusaS and BUDDY	quality of tracking using CNR metrics	PARTIALLY COMPLETED
1.4. simulation of complete Experiment 2 – "buddy pointer" and "underwater leader" experiment	successful completion of guiding the diver	NOT COMPLETED

2.2.2 *setting up USBLs*

Validation procedure:	Validation output:	Result:
1.5. USBL mounted on MedusaS, georeferenced modem placed on seabed; MedusaS performs the usual USBL testing scenario	high quality correlation between GPS and USBL obtained positions	PARTIALLY COMPLETED. Range measurements match expected values up to ~0.5 m; bearing measurements exhibit mismatches of up to 15 degrees. Both the range and bearing mismatches seem correlated with the expected value of bearing.

2.2.3 *integration of interrogation scheme using real vehicles*

Validation procedure:	Validation output:	Result:
1.6. all three items exchange all possible data	percentage of package losses	PARTIALLY COMPLETED The data was exchanged through WiFi

1.7. tablet becomes unavailable, BUDDY and Medusa continue interrogation cycle	percentage of package losses	COMPLETED The data was exchanged through WiFi

2.2.4 *"underwater leader" experiment with MedusaD*

Validation procedure:	Validation output:	Result:
1.8. MedusaD is given the area to be covered and starts lawnmower of the area; MedusaS follows the underwater vehicle and aids in its navigation while it performs the lawnmower	quality of tracking using CNR validation metrics	COMPLETED Mean distances between vehicle position and the reference path were 0.09m for line and 0.22m for turn sections

2.2.5 *"underwater leader" experiment with BUDDY*

Validation procedure:	Validation output:	Result:
1.9. BUDDY is given the area to be covered and starts lawnmower of the area; MedusaS follows the underwater vehicle and aids in its navigation while it performs the lawnmower	quality of tracking using CNR validation metrics	NOT COMPLETED No log files for this

2.2.6 *complex gesture recognition on dryland and underwater*

Validation procedure:	Validation output:	Result:
1.10. Perform diver calibration procedure	Qualitative assessment of diver's hand and head tracking	COMPLETED
1.11. Recognition of command: "perform mosaic of m x n area" – repeat N times	Percentage of correct interpretations	COMPLETED
1.12. Recognition of a list of static commands or another complex command (TBD) – repeat N times	Precision recall metrics for each command or Percentage of correct interpretations	COMPLETED
1.13. Repeat 1-3 underwater *(depending on performance try to do it online or offline)	Same as 1 to 3	PARTIALLY COMPLETED

		For underwater gestures calibration procedure is not needed; and CADDIAN slang was tested instead of full complex commands like "perform mosaic"

2.2.7 creating the mosaic

Validation procedure:	Validation output:	Result:
1.14. Objects of known sizes and positions are placed on the seabed in order to validate the results	objects visible in obtained mosaic	COMPLETED: 5 numbered concrete blocks were placed in the pool with known distances from each other
1.15. run a lawnmower and collect data for mosaicking	3D mosaic compared against ground truth of positioned objects	PARTIALLY COMPLETED: Lawnmower mission was run over the blocks, the blocks are visible in the mosaic, but no comparison to the ground truth has been done

2.2.8 1st Experiment integrated

Validation procedure:	Validation output:	Result:
1.16. command from surface using CADDIAN to perform m x n mosaic	successful completion of all tasks in experiment	PARTIALLY COMPLETED Diver only initiated the mission Missing interface that generates the mission
1.17. Execute the "underwater leader" experiment	successful completion of all tasks in experiment	COMPLETED "Underwater leader" has been executed
1.18. Generate 3D mosaic of the seabed	successful completion of all tasks in experiment	COMPLETED Mosaic has been generated.

2.3 Results

2.3.1 Interrogation Scheme

Regarding the interrogation scheme, a simplified version was used. The strategy was that only the buddy vehicle pinged, it pinged alternately the surface vehicle, waited for the reply and then the diver. All the information was exchanged through WiFi (UDP) however we transmitted 8 bytes of dummy data, allocating space for future implementation.

We tried to implement something close to what we would get with the acoustic communications, therefore all the information was sent at a rate not higher than 1/6 Hz. From the surface vehicle, we sent its inertial position and from the buddy we sent the USBL fix and its velocity.

2.3.2 Setting up USBLs

The procedure to set up the USBLs (UltraShort Baseline) consisted of comparing the output of range and bearing measurements with the expected ones (i.e. obtained from a more precise source). Following this approach, one mission was initially performed with two MEDUSA vehicles at the surface, so as to use GPS data as a precise reference. One of the MEDUSA vehicles, with a USBL onboard, remained static; the other vehicle, carrying an acoustic modem, followed a circular trajectory around the other vehicle twice at a constant speed. For each mission of this kind the mismatch in range and bearing values was computed.

After the acoustic modem was lowered to a position farther away from the body of the vehicle, the range measurements matched the expected values with a maximum mismatch of around 0.6 m (note that the precision of the vehicle's GPS and IMU could have a reasonable influence when computing a mismatch of this magnitude). As for the bearing, a mismatch was detected which seemed correlated with the true value of bearing. Initially, this was suspected to be due to the influence of the body of the MEDUSA vehicle. In an attempt to confirm this, the mission was repeated with the USBL mounted in the same position but rotated 180 degrees about its vertical axis. The results of these two missions lead to the conclusion that the error in bearing provided by the USBL was correlated with the bearing *as seen in the frame of the USBL itself*, and not the bearing as seen in the vehicle frame - therefore excluding interference from the body of the vehicle as the main cause of bearing error. Fig. 2.4. and 2.5. illustrate the mismatch in bearing and range respectively, as a function of expected bearing. Both data sets exhibit some interesting structure, and while the mismatch in range could be partially explained by GPS and IMU imprecisions, the one in bearing cannot. This suggested that the USBL devices would benefit from additional testing and/or calibration - a subject of future work by UNEW.

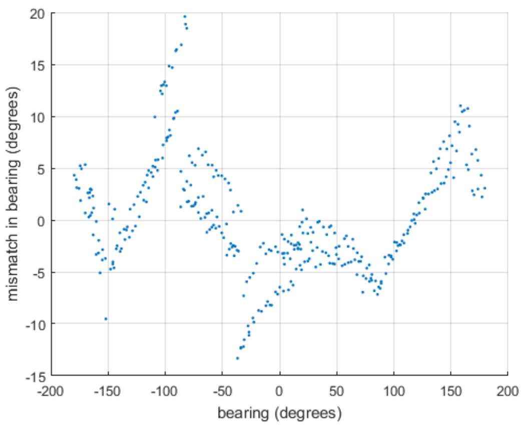


Fig. 2.4.

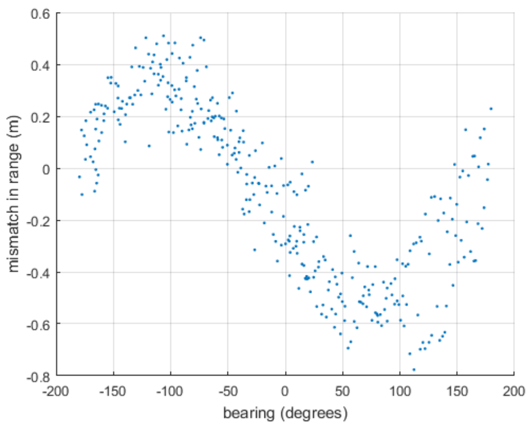


Fig. 2.5.

2.3.3 Underwater Leader Experiment

2.3.3.1 Navigation Filter

Both the leader and the follower vehicles ran an Extended Kalman Filter (EKF) to independently estimate the positions and velocities of both vehicles in the experiment. The surface vehicle needs to estimate the position of the underwater one to be able to track it; the underwater vehicle needs to estimate the position of the surface one in order to use the USBL measurements (range and bearing between vehicles) to infer its own position. Note that bearing and range measurements are used by the filter as separate measurements, so that the variance of the bearing measurement noise can be assumed much bigger than that of the range. Indeed, the filter was set to be only slightly affected by bearing measurements, reducing the effect of big deviations like those observed in Fig. 2.4..

Still, the underwater vehicle relies mainly on DVL measurements for short-term navigation, so its estimate of the surface vehicle position is not so critical. However, the estimate of the *underwater* vehicle computed on the *surface* one is important, since the tracking is based only on this estimate. We focus here on illustrating this. Fig. 2.6. shows the residual of range measurements, i.e. the difference between each range measurement and the expected range value from the EKF state. Note the performance is reasonable since these measurements are obtained only around once every 6 seconds and the surface vehicle has no extra information regarding the motion of the underwater one. In particular, the velocity of the underwater vehicle is very hard to estimate with so little data. In the future, the underwater vehicle will broadcast its velocity and we expect the performance of this filter to improve.

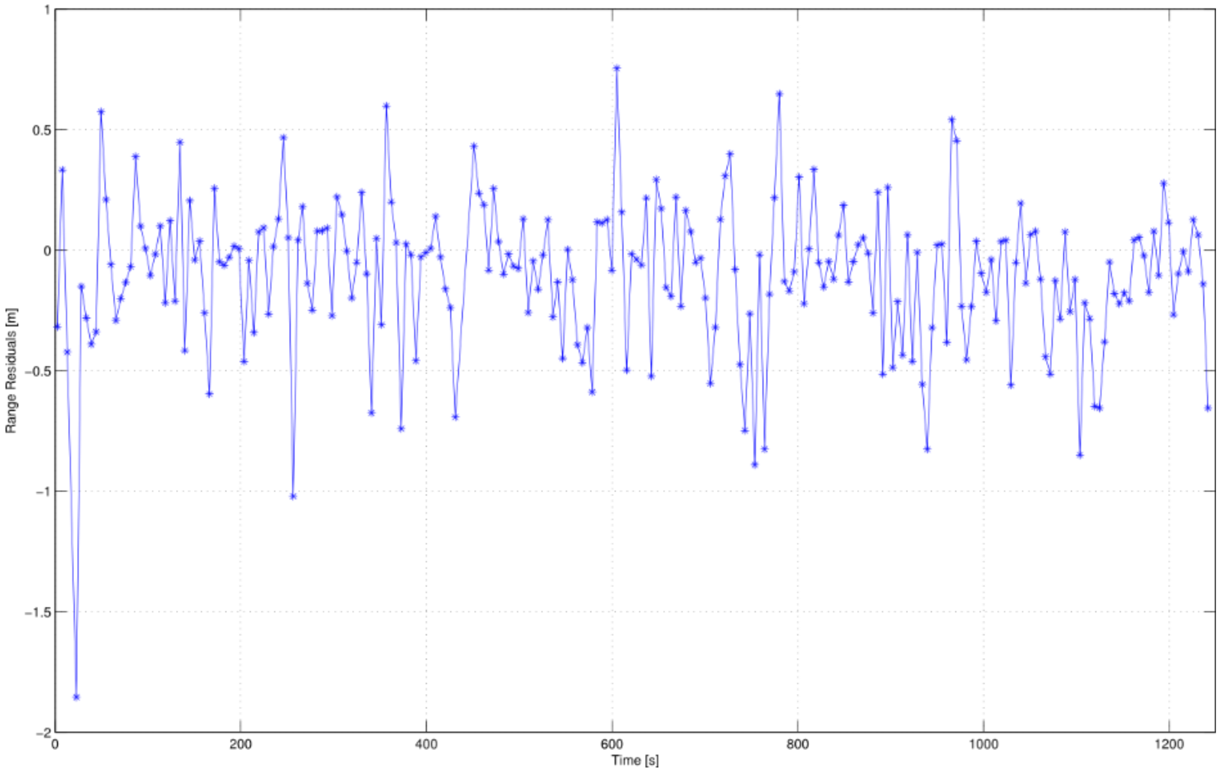


Fig. 2.6. Range residuals on a filter update.

2.3.3.2 Underwater Path-Following

The underwater path-following nominal mission consisted on a lawn-mower pattern with leg distances of 1 meter, 1.5 meters altitude from the seafloor and at nominal speed of 0.3m/s. If a precise following was achieved the acquired horizontal image overlap would be around 50%. The survey area is defined by the diver in real time when initiating the mission (for the data shown in Fig. 2.7. was 20m by 45m).

Since the distance between two consecutive lines was too small some connection paths were included to increase the turning radius to 2.5m.

The achieved overall performance was good with maximum errors on the line's beginning reaching 0.5m and with a high convergence rate to 0, shown in Fig. 2.8.

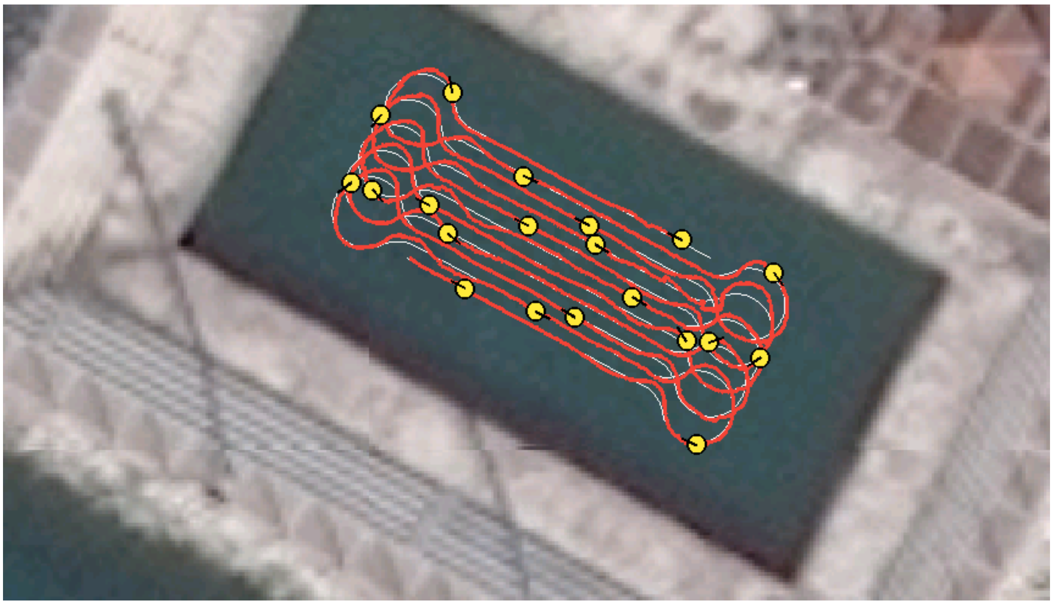


Fig. 2.7. Lawn-mower pattern mission inside a pool: nominal mission in white; vehicle path in red and vehicles pose the yellow circles.

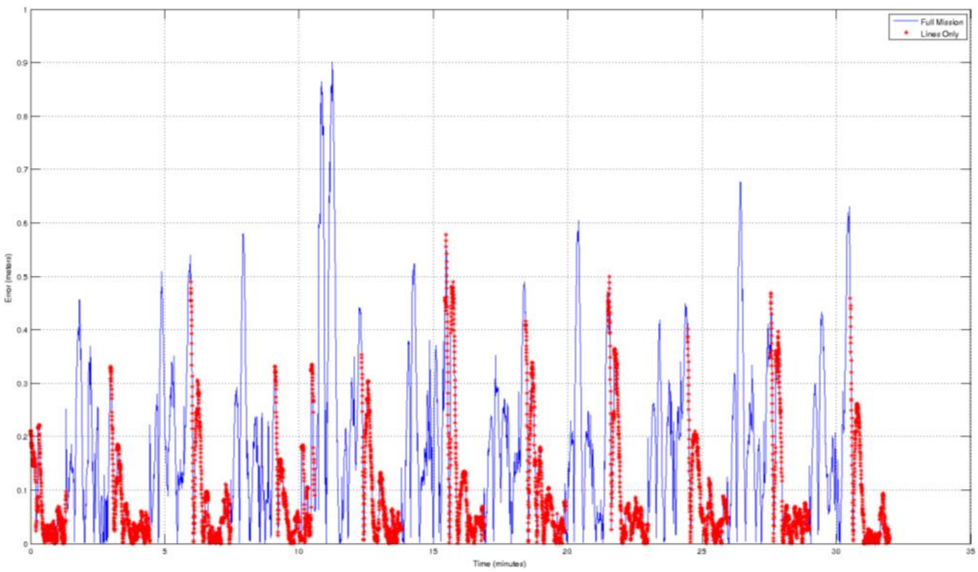


Fig. 2.8. Cross track error for the lines and full mission.

Motion performance of the MedusaD has been computed and evaluated using the CNR metrics. Line sections, Fig. 2.9 and turn sections, Fig. 2.10. of the lawn-mower are analysed separately. The results are summarized in Table 1. The results show excellent MedusaD underwater path following performance with mean distance to path of 0.09 meters along the line sections and 0.22 meters for turn sections. More details regarding the applied metrics can be found at http://dx.doi.org/10.1016/j.arcontrol.2015.08.006

MEDUSA				
reference	**Line**		**Turn**	
Test No.	**dA [m]**	**dH [m]**	**dA [m]**	**dH [m]**
1	0,08	0,22	0,16	0,46
2	0,06	0,33	0,23	0,52
3	0,08	0,47	0,18	0,58
4	0,09	0,34	0,34	0,9
5	0,08	0,32	0,22	0,53
6	0,13	0,58	0,2	0,49
7	0,09	0,41	0,19	0,61
8	0,1	0,5	0,22	0,45
9	0,08	0,38	0,23	0,68
10	0,1	0,47	0,22	0,62
11	0,07	0,42	----	----
Max	**0,13**	**0,58**	**0,34**	**0,9**
Mean	**0,09**	**0,4**	**0,22**	**0,58**
Std Dev	**0,02**	**0,1**	**0,05**	**0,13**

Table 1. MedusaD Path following performance.

dA = area between the vehicle position points and the reference path divided by the path lenght (indication of the mean distance)

dH = maximum of all the distances from the vehicle position points to the reference path (indication of the maximum distance)

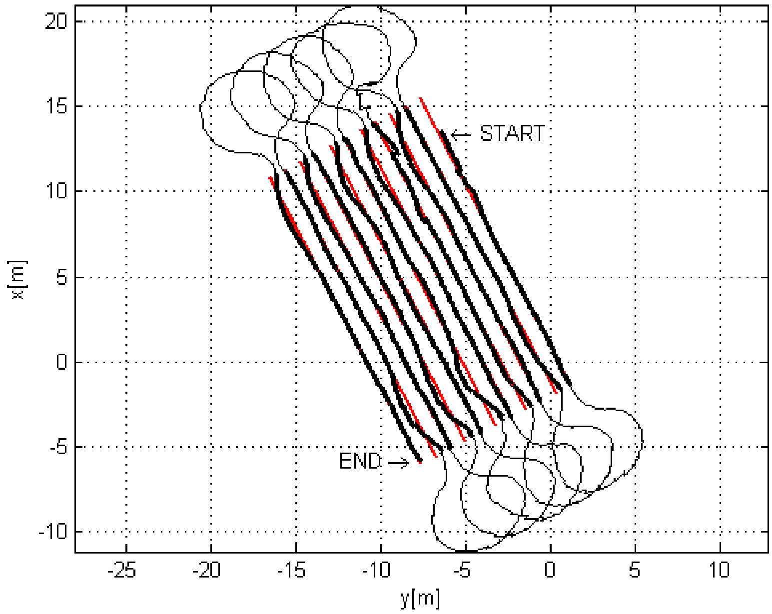


Fig. 2.9. Line section of the lawn-mower.

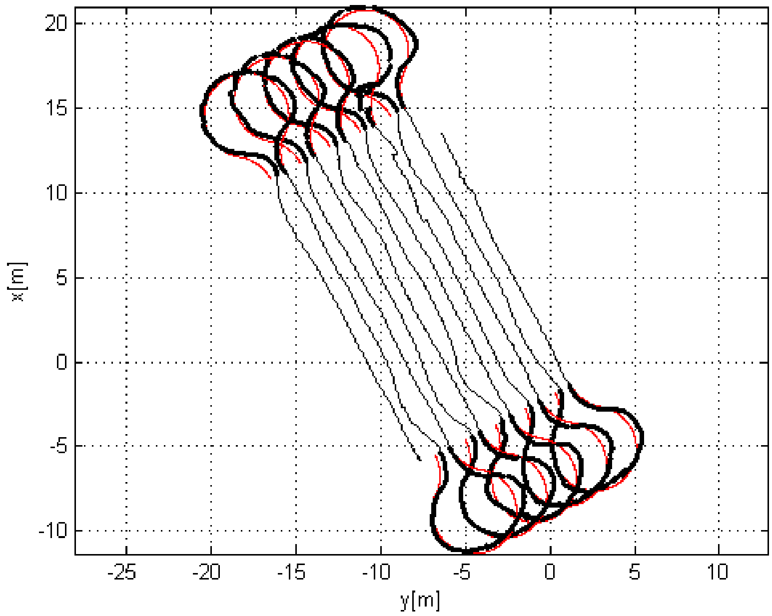


Fig. 2.10. Turn sections of the lawn-mower.

Surface Tracking

The Surface Tracking Controller was designed so that the surface vehicle is in a certain area that improves, among other things, the acoustic communications with the underwater vehicle, and at the same time tries to avoid being on top of it. The choice of this approach, instead of tracking a specific point, was due to the fact that the underwater vehicle can perform any type of mission and therefore the position estimation can be an extremely difficult task.

To implement this, an artificial potential field technique was used and the corresponding velocity profile towards the target is shown in Fig. 2.11. This figure relates the distance between the surface and underwater vehicles and the desired speed for surface vehicle.

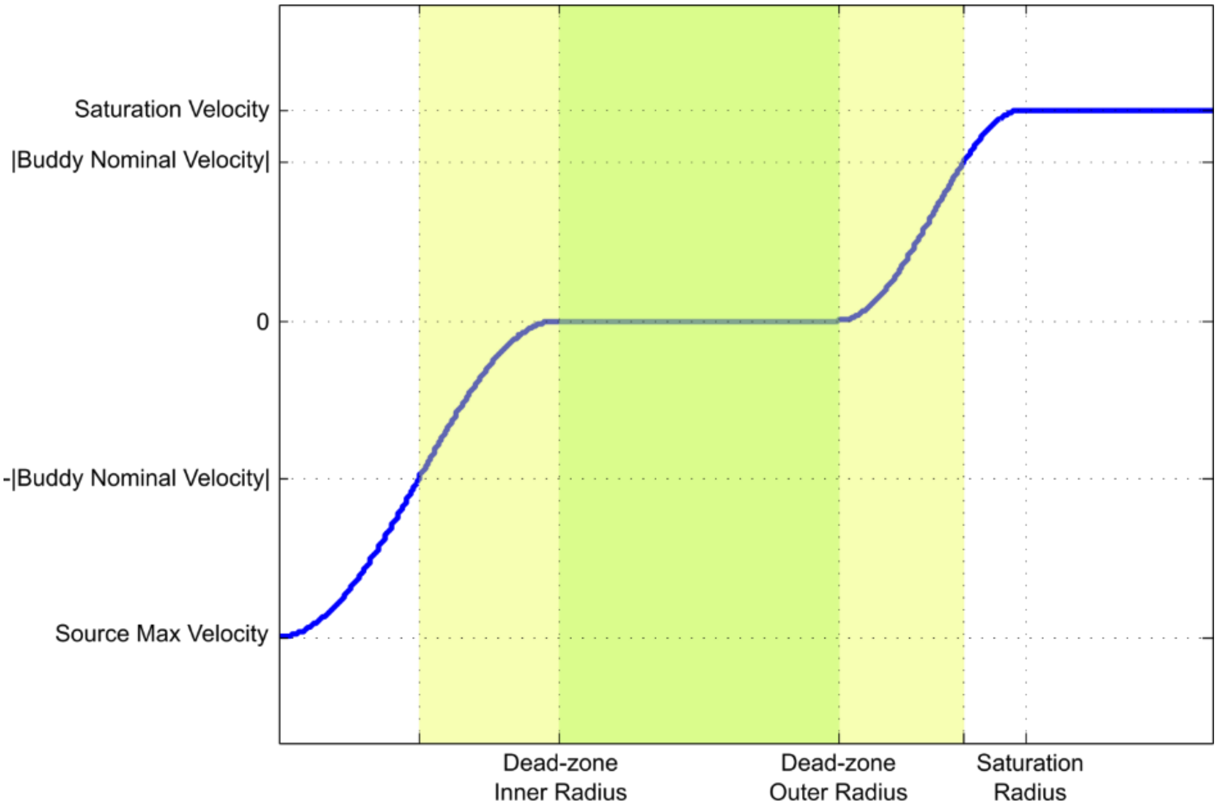


Fig. 2.11. Velocity profile for the surface tracking.

The velocity profile represented in Fig 2.11. can be configured using some parameters, but in the end it results in two different areas: Dead-zone (green) and Equilibrium zone (yellow). The dead-zone is a "comfortable" area, where the surface vehicle is stopped just giving support to the underwater vehicle. The equilibrium zone, that includes also the Dead-zone, corresponds to the expected operation region. The limits of this area depend on the maximum speed of the target being tracked (the underwater vehicle), because when the whole system converges, the surface vehicle must have the same velocity as the underwater one.

With this idea in mind, in Fig. 2.12. the inter-vehicle distance over time is presented. In this figure, the range was used as a "ground-truth" measurement and the upper and lower limits of the equilibrium zone were calculated based on the parameters used on a specific mission.

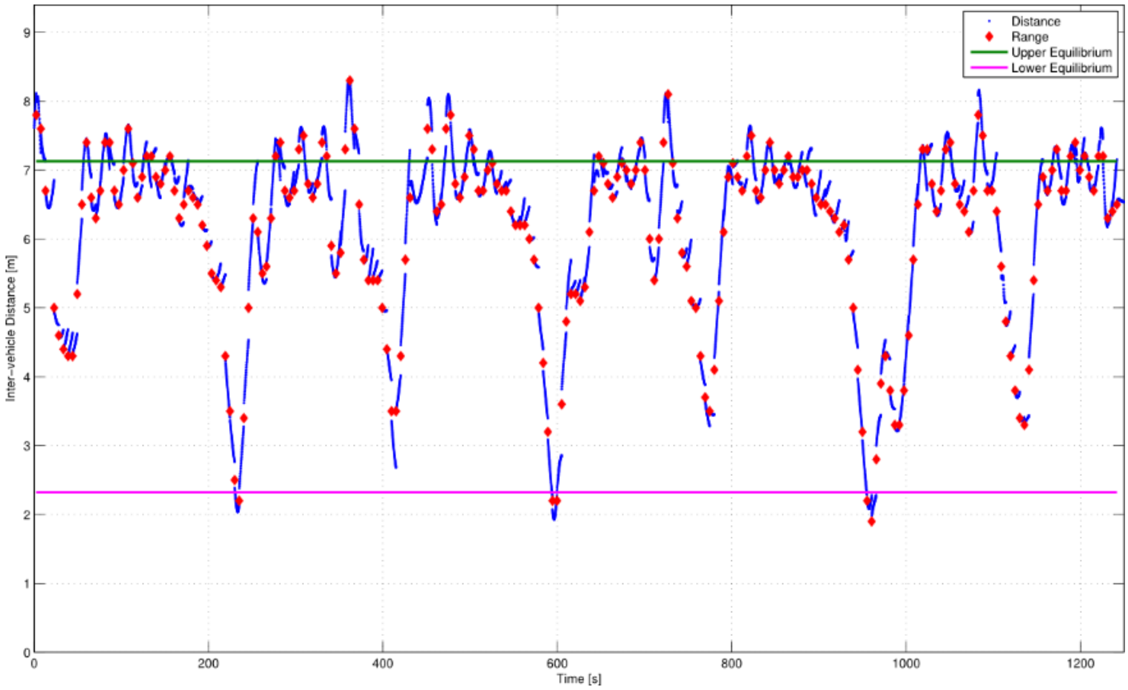


Fig. 2.12. Surface tracking performance.

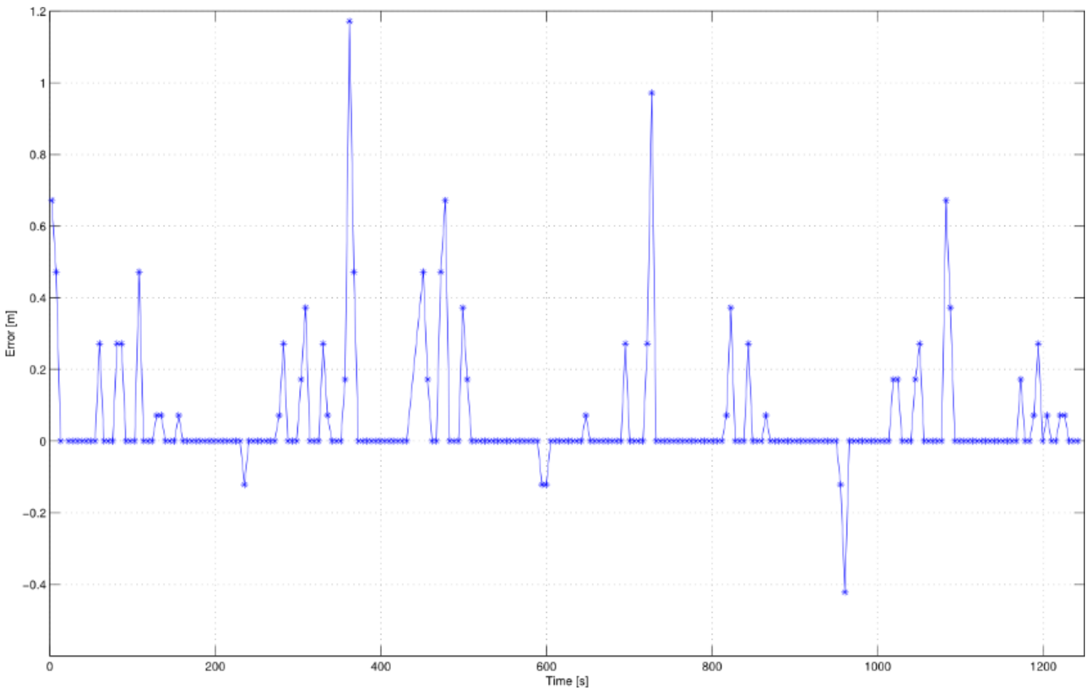


Fig. 2.13. Error between inter-vehicle distance and the Equilibrium zone

As can be seen in Fig. 2.13., the overall performance was good with maximum error of 1.2 meters. The controller can be tuned to improve the performance, but since the acoustic period is too high and the experiment was done on a very confined space, a set of very relaxed parameters were used to avoid aggressive control actions.

2.3.4 Complex gesture recognition on dry land

The first approach followed to complete this task was the use of 3D information from the Bumblebee XB2 stereo camera i.e. disparity values, to track hand motion and classify the gestures from shape. However, this proved to be not a stable method since features to generate matches between pixels from the two cameras are not constant to a sufficient number of frames; hence, a 3D shape with enough quality to perform classification could not be obtained.

Therefore, the second approach used 2d information to detect and classify the hand gesture; and only 3D information was used to validate the detection of the hands. Specifically, a hierarchical pipeline implemented for classification uses first Haar Cascade classifier to detect possible hands candidates in the 2D image, and then this candidates are filtered out using Multi-Descriptor Random Forests trained to classify between the different type of gestures and background imagery.

The reason for this combination is that Haar Cascades provide a real-time multi-scale localization of the hands in the image; however, this classifier normally needs thousands (or more) positive and negative samples to achieve good precision results. Since it is hard to create a dataset of such size, the classifier was trained to overfit the data such that it always detect the hands and the cost of having a great number of false positives. Then, this false positive samples are disregarded by the Multi-Descriptor Random Forest. This classifier is used because commonly the set up for performing the gestures was not always the same. For example, the time of day and weather produced different illumination artifacts and every diver performing the commands, do this in slightly different ways. Thus, we would like to represent the images with different complementary features; each of them invariant to different type of phenomena. After some experimentation, it was found that using SURF, HOG (histogram of oriented gradients) and HSV color information output the best result.

Gesture	Classif. Rate per frame	Final Classif. Rate	No. misses
Number 1	.901	.888	2
Number 2	.882	.888	2
Number 3	.712	.777	4
Number 4	.867	.833	3
Number 5	.921	.833	3
Initiate comm.	.809	.888	2
End comm.	.763	.777	4
Do mosaic	.935	1.0	0
Number delimiter	.895	.944	1

Table 2. Performance parameters for the hand gesture classifier.

It is important to mention that to help the accuracy of the classifier other factors were taken into consideration like relative position of the hands to the head, 3D pose as mentioned and number of consecutive frames containing a type of gesture. Likewise a calibration procedure was done beforehand, in order to estimate the overall size of the hands and to enable head tracking in case the diver was not static. Table 2. shows two classification rates for the different type of individual gestures. The first one is just the accuracy of the hierarchical approach described (Haar+Random Forests) using the classification of every frame. The second one is the accuracy integrating all other cues mentioned, and each gesture was tested 18 times using 12 different people. Hence, although in the table we see final classification rates (fcr) smaller than the ones per frame (fcr can vary only in steps of .055), the algorithm misclassified or missed the gestures a few number of times.

Afterwards, the recognition of one complex command was tested: Do a mosaic of M x N meters. For this a syntax checker based on the CADDIAN language was used in order to detect the right sequence of gestures (a brief description of the syntax checker is presented in the following subsection). The following results were obtained from the 18 sequences analyzed.

- 4 of the sequences were not successfully recognized; which in all cases happened due to the misclassification of the end communication command.
- 6 of the sequences were recognized but there was an error in the recognition of the parameters to perform the mosaic i.e. the numbers M and N that define the area.
- Two of the sequences were used to test the full communication pipeline between the gesture recognition and the UAV interface; which successfully triggered the mission concerning Experiment 1.

Fig. 2.14. shows the output of the hand detection pipeline. All possible hand candidates from the Haar Cascade classifier are shown with a circle; then only the valid recognized gestures by the Multi-Descriptor Random Forests are shown with green.

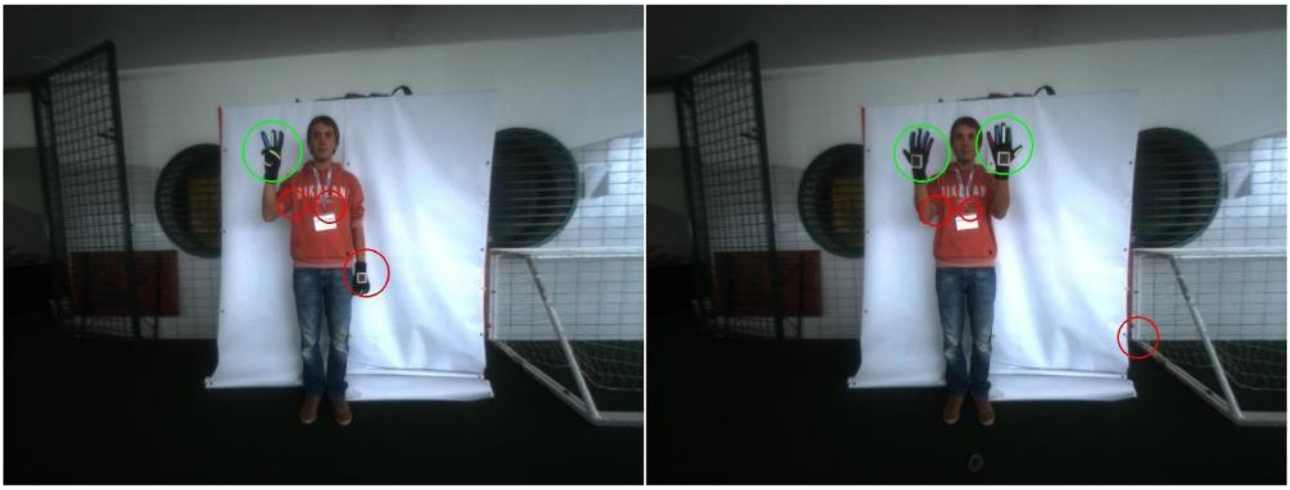


Fig. 2.14. Hand detection and classification.

Syntax checker

Each sequence performed by the diver in the CADDIAN language must undergo a syntax check to be validated before being passed to the robot for the require task execution. Such a check is based on the syntactic rules of CADDIAN that are applied to the sequence to understand if it has a correct structure (only its syntax is checked but not its semantics).

During these validation trials only a subset of (static) gestures has been taken into account. These gestures could be subdivided into the following categories: **Number**, **Caddian-related**, **Slang**, **Emergency**, **Direction**, **Work** and **Place**.

These groups are structured as follows: a) **Number** includes *numbers from 1 to 5*; b) **Caddian-related** consists of *open* and *close communication* and *number delimiter*; c) **Slang** includes *boat*, *out of breath*, *out of air*, *problem* and *danger*; d) **Emergency** is made up of *general evacuation*; e) **Direction** groups *go up*, *go down*, *go forward* and *go backward*; f) **Work** consists of *mosaic*, *photo* and *carry*; g) **Place** includes *boat* and *here*.

The considered gestures belonging to the Caddian-related group are useful for sequence segmentation: the diver can issue many different complex commands in a row before concluding with the *close communication* one. Each complex command must start with the *open communication* symbol, to allow its segmentation; each complex command can be made up of one or many gestures.

According to which gesture has been found after the *open communication*, the Syntax Checker goes on by applying the Caddian syntax rules; in particular:

1. if the second symbol belongs to the **Slang** category and the following one is either an *open* or a *close communication*, the Syntax Checker validates the sequence, since the slang gestures are performed alone (apart for the **Caddian-related** symbols) in a "quick" communication fashion;

2. if the second symbol belongs to the **Direction** group, the Syntax Checker verifies the following symbols: if the subsequent gestures are (one or even more) digits of a *number*, followed by its *number delimiter* and then by an *open* or *close communication*, then the sequence is marked as valid;

3. if the second symbol belongs to the **Work** group, the Syntax Checker distinguishes between works that require one or more arguments and works without arguments. In the first case, the possible arguments (i.e. the subsequent gestures in the sequence) could be either a **Place** or one or two **Numbers** (each one consisting of one or more digits) plus their *number delimiters*. After that, if an *open* or a *close communication* is found, the sequence is validated. In the second case, the sequence is validated only if the subsequent (i.e. third) gesture is either an *open* or a *close communication*;

4. if the second symbol belongs to the **Emergency** category, similarly to the **Slang** group, the Syntax Checker validates the sequence only if the successive symbol is either an *open* or *close communication*;

5. if after the first *open communication* symbol, the Syntax Checker finds either another *open communication* or a *close communication* gesture, the sequence is marked as valid, corresponding to the null command (no operations);

6. in all the other cases the Syntax Checker marks the sequence as non valid (e.g. if the second symbol belongs to the **Number** or **Place** group).

The Syntax Checker has been realized as a ROS node that checks and validates each command before allowing the robot to execute it. For the first validation trials, the set of recognized gestures has been restricted but it will be integrated with all the other ones in a future stage and the Syntax Checker will be extended as well to validate sequence containing also these additional symbols.

2.3.5 Creating the mosaic

Firstly, concrete blocks of known size (39.9 cm x 39.9 cm x 4.8 cm) were placed in the survey area in a set pattern, and their distances measured. The relative positions of the concrete blocks can be seen in Fig. 2.15. The markers are clearly visible in the images of the down looking camera, allowing them to be identified easily.

After the mission, the image data was collected from the down looking stereo camera system and integrated with the position estimate of the navigation system on the medusa vehicle. The result of the complete mosaic can be seen in Fig. 2.17. The markers can clearly be seen in the mosaic. Fig. 2.16. shows the relative position of the markers in the mosaic. This can be used to get a metric quality of the generated map and position estimate.

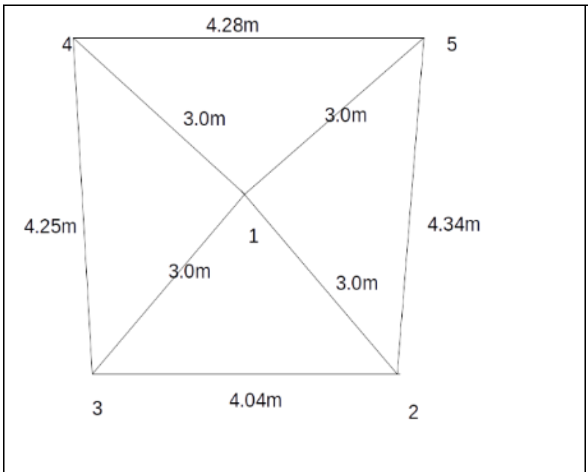


Fig. 2.15. Ground Truth Relative Marker Positions

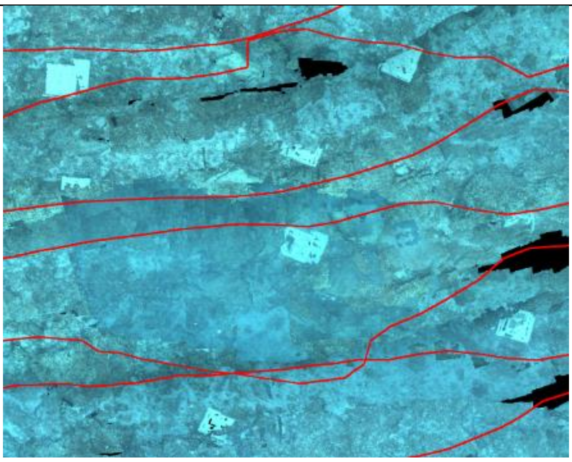


Fig. 2.16. The Concrete Markers

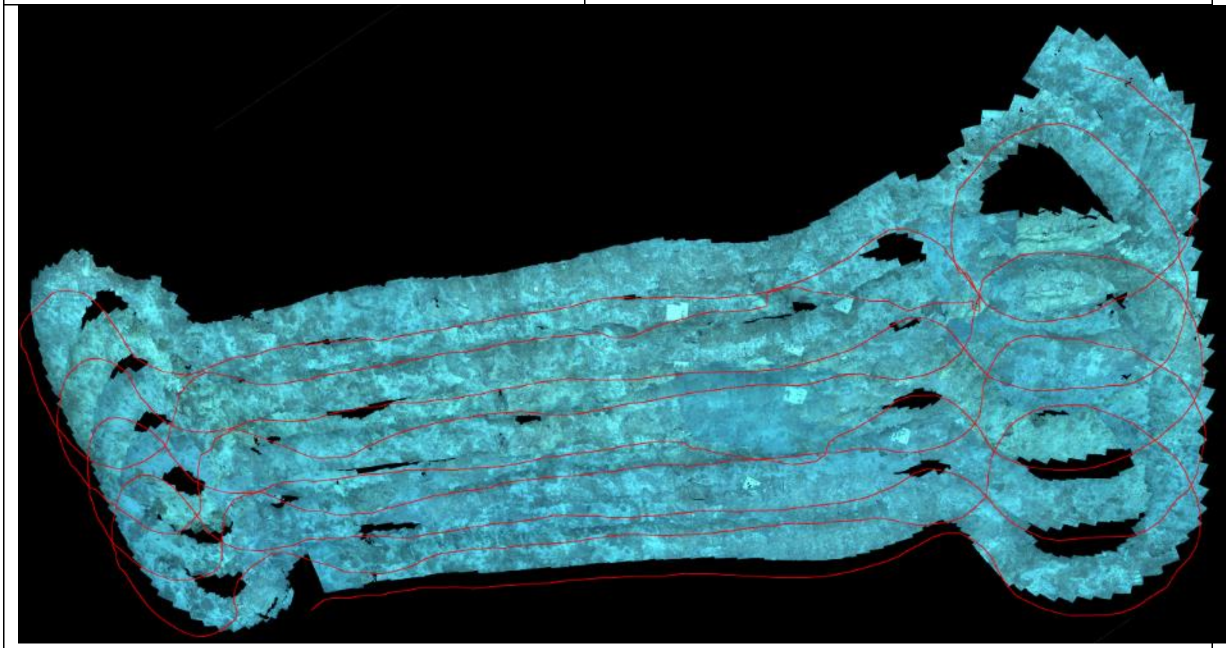


Fig. 2.17. Complete Mosaic of a run

2.4 To-do list

Interrogation scheme:

- Implement a mitigation strategy for the case where the buddy is lost
- Transmit the data through the acoustic channel

Setting up USBL:

- Improve bearing measurements (decrease the correlation of the errors in range and bearing with the bearing angle)

Navigation Filter:

- Use the velocity of the underwater vehicle broadcast through the acoustic channel in the estimator running in the surface vehicle
- Improve the performance of the outlier rejection

Underwater Path-following:

- Improve performance on the section transition to reduce the initial cross track error

Surface Tracking:

- Adjust the gains to reduce oscillations
- Include the leader estimated speed on the controller
- Develop a strategy to handle diver’s position

Complex gesture recognition:

- Inclusion of other complex gestures, both for the classifier and the syntax checker
- Enable hand tracking in 2D or 3D to fine-tune classification of the gestures (improve performance) and avoid the step of filtering out background noise.

3 Experiment 2: Buddy “slave”

3.1 Description of experiment

The second experiment is envisioned to demonstrate the buddy “slave” functionality of the CADDY concept, where underwater vehicle executes a series of tasks that are commanded using CADDIAN slang gestures from the underwater.

<u>Main task of the experiment</u>

Command a series of tasks using a simplified version of CADDIAN language (CADDY slang). The diver is positioned within the field of view of the underwater vehicle and issues the following list of commands:

- “go back/forward 1m” – the vehicle moves 1m in the commanded direction (Fig. 3.1.)
- “go up/down 1m” – the vehicle changes depth by 1m in the commanded direction (Fig. 3.2.)
- “take a photo” – the vehicle takes a photo of the seabed below, or takes a photo of the diver (Fig. 3.3.)
- “bring me something from the surface” – the vehicle goes to the surface and returns to the same position from where it started (Fig. 3.4.)

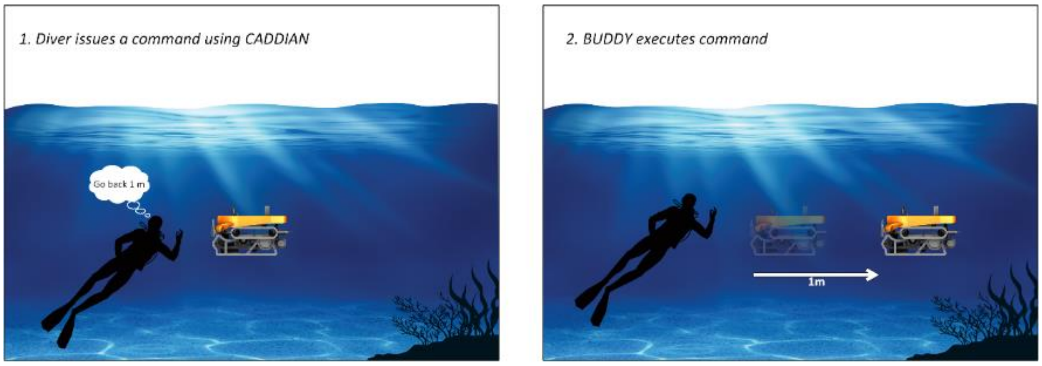


Fig. 3.1. Issuing the “go back” command

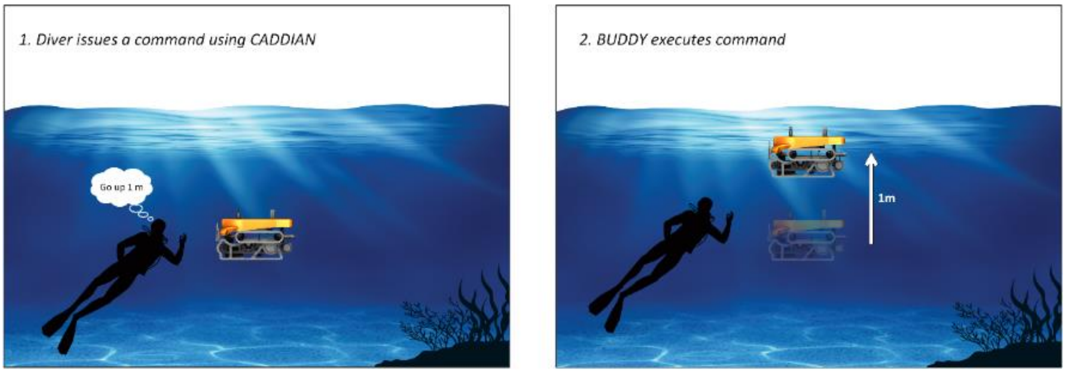


Fig. 3.2. Issuing the “go up” command

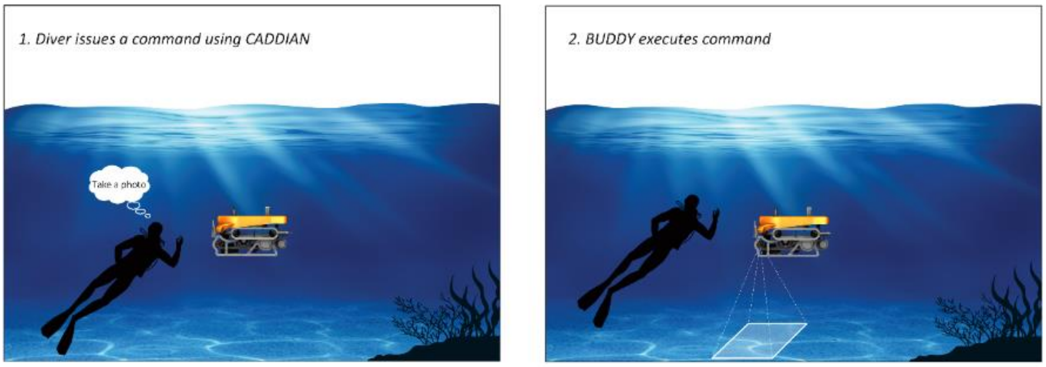


Fig. 3.3. Issuing the "take a photo" command

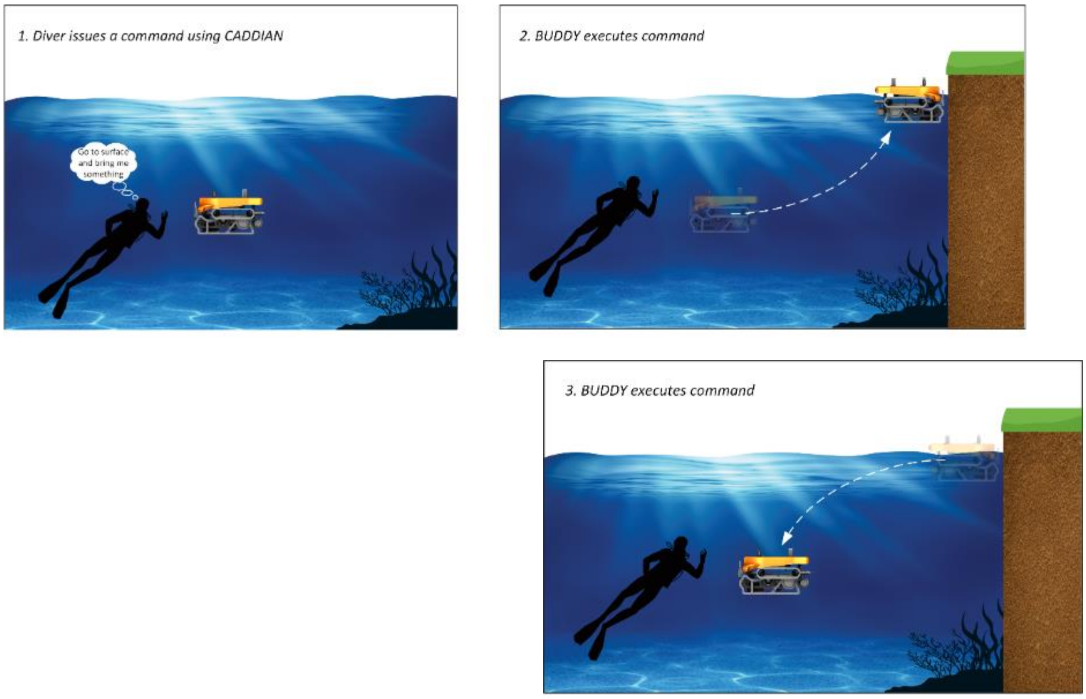


Fig. 3.4. Issuing the "bring me something from the surface" command

Vehicles

In the first trials, R2 will be used while ultimately BUDDY will be used.

Experiment subtasks

- **gesture recognition of buddy tasks from underwater**

Diver issues a command that are recognized by the developed software, taking into account a highly dynamic scene (diver moving, underwater vehicle moving) and low quality visibility conditions.

- **execution of basic buddy tasks**

This subtask is conducted first by using a virtual diver (issuing commands directly from a computer), then diver on the surface and finally with the diver underwater.

- **integration with the mission planner**

Recognized CADDIAN slang gestures have to be transmitted via a mission planner to commands executed by the vehicle.

3.2 Validation procedure

3.2.1 *gesture recognition of buddy tasks from underwater*

Validation procedure:	Validation output:	Result:
2.1. command “go back/forward 1m”	successful interpretation	PARTIALLY COMPLETED Go forward gesture will be change in the CADDIAN language
2.2. command “go up/down 1m”	successful interpretation	COMPLETED
2.3. command “take a photo”	successful interpretation	COMPLETED
2.4. command “go to surface and come back (bring me something)”	successful interpretation	COMPLETED

3.2.2 *Basic buddy tasks with R2 – virtual diver*

Validation procedure:	Validation output:	Result
2.5. go back/forward 1m	successful completion of basic buddy tasks	COMPLETED. The length of motion is parametrized, so that the vehicle can move back/forward of x m from the actual position.
2.6. go up/down 1m	successful completion of basic buddy tasks	COMPLETED. The length of motion is parametrized, so that the vehicle can move up/down of x m from the actual depth. The vehicle also maintains its horizontal position if gps/usbl measure is available.
2.7. take a photo	successful completion of basic buddy tasks	COMPLETED. The vehicle moves to a predefined altitude from the sea bottom, take the photo and go back to the starting depth.
2.8. go to surface and come back (bring me something)	successful completion of basic buddy tasks	COMPLETED. The vehicle emerges and reach a predefined location, waits for a few seconds (simulating the action of

		taking something) and then recover its starting position and depth.

3.2.3 2nd Experiment: Basic buddy tasks with R2 – diver underwater

Validation procedure:	Validation output:	Result
2.9. command "go back/forward 1m"	successful completion of basic buddy tasks	PARTIALLY COMPLETED Go forward command will be changed in the CADDIAN language
2.10. command "go up/down 1m"	successful completion of basic buddy tasks	COMPLETED
2.11. command "take a photo"	successful completion of basic buddy tasks	COMPLETED
2.12. command "go to surface and come back (bring me something)"	successful completion of basic buddy tasks	COMPLETED

3.3 Results

3.3.1 *Basic buddy tasks with R2 – virtual diver*

The goal of this experimental phase is to test the modules responsible for the mission action execution in response to a (virtual diver) command.

The commands considered in this validation phase are the following ones:

- go back (1 m)
- go forward (1 m)
- go up (1 m)
- go down (1 m)
- take a photo
- go to surface and come back (bring me something)

Considering the whole architecture, these commands are generated from the gesture recognition module. For this validation phase the commands are manually issued by the human operator.

<u>Execution of the mission actions:</u>

- "go back" and "go forward" actions - during the trials in Biograd Na Moru 2015, the CNR R2 vehicle was equipped only with a GPS system for the absolute positioning. For this reason, these two actions were performed on surface.

The actions are carried out with the vehicle standing still in a desired position by means of dynamic position procedure. As the operator triggers the command, the positioning references are changed in such a way to move the vehicle forward/backward of the defined distance, with respect to the actual orientation of the vehicle.

In Fig. 3.5., the horizontal forward/backward motion of the vehicle is reported (the motion is of about 3.5 m for the purpose of better observation of the motion during the at-field validation procedure).

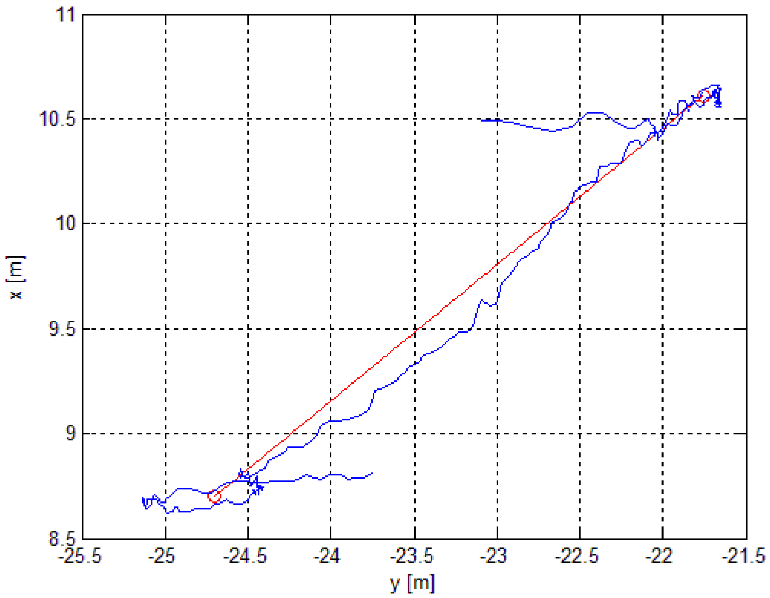


Fig. 3.5. Horizontal motion of the vehicle in response to the "go back/forward" commands

- "go up" and "go down" actions - due to the lack of an underwater positioning system (e.g. USBL), the vertical motion was constrained to a few tenth of centimeters below the water surface, in order to maintain the GPS antenna above the water line through an extension pole. Despite this limitation, it was anyway possible to validate the response of the vehicle to the issued commands as reported in Fig. 3.6., where the vehicle goes up and down changing its depth of about 0.6 meters with respect to the actual vehicle depth.

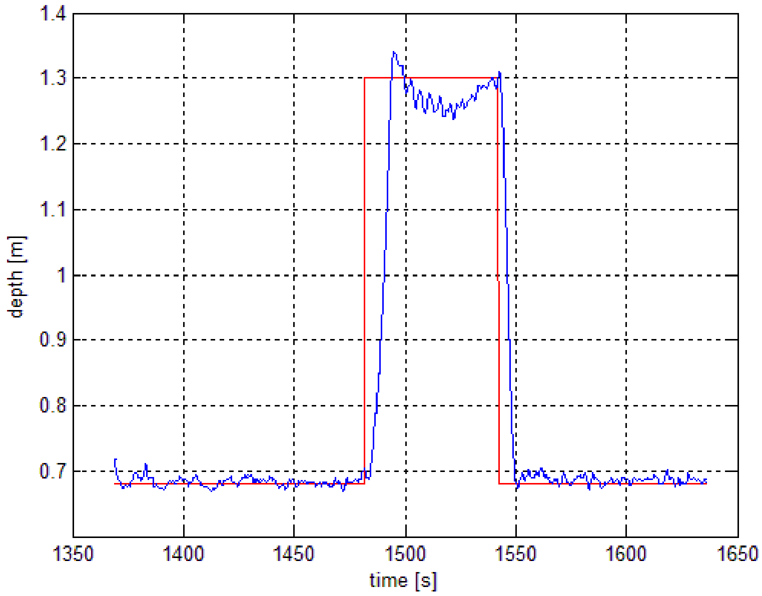


Fig. 3.6. Vertical motion of the vehicle in response to "go up/down" commands.

- "take a photo" - when the action is triggered, the vehicle stores its current depth; then, maintaining its horizontal position (if underwater positioning is possible), it starts a descent towards the sea bottom until it reaches a predefined threshold altitude (during the validation trials it was set to 0.6 m). As it reaches the altitude threshold, a photo of the sea bottom is taken (during the trials the action was simulated blinking the front lights of the vehicle) and then the vehicle recovers its starting depth. The behavior of this action is reported in Fig. 3.7.

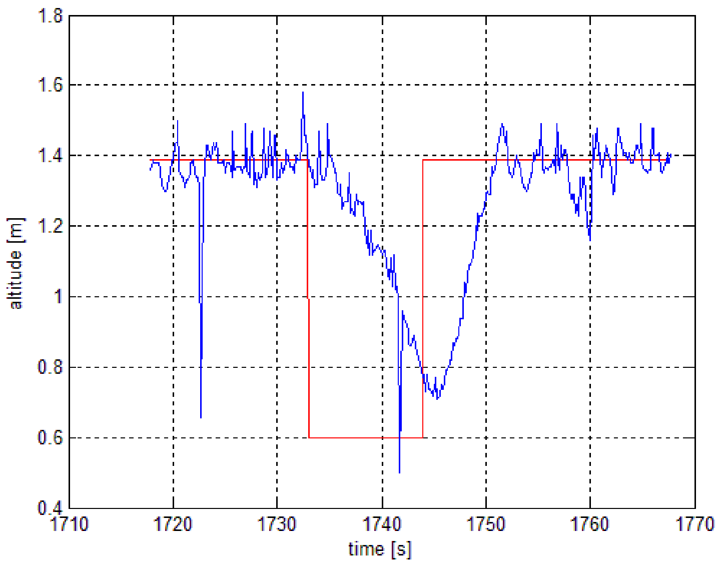


Fig. 3.7. Vertical motion of the vehicle during the execution of the "take a photo" command.

- go to surface and come back - this action summarize the behaviors of the previous command responses. When the command is issued, the vehicle stores its current position and depth; then the vehicle surfaces and moves to a specific "home" point where the vehicle is loaded with the object to br brought to the diver (during the trials, this phase is simulated by blinking the lights while standing still at the "home" point for 5 seconds). After that, the vehicles return to the initial position and depth.

3.3.2 2nd Experiment: Basic buddy tasks with R2 – diver underwater

For the execution of this part of the experiment, the same hierarchical approach as in Experiment 1 was followed: first Haar Cascades detect the possible hand locations and then Multi-Descriptor Random Forests classify the gestures and filter the background noise. In this case, no extra validations steps were taken into consideration because underwater scenery is a lot more homogeneous than on dry land, and all diver carry almost identical suits.

In these experiment, although data was collected for complex gestures (sequences of simple gestures); only the CADDIAN slang was tested due to weather conditions and time constraints. CADDIAN slang represents the same message as complex structures but with only one gesture; which was designed for convenience of the divers. This slang is the same as in the virtual diver experiment: *go forward, backward, up, down, take a photo, and go to the surface to pick up equipment.* While doing the experiments, it was noticed that the go forward and backward command were very difficult to detect since the stereo-camera commonly seed only the back of the hand or the tip of the index finger respectively. In this position the hands do not offer a lot of features to track, and if only the backhand is seen it can be easily confuse with the gesture for *number delimeter*. Thus, it was concluded to change these gestures in the CADDIAN language after the trials so they can be easier to recognize.

Table 3 shows the classification rates for these gestures; like in Experiment 1, accuracy per frame and final accuracy (the gesture has to be detected in a certain amount of consecutive frames). For this occasion, we use 4 divers in total, their data generates Table 3; but only 2 divers were used to instruct the UAV to perform the corresponding commands and test the whole communication pipeline. The number of times each diver performed the gestures was 3.

Gesture	Classif. rate per frame	Final classif. rate	No. misses
Go up	.952	1.0	0
Go down	.922	1.0	0
Take a photo	.958	0.916	1
Bring something	.934	0.833	2

Table 3. Performance parameters of hand gesture classifier

As it can be seen the number of misses are very low, and ever the classification frame per rate is very high. It is important to mention that the testing conditions were harsh during the execution of the experiments: heavy winds which generate waves causing the diver to be unstable. Hence, it proves the robustness of the classifier and its ability to detect the same gesture at different scales (divers were moving forward and backward constantly due to the waves). In the same fashion as in experiment I, we showed in Fig. 3.8. the detection of hand candidates and the final gestures. Notice now, how the hand candidates overlap since there's little background noise.

Fig. 3.8. Hand gesture classification shown at different scales.

The third experiment was fusion of the first two, showing fully achieved slave functionalities. Accordingly, whenever the gesture was recognized, the R2 AUV performed the commands as described in the virtual diver section without any issue.

3.4 To-do list

Even if a positive evaluation of the buddy tasks execution by means of virtual commands was obtained, there could a tentative re-execution of the trials to overcome the two following issues experienced during Biograd trials:

- validation trials were carried out in bad weather conditions (presence of wind and sea current) that affected the results introducing disturbances in the gathered data;
- lack of underwater positioning system.

For such reasons, there would be the possibility to execute again the trials in a pool (Genova, Italy), allowing better water condition. Also a USBL system will be available, allowing absolute positioning capabilities underwater.

As for the gesture recognition module:

- Like in experiment 1, more static and complex gestures will be included. *(If trials are to be conducted again, the complex gestures equivalent to the slang will be tested.)

4 Experiment 3: Buddy "guide"

4.1 Description of experiment

The third experiment is envisioned to demonstrate the buddy "guide" functionality of the CADDY concept, where underwater vehicle guides the diver to the specific point of interest.

Main task of the experiment:

The operator at the surface picks a point where the diver should be taken to (Fig. 4.1.). The BUDDY positions itself relative to the diver in such a way to point in the direction towards the required point of interest, acting like a pointer (Fig. 4.2.). Should the diver not cooperate and follow the vehicle, the buddy "guide" must always stay in the field of view of the diver, pointing in the direction where the diver should be heading (Fig. 4.4. – 4.7.). At all times BUDDY knows about the diver position based on sonar and USBL measurements.

Fig. 4.1.

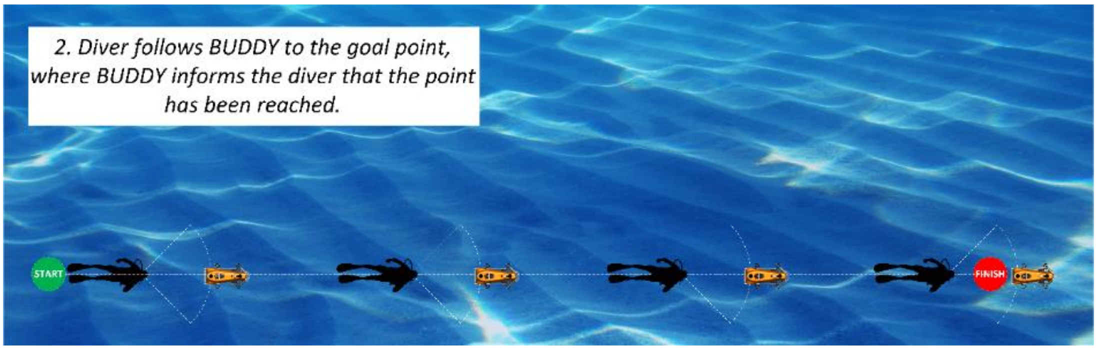


Fig. 4.2.

Fig. 4.3.

Fig. 4.4.

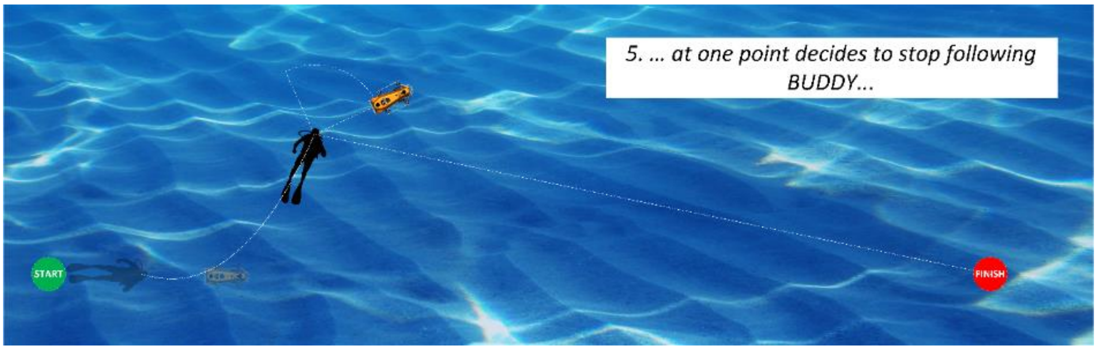


Fig. 4.5.

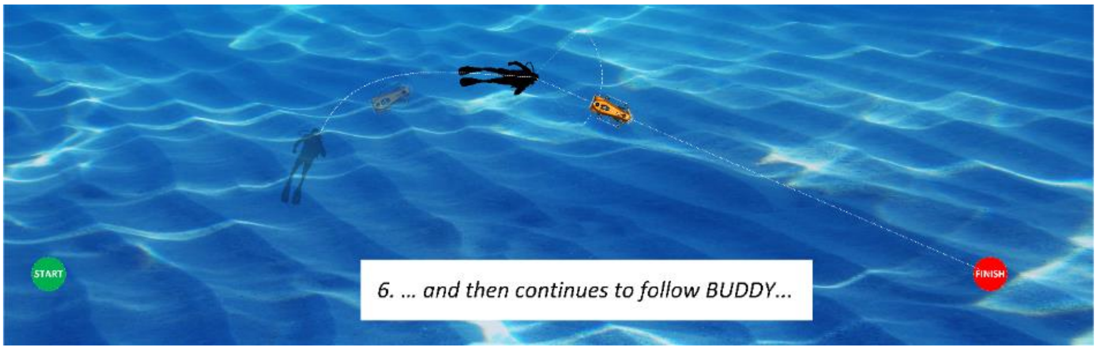


Fig. 4.6.

Fig. 4.7.

Fig. 4.8.

<u>Vehicles:</u>

In this experiment, BUDDY serves as the underwater vehicle and MedusaS as the surface vehicle.

<u>Experiment subtasks:</u>

- **"buddy pointer" experiment – virtual diver, ROV as diver, real diver**

This experiment includes the integration of the developed algorithms for BUDDY positioning with respect to the diver. The experiment is carried out in three phases. First, with virtual diver, then with ROV instead of the diver (with acoustic communications to the BUDDY vehicle) and finally with the real diver. In all three phases, the following experiments are executed:

- testing the approach phase – making sure that the BUDDY approaches the diver without entering the safety perimeter around the diver,
- diver changes orientation while BUDDY positions itself on the circle around the diver in order to stay within the diver's field of view,
- diver changes only position, while BUDDY positions it itself in order to stay within the diver's field of view.

- **"underwater leader" experiment – virtual diver, ROV as diver, real diver**

Similar to experiment 1, the surface vehicle has to track the underwater agents. The main difference is that in this experiment the surface vehicle should position itself half way between the BUDDY and the diver in order to maintain the formation.

- **tracking ROV/diver in BUDDY sonar image**

Since BUDDY perceives the diver using sonar (high precision, low range) and USBL measurements (low precision, high range), this subtask is in charge of fusing these to sensors in such a way that estimates of the diver position are available even in cases when diver is not available in the sonar image.

4.2 Validation procedure

4.2.1 tracking ROV/diver in BUDDY sonar image

BUDY with sonar is pointing towards the VideoRay ROV/diver and distance to BUDDY is determined from sonar image. When the experiment with diver is executed, bubbles are not tracked since diver tracking estimator is integrated.

Validation procedure:	Validation output:	Result:
3.1. ROV moves within sonar image, leaves sonar image, gets back in sonar image	distance between BUDDY and ROV calculated and published	Successful, in all three experiments the ROV was tracked. The combination with USBL measurements proved to be an excellent solution.
3.2. diver moves within sonar image, leaves sonar image, gets back in sonar image	distance between BUDDY and diver calculated and published, bubbles not tracked	Successful, diver was tracked and bubbles did not interfere much.

4.2.2 "buddy pointer" experiment – virtual diver

Virtual diver is positioned at a specified location; target location is set. BUDDY acts as buddy.

Validation procedure:	Validation output:	Result:
3.3. virtual diver position and orientation fixed, BUDDY approaches the diver and positions itself collision free	collision free positioning of BUDDY	COMPLETED The experiments were carried out for different distances from the diver to analyse the approach speed and overshoot. Results are shown in Fig. 4.12. – 4.14.
3.4. virtual diver changes orientation	BUDDY positions itself according to "buddy pointer" algorithm	COMPLETED The experiment was used to measure the agility of BUDDY due to fast orientation changes of the diver. Results are shown in Fig..4.15. – 4.16.
3.5. virtual diver moves towards the location	BUDDY positions itself according to "buddy pointer" algorithm	COMPLETED The experiment was completed without a specified target to solely validate the tracking behaviour in case of a moving diver. Results are shown in Fig. 4.17. – 4.18.

3.6. virtual diver moves away from target	BUDDY positions itself according to “buddy pointer” algorithm	COMPLETED The experiment is simulated with a 180° turn away from the normal path as shown in Fig. 4.17. – 4.18.

4.2.3 “buddy pointer“ experiment – ROV is diver (acoustic comms)

ROV is positioned at a specified underwater location; target location is set. BUDDY acts as buddy.

Validation procedure:	Validation output:	Result:
3.7. ROV position and orientation fixed, BUDDY approaches the diver and positions itself collision free	collision free positioning of BUDDY	NOT COMPLETED The experiment was not carried out due to technical issues.
3.8. ROV changes orientation	BUDDY positions itself according to “buddy pointer” algorithm	COMPLETED The experiment was carried out with the PlaDyPos vehicle in surface operation. Results are shown in Fig 4.19. – 4.20.
3.9. ROV moves towards the location	BUDDY positions itself according to “buddy pointer” algorithm	COMPLETED The experiment was carried out using the PlaDyPos vehicle in surface operation. The guidance target was not set. Results are shown in Fig 4.21. – 4.22.
3.10. ROV moves away from target	BUDDY positions itself according to “buddy pointer” algorithm	COMPLETED The experiment was carried out using the PlaDyPos vehicle in surface operation. The guidance target was not set. Movement away from the target was simulated with 180° turns. Results are shown in Fig 4.21. – 4.22.

4.2.4 *“underwater leader” experiment – ROV is diver (acoustic comms) + BUDDY*

BUDDY positioned underwater and ROV diver positioned somewhere close to BUDDY. MedusaS at the surface has to position half-way between them.

Validation procedure:	Validation output:	Result:
3.11. BUDDY moves, ROV diver static	MedusaS positions itself halfway between BUDDY and ROV diver	The experiment was not carried out.
3.12. BUDDY static, ROV diver moves	MedusaS positions itself halfway between BUDDY and ROV diver	The experiment was not carried out.

4.2.5 *“buddy pointer“ experiment –diver*

Diver is positioned at a specified underwater location; target location is set. BUDDY acts as buddy.

Validation procedure:	Validation output:	Result:
3.13. diver position and orientation fixed, BUDDY approaches the diver and positions itself collision free	collision free positioning of BUDDY	The experiment was not carried out.
3.14. diver changes orientation	BUDDY positions itself according to “buddy pointer” algorithm	The experiment was not carried out.
3.15. diver moves towards the location	BUDDY positions itself according to “buddy pointer” algorithm	The experiment was not carried out.
3.16. diver moves away from target	BUDDY positions itself according to “buddy pointer” algorithm	The experiment was not carried out.

4.2.6 3rd experiment – buddy guide

Diver and BUDDY underwater, MedusaS at the surface. At the surface, a target point is set.

Validation procedure:	Validation output:	Result:
3.17. diver follows the BUDDY, BUDDY reacts when target reached	formation kept at all times, diver reaches the target point	The experiment was not carried out.
3.18. diver does not follow the BUDDY	formation kept at all times, diver eventually reaches the target point	The experiment was not carried out.

4.3 Results

4.3.1 tracking ROV/diver in BUDDY sonar image

ROV experiment 1

The first experiment was conducted with BUDDY vehicle tracking the IST Medusa vehicle in sonar image and publishing the Medusa's relative location as a range-bearing pair. Medusa was conducting other experiments and BUDDY was positioned to occasionally see it in the sonar image. There was no communication between the vehicles and the tracking results were only used to manually confirm that the Medusa was correctly recognized in the image and that the messages were published. BUDDY was remotely operated to point towards the Medusa or to intentionally lose it out of sight.

ROV experiment 2

In the second set of ROV experiments, we used the PlaDyPos platform as a tracking target. Three different tests were conducted:

1. PlaDyPos moving, BUDDY station keeping.
2. PlaDyPos station keeping, BUDDY moving.
3. Both PlaDyPos and BUDDY moving.

In all three test cases the tracking proved to work very well. However, the problem could occur if the target would exit the sonar's field of view, and another ROV (or an object of similar dimension) that produces similar sonar image enters it. In that case, it is very difficult to distinguish from the low quality sonar image if that is the same vehicle.

To cope with that, fusion between USBL and sonar measurements was incorporated. The low precision USBL measurements are used by the estimator to give an approximate of the target position (with higher variance). This information is used by the sonar target detector to set the region of interest in which the target is located. Finally, if the sonar detector finds the target in this region of interest, estimator is updated with the high precision sonar measurement.

The following image illustrates the size of the region of interest – the estimated location of the target – in case there is only USBL measurement (left) and with both USBL and sonar measurements (right).

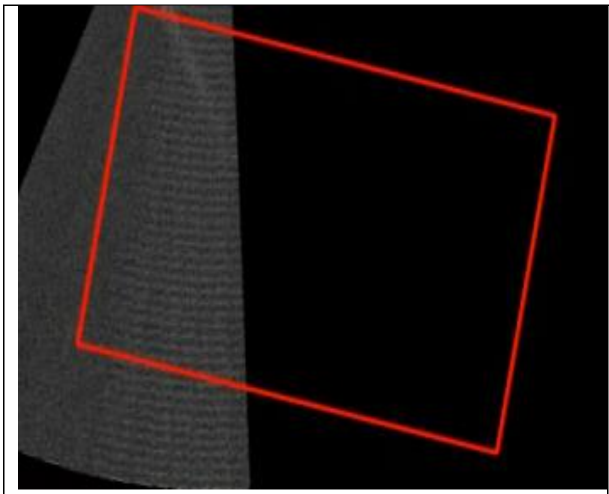


Fig. 4.9.

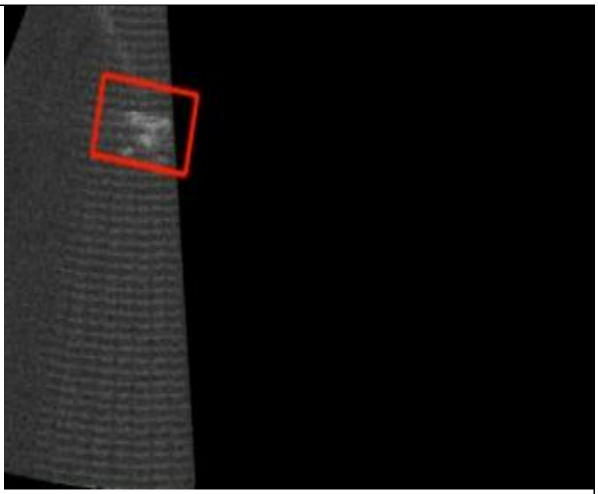


Fig. 4.10.

The image below shows approximate estimation of the target compared to the GPS measurement. The actual error is even smaller as the GPS units on the vehicles were not placed in the centre of the vehicles so the error is dependent on their headings.

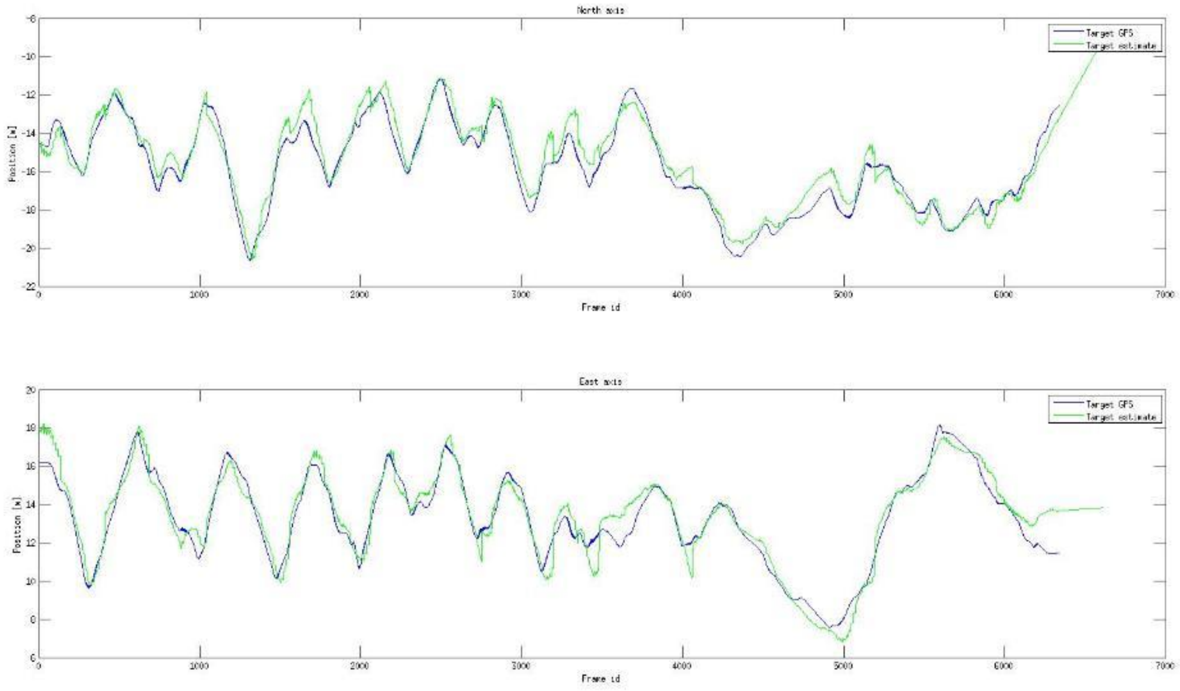


Fig. 4.11.

ROV experiment 3

The final experiment with the ROV was also used as measurement for the pointer experiment. Again, PlaDyPos was used as the target, and BUDDY was supposed to always position itself in front of the PlaDyPos. Raw sonar measurements were used as input to the positioning estimator. USBL was not used in this experiment.

During approximately 15 minutes of the experiment, PlaDyPos was never lost and BUDDY was consistently managing to position itself in front of the PlaDyPos. There wasn't a single human intervention to correct BUDDY's behaviour.

Human diver experiment

In the experiment with the human diver, BUDDY was station keeping and a diver was freely diving in the approximate area of sonar's field of view, at a distance between 1m and 10m. The diver did not have a modem mounted, so the only validation was done subjectively. The tracking proved to work well in case there were no other object of similar size and shape in the image.

4.3.2 "buddy pointer" experiment – virtual diver

The experiments utilized the Buddy vehicle and a simulated diver position. The goal of the experiment is to analyse the stability and basic performance of the algorithm operating on the target vehicle. Other influences on the performance, such as acoustic channel quality, diver behaviour and image processing for diver tracking; are excluded in this way. The tracking performance, rather than diver guidance, was of interest during the experiments.

Experiments were split into three groups:

- approach phase – Buddy approaches a static diver

- rotating diver – Buddy positions itself in front of a diver which rotates in place
- dynamic diver – Buddy positions itself in front of a freely moving diver

I. Approach phase

The first phase is designed so that Buddy is positioned at a certain distance away from the diver and the diver is facing away from Buddy. This forces Buddy to converge towards the furthest point of the safety circle. The experiment was carried out for approximately 10, 15, 20 and 25 meter distances that were available in the pool. The traced-out path of Buddy during the approach can be seen in Fig. 4.13. The absolute distance to the diver and the path distance are shown in Fig. 4.12. Observe that the vehicle approaches similarly independently of the distance. Depending on the approach vector either a left or a right takeover is done by Buddy. The overshoot occurs only during the 15m approach and does not seem repeatable concluding that it is a result of a navigation problem or influence of the vehicle debug tether. The distance keeping quality is shown in Fig. 4.14. The distance was observed from the point the vehicle enters for the first time the +/-2.5% region around the ideal distance. It can be observed that there is up to +/- 0.4 m variance in the distance keeping relative to the diver. This is 10% of the desired radius but is larger than expected. Improving the navigation filtering and vehicle sway dynamic model should reduce the variance.

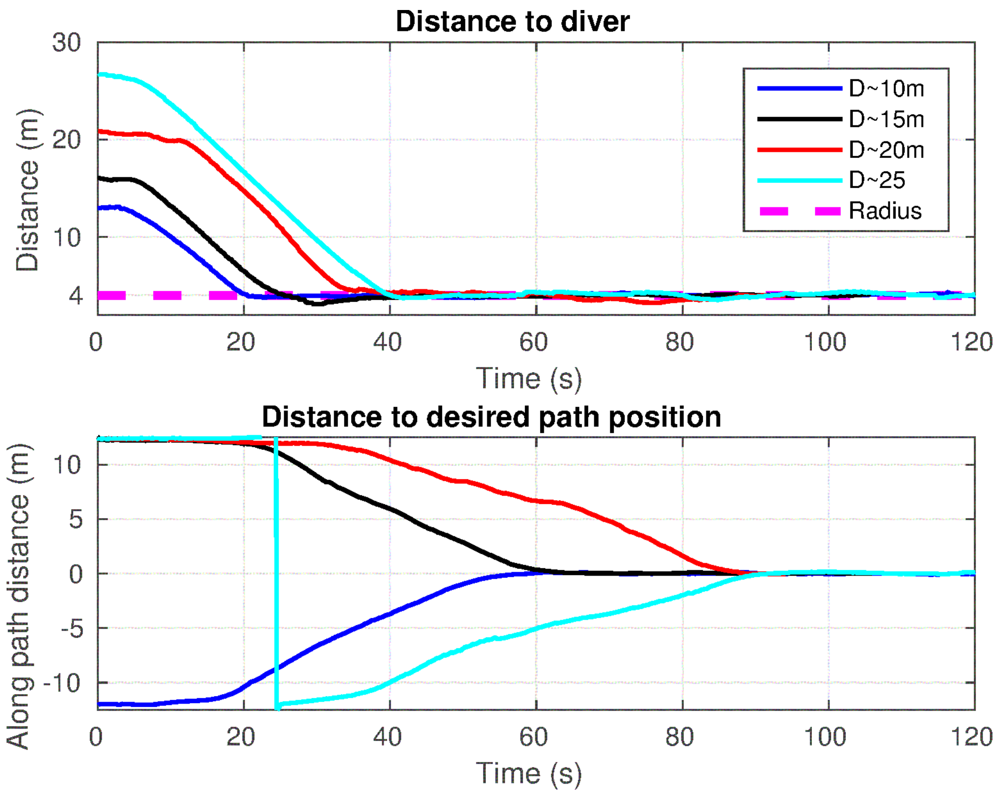


Fig. 4.12. The real distance to the diver and the path distance

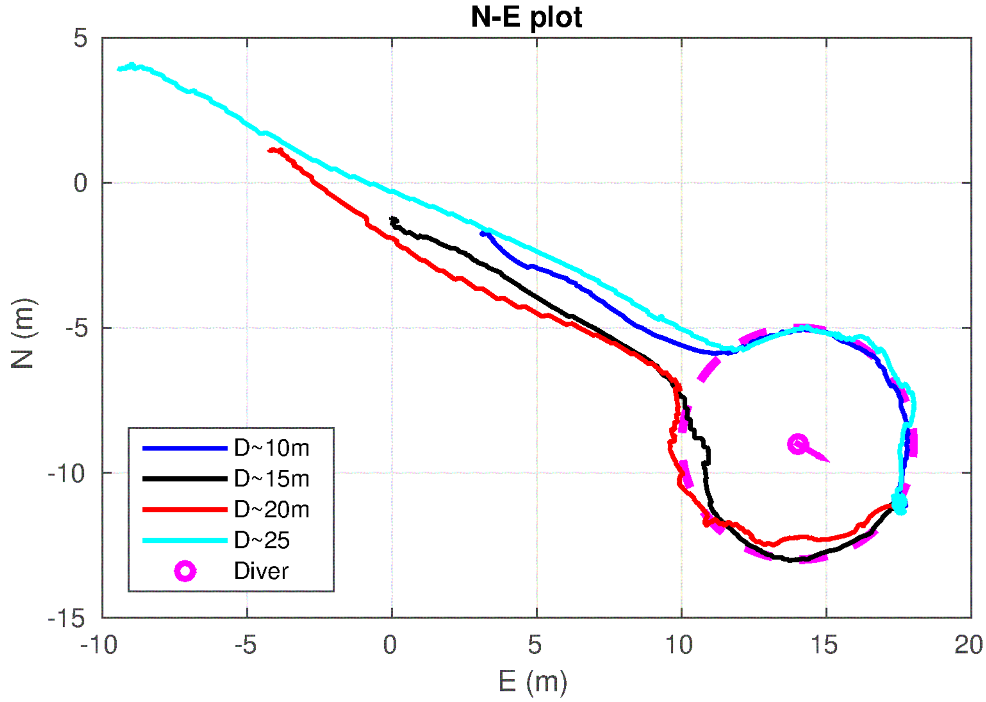


Fig. 4.13. The Buddy position during approaches

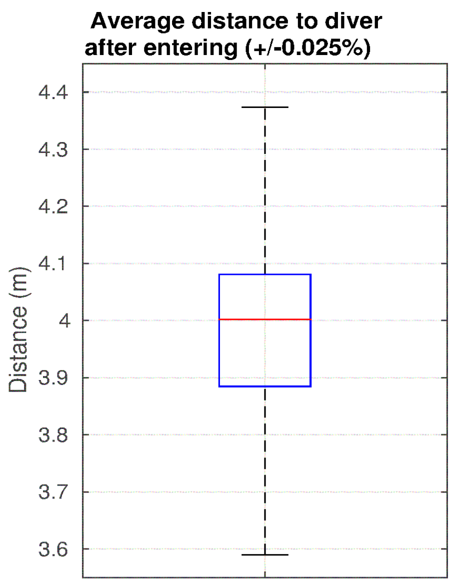


Fig. 4.14. The distance to diver statistics after stabilization to path

II. Rotating diver

The rotating virtual diver experiment is designed to estimate the convergence speed of the algorithm in case the diver orientation is changed rapidly. Faster convergence is desired in order to ensure optimal monitoring; however, the vehicle sway speed and the safety distance represent a limiting factor. During transitions the distance keeping statics is shown in Fig 4.15. Through the experiment the average distance remains within +/- 0.15m bounds of the ideal safety radius. The along path error during each transition is shown in Fig. 4.16. The diver rotation steps were 15°, 30°, 45° and 90°. The average for each transition is shown in a full line while individual transitions are indicated with dashed lines. It can be seen that the transition time increases with the turn step. Additionally increasing gains can improve performance but care has to be taken not to indirectly increase the distance keeping error.

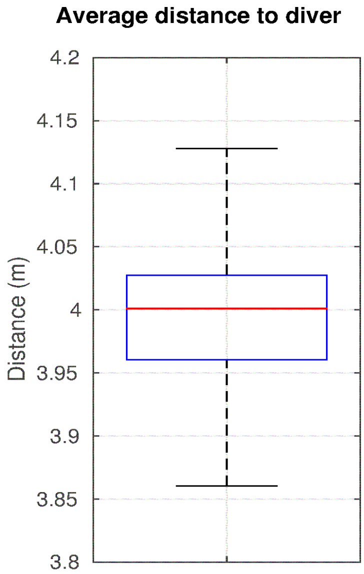


Fig. 4.15. The distance to diver statistics during transitions

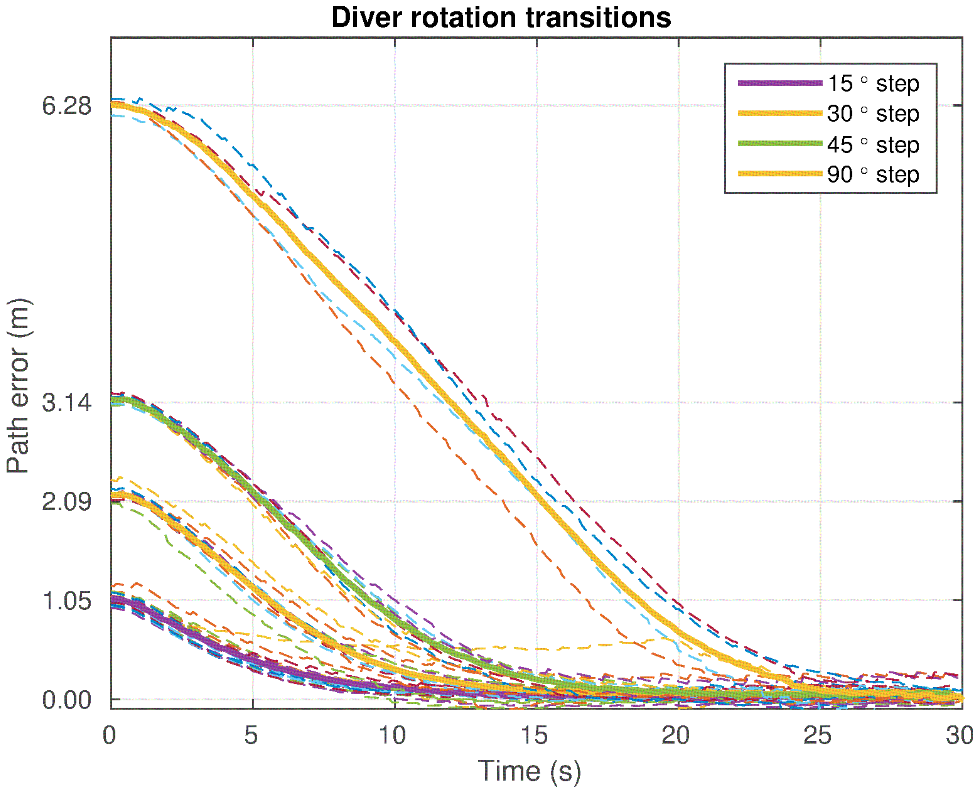


Fig. 4.16. The path error during transitions

III. Dynamic diver

Movement of the virtual diver is simulated with a zigzag manoeuvre indicated in Fig. 4.17. where two repeated experiments are shown. The virtual diver moves with 0.2 m/s and the safety radius for the vehicle is 4m; same as in experiments before. After the zigzag movement the diver turns 180° and continues down a straight path to display the Buddy overtaking manoeuvre. However, due to limited sway speed the Buddy vehicle does not completely overtake the diver before entering the safety perimeter of other vehicles operating in the region. The last part of the mission, overtaking, was stopped in both cases due to collision avoidance. Finally, the distance to diver statistics is shown in Fig. 4.18. The distance keeping variance is increased to around +/-0.7m when introducing the diver movement as an additional factor.

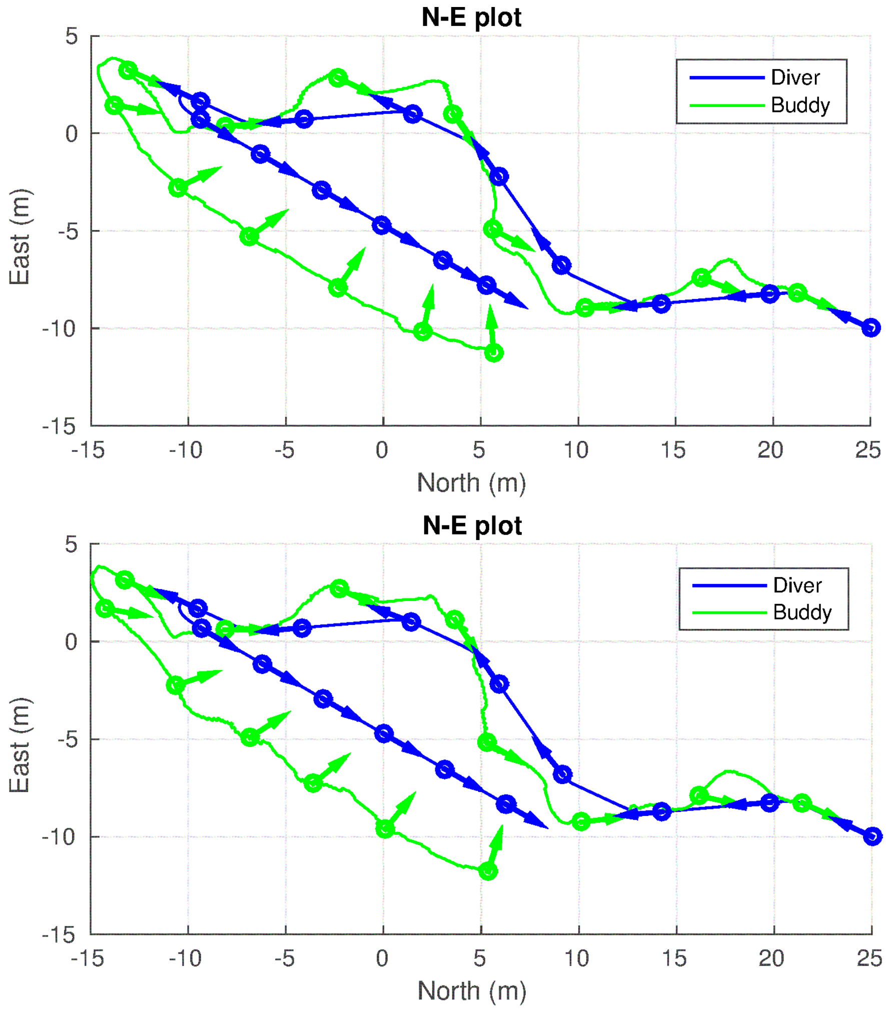


Fig. 4.17. North-East plot of diver tracking

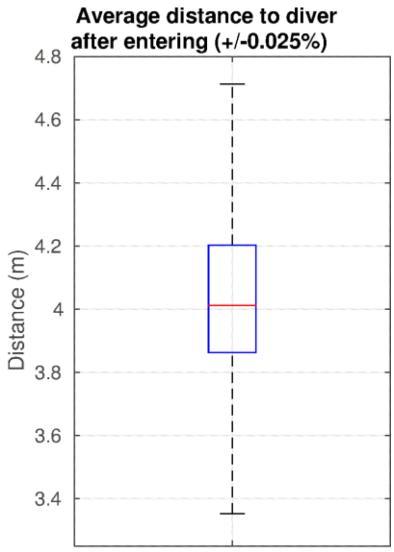


Fig. 4.18. Tracking error analysis

4.3.3 "buddy pointer" experiment – ROV is diver (acoustic comms)

The virtual diver experiments validated the basic operations of the "buddy pointer" algorithm. The next step was incorporating a real vehicle instead of the diver. Initial plans were to use a human operated ROV but due to technical difficulties the ROV was replaced with the surface platform, PlaDyPos. Parallel operations in the area already using acoustic communication made use of acoustic communication unpractical. The diver heading data was replaced with a UDP simulated link from the surface platform and the acoustic localization of the diver utilized only sonar image processing. Initial acquisition of the surface platform in the sonar image was aided by the operator.

The experiment has the same three phases as with the virtual diver.

I. Approach phase

However, due to unavailability of the USBL device the approach phase was not tested as the maximum practical range of the sonar is less than 15 m.

II. Diver approach

The diver rotation phase was carried out with two tests for 15°, 30°, 45° and 90°. The results are shown in Fig. 4.19. The dynamics is as expected from the results with the virtual diver. The only difference is that the heading of the surface platform changes continuously, rather than instantaneously. Notice that tracking noise is increased compared to the virtual diver. This is due to noise of the surface vehicle compass and delay between the measurement transmissions.

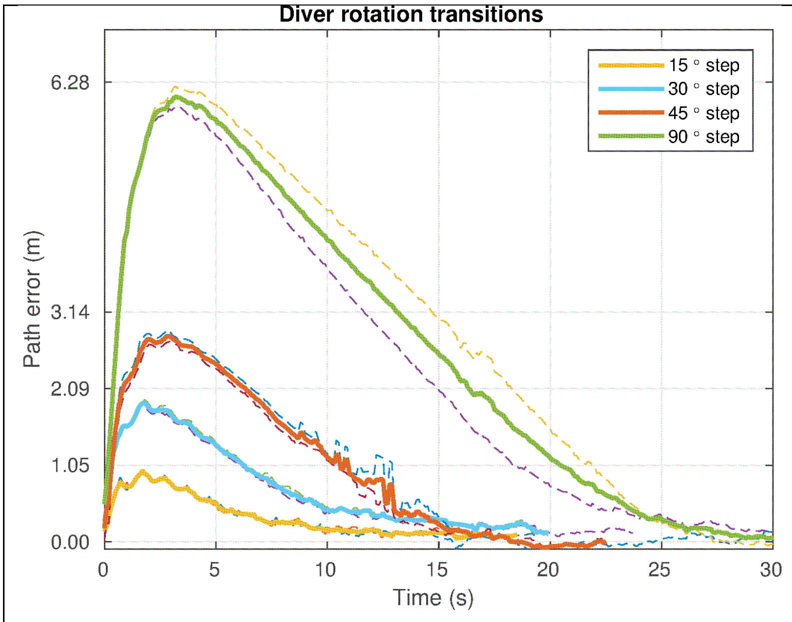


Fig. 4.19. Tracking error analysis

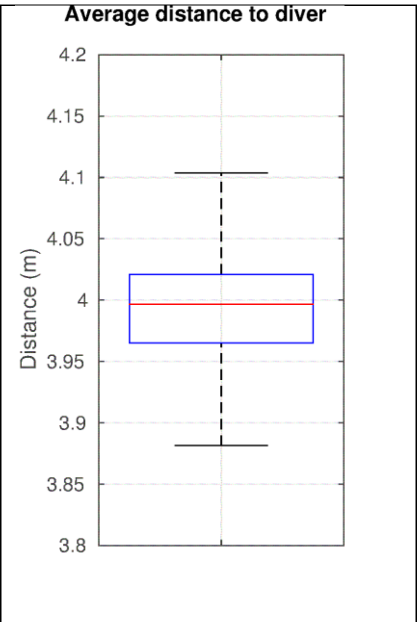


Fig. 4.20. Tracking error analysis during transitions

III. Dynamic diver

The tracking analysis was carried out over a 25 min session where the surface vehicle, emulating the diver, was under manual operation traversing random trajectories which included instant direction reversal, abrupt orientation changes surge and sway movements towards and away from the Buddy AUV. Fig. 4.21. shows an overtaking example where the operator reverses the course of the surface vehicle. Observe that Buddy is keeping distance and orientation from the diver during the overtaking manoeuvre. The distance to diver variation, taken for the whole session in duration of 25 min, is shown in Fig. 4.22. The spread increased up to almost +/-1 meter, indicating the uncertainty around +/-0.3m is introduced by the sonar image processing and detection algorithms. Note that the emulated diver speed was not used during this trial. The lack of exact feed-forward introduces a static error during tracking due to the proportional nature of the controller. This explains the median offset from the ideal safety radius and somewhat larger spread towards the smaller distances.

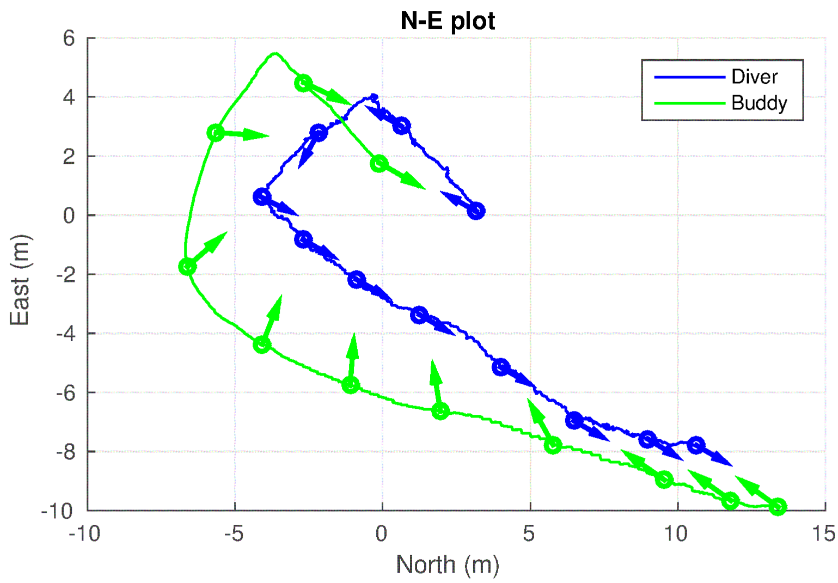


Fig. 4.21. Buddy overtaking surface platform during turns

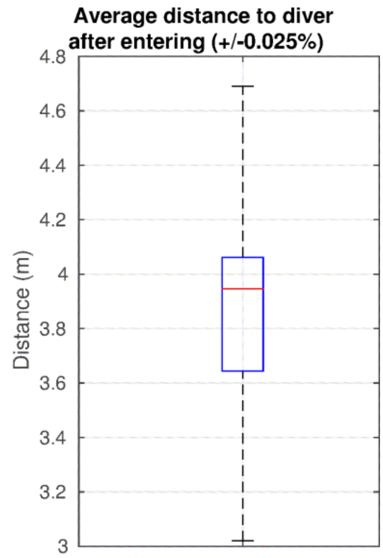


Fig. 4.22. Tracking error analysis during the whole experiment (T=25min)

4.4 To-do list

While virtual diver experiments validated the correct algorithm behaviour, one additional step has to be performed in order to demonstrate the guidance capability of the pointer experiment. Remaining steps require introduction of acoustic communication and localization during the diver emulation with an underwater vehicle. Underwater operation requires the surface agent to be included in the control scheme to provide correct absolute position updates to BUDDY. Underwater execution of the three phase experiment is required to complement the surface experiments. Fully functioning ROV with video is required for this experiment with basic navigation capabilities and acoustic modem. Finally, the experiments with the real diver have to be completed successfully to validate real-life operation. To sum up the following experiments need to be performed:

1. Virtual diver behaviour with a pre-set target for guidance capability demonstration
2. Underwater operation of BUDDY+ROV with a surface platform for absolute localization (the ROV has the same behaviour as the virtual diver)
3. Human operated ROV moving along and guided to target by BUDDY (using ROV video)
4. Human diver replicates experiments performed by virtual diver and ROV

Additionally, the technical problem of compass calibration differences needs to be addressed either by offset calibration through 360°, joint calibration of compasses using other means. Experiments with the surface platform acting as the diving buddy will not be performed as surface operation with BUDDY achieves the same goal.

5 Experiment 4: Maximizing system observability by using extremum seeking

5.1 Description of experiment

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 underwater vehicle navigation filter.

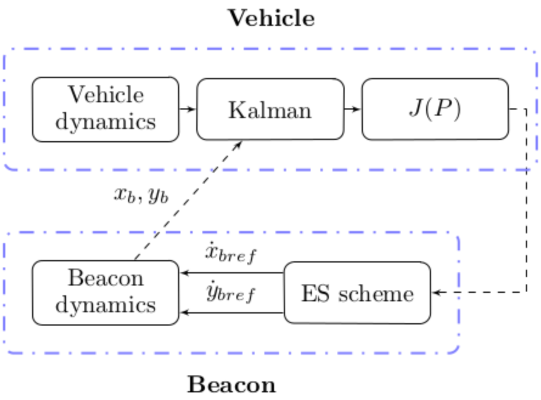


Fig. 5.1.

Fig. 5.1. 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. It is important to note that in this initial experiments all the calculations are performed onboard the beacon vehicle, and only range is measured using acoustic modems, meaning there is no data exchange through acoustic channel.

Since better observability is achieved when beacon vehicle is sufficiently close to underwater vehicle in horizontal plane, algorithm has a positive side effect that it also enables beacon vehicle to track underwater vehicle. Fig. 5.2. depicts first test scenario where underwater vehicle is virtual, and range measurements used to calculate cost function are simulated. It is clearly visible that we have a part where beacon vehicle approaches underwater vehicle while vehicle is static, and a second part of test where underwater vehicle is following straight line trajectory.

Fig. 5.3. depicts the same scenario with the difference that range measurements acquired through acoustic communication are used. It is important to note that such measurements are delayed.

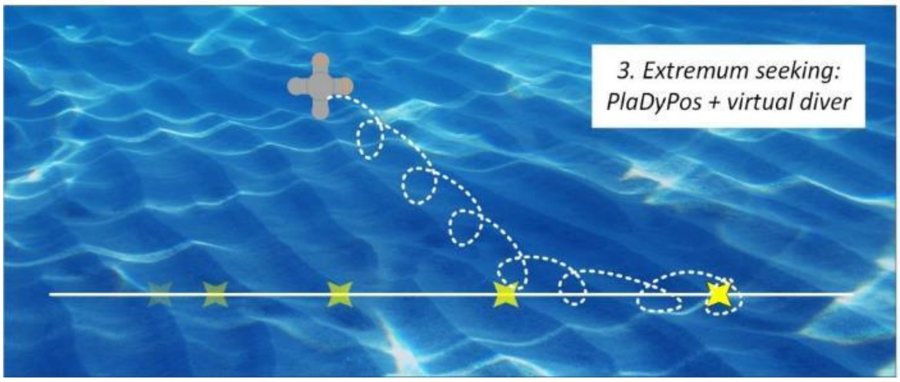


Fig. 5.2. Virtual underwater target.

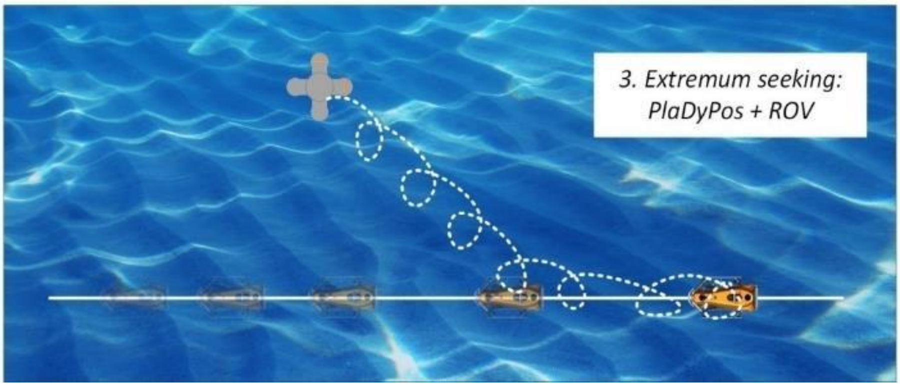


Fig. 5.3. Buddy as underwater target.

5.2 Validation procedure

5.2.1 virtual underwater target, PlaDyPos as beacon vehicle

Validation procedure:	Validation output:	Result:
4.1. Virtual target underwater is static, PlaDyPos tracks the target using the new ES method, range measurements simulated	PlaDyPos converges towards the virtual target	Pladypos successfully converges to virtual static target. Cost function is decreasing towards minimum
4.2. Virtual target underwater is moving along a straight line, PlaDyPos tracks the target using the new ES method, range measurements simulated	PlaDyPos converges towards the virtual target	Not tested due to time constraints imposed by bad weather

5.2.2 BUDDY underwater, PlaDyPos as beacon vehicle

Validation procedure:	Validation output:	Result:
4.3. PlaDyPos converges towards static BUDDY (underwater) using the new ES method, range measurements obtained via acoustic link	PlaDyPos converges towards BUDDY	Pladypos successfully converges to position above Buddy vehicle. Cost function is decreasing towards minimum
4.4. PlaDyPos converges towards BUDDY (underwater) moving along a straight line, using the new ES method, range measurements obtained via acoustic link	PlaDyPos converges towards BUDDY	Pladypos successfully converges to position above BUDDY. Cost function is decreasing towards minimum

5.3 Results

In this section results for experiments 4.2 where virtual underwater target was used and experiments 4.3 and 4.4 where Buddy vehicle was used as underwater vehicle are shown.

Figures 5.4., 5.5., 5.6., 5.7. represent results of experiment 4.1. Label “Beacon” denotes beacon vehicle trajectory, while Label “Single range” denotes underwater vehicle position estimate given by the extremely simple relative distance navigation filter whose covariance matrix P is also used for calculating observability cost shown in Fig. 5.7. It is visible that proposed algorithm steers the cost towards its minimum and beacon vehicle towards circular trajectory around the vehicle. Such trajectory is known to have good observability properties when using single range measurements. In the end of the test, around 1100 seconds mark, algorithm was stopped in order to show how cost function grows unbounded when algorithm is not active.

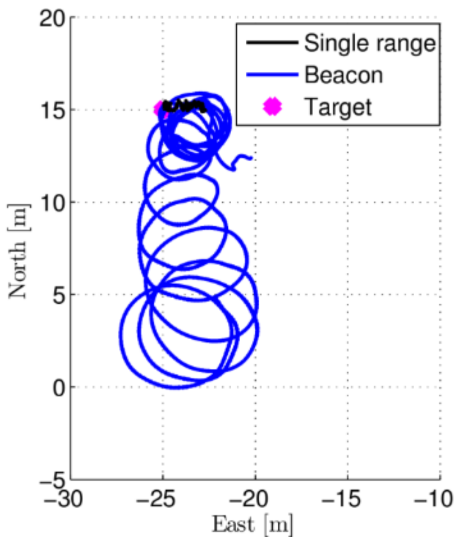


Fig. 5.4. Beacon and vehicle trajectories for experiment 4.1.

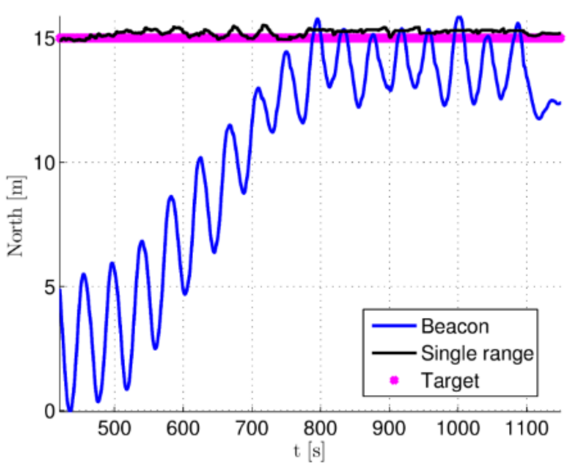


Fig. 5.5. North coordinate for experiment 4.1.

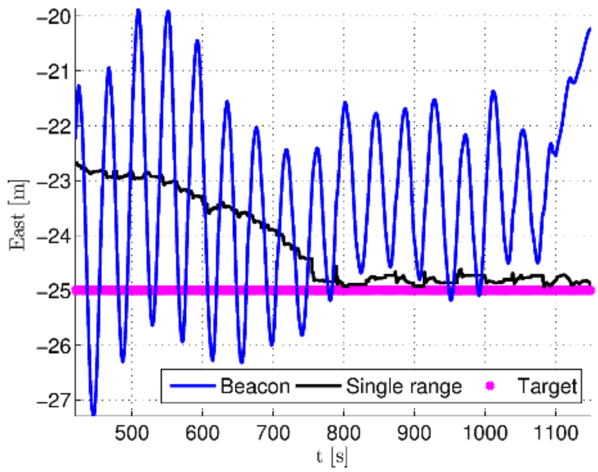


Fig. 5.6. East coordinate for experiment 4.1.

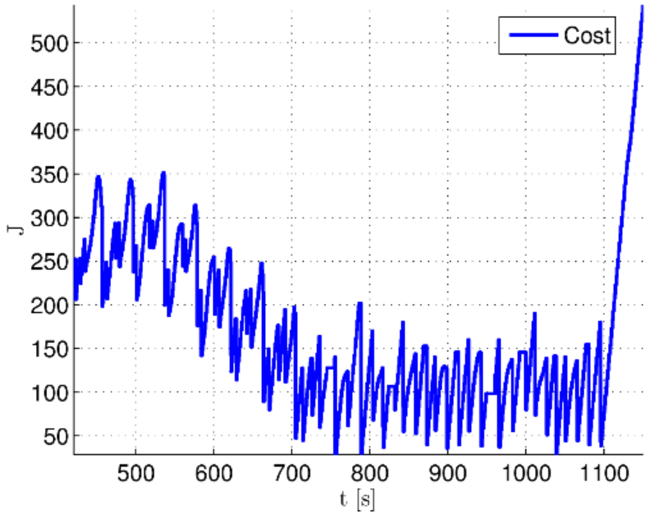


Fig. 5.7. Cost value for experiment 4.1.

Next, results for experiments 4.3 and 4.4 where Buddy vehicle was used as underwater vehicle are shown. Fig. 5.8. shows underwater vehicle and beacon trajectories for experiment 4.3. In conducted experiments USBL measurements were used as ground truth, while "Single range" label denotes underwater vehicle position estimate given by the simple relative distance navigation filter. Observability cost calculated from covariance matrix P is shown in Fig. 5.11. It is visible that even in case of delayed acoustic measurements proposed algorithm steers the cost towards its minimum and beacon vehicle towards circular trajectory around the vehicle.

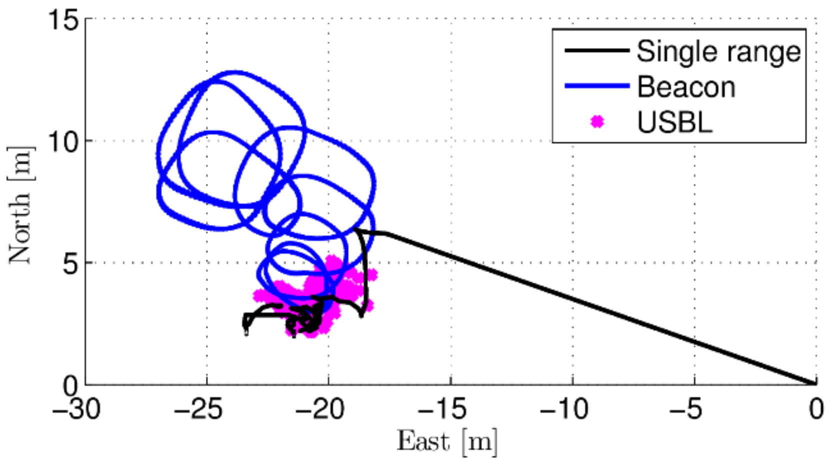


Fig. 5.8. Beacon and vehicle trajectories for experiment 4.3.

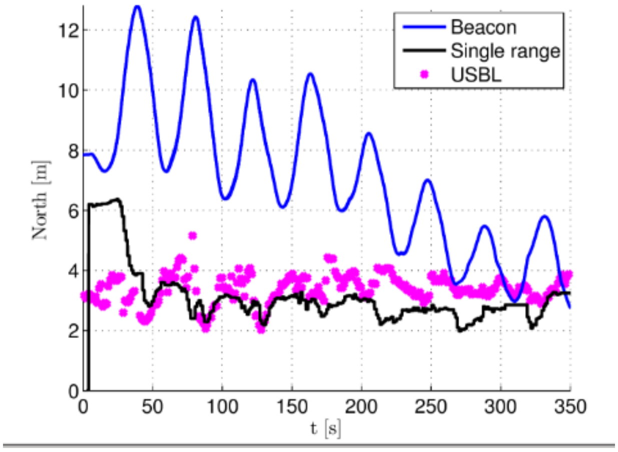


Fig. 5.9. North coordinate for experiment 4.3.

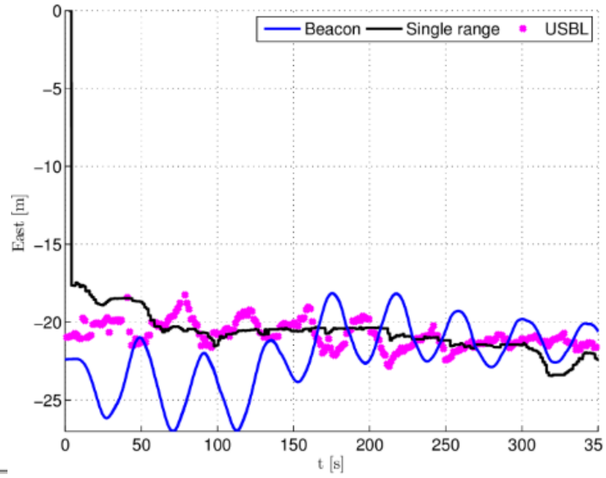


Fig. 5.10. East coordinate for experiment 4.3.

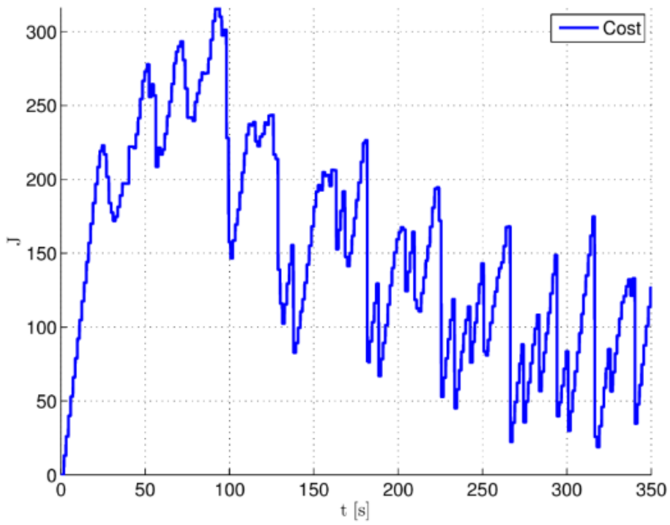


Fig. 5.11. Cost value for experiment 4.3.

Figure 5.8. shows underwater vehicle and beacon trajectories for experiment 4.4. where underwater vehicle executes straight line trajectory. Looking at observability cost shown in Fig. 5.15. it is clear that cost value is bounded thanks to algorithm acting on beacon vehicle. As expected beacon vehicle moves along the underwater vehicle trajectory while simultaneously circulating in order to ensure good observability.

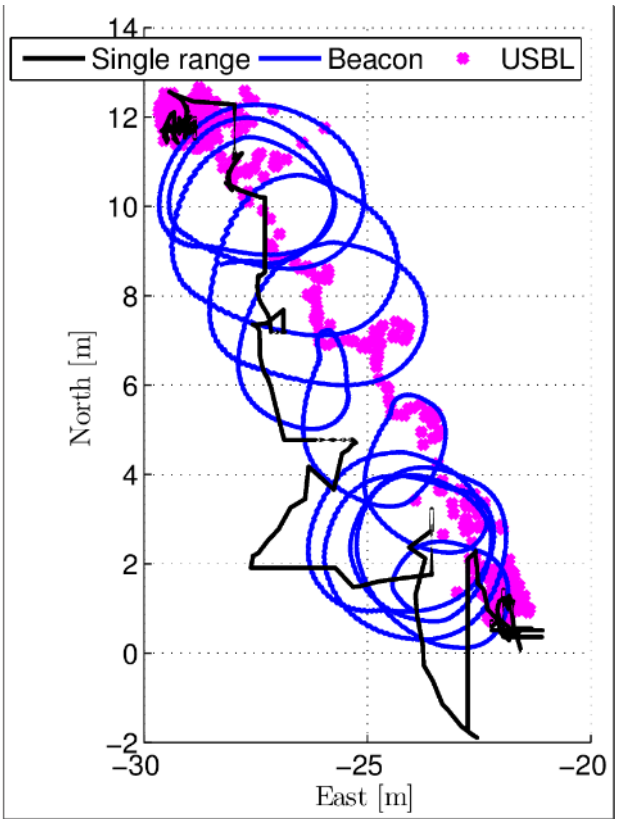


Fig. 5.12. Beacon and vehicle trajectories for experiment 4.4.

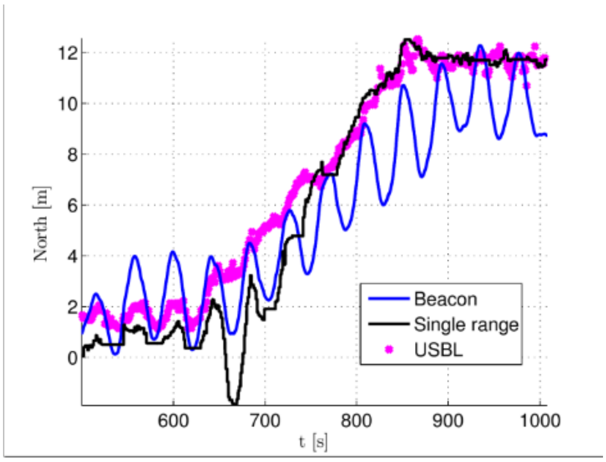


Fig. 5.13. North coordinate for experiment 4.4.

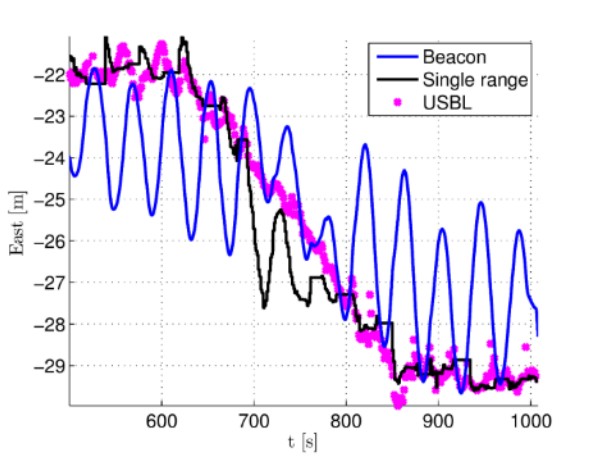


Fig. 5.14. East coordinate for experiment 4.4.

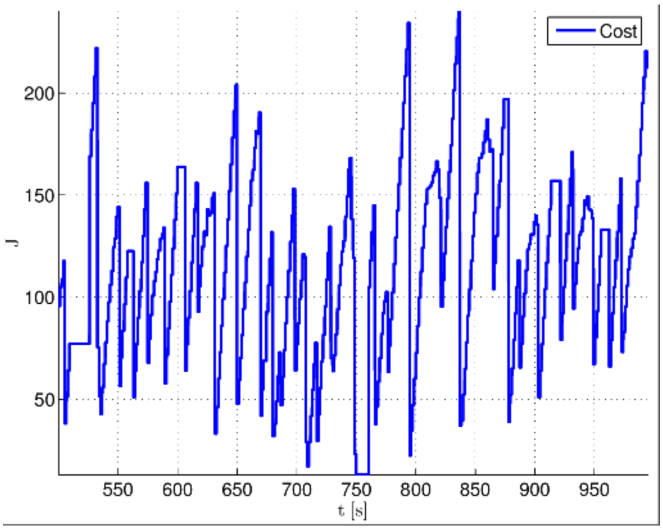


Fig. 5.15. Cost value for experiment 4.4

5.4 To-do list

Since these were preliminary tests, conducted in order to show feasibility of proposed approach, there are further steps to be done.

- Implement further adjustments to the algorithm.
- Test complete scheme with communication cycle included as depicted in Fig. 5.1.
- Compare efficiency of approach by comparing localization accuracy achieved by proposed approach, with the case of static beacon, beacon executing circular trajectory etc.

6 Experiment 5

6.1 Description of experiment

The fifth experiment is envisioned to demonstrate the buddy "observer" functionality of the CADDY concept, by using DiverNet.

Main task of the experiment:

Diver is underwater with DiverNet. Diver flipper rate and breathing rate are calculated on the underwater tablet and transmitted via acoustic link to the surface. In case of high flipper/breathing rate detection, the surface is alarmed. The ultimate goal is to be able to playback diver position, posture and breathing parameters.

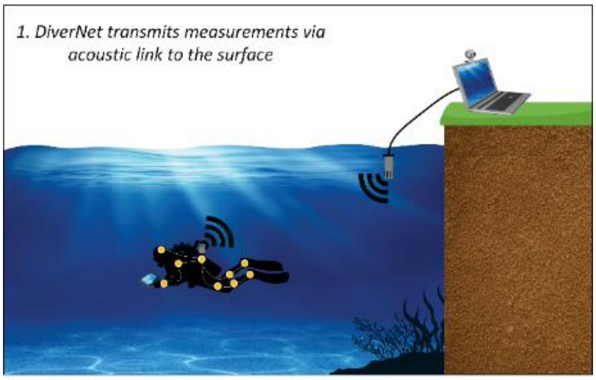


Fig. 6.1.

Vehicles:

In this experiment, DiverNet and USBL is used.

Experiment subtasks:

- **determine and transmit diver flipper frequency**

With DiverNet mounted on the diver, flipper rate is determined. Measurements are transmitted via Bluetooth to the underwater tablet where all the processing is performed. High level information (such as alarms and/or calculated rates) are transmitted to the surface via acoustic link. The subtask is performed in the following experimental steps

- diver paddling without flippers at the surface, in a frequency set by the metronome
- diver paddling with flippers at the surface, in a frequency set by the metronome
- diver paddling without flippers underwater, in a frequency set by the metronome
- diver swimming in a slow/fast rate in the swimming pool

- **determine and transmit diver breathing frequency**

Two options will be examined. Additional data will be collected using breathing belt and data using hydrophone to measure breathing rate will be collected. For the hydrophone experiments, the subtask is performed in the following experimental steps

- diver breathing underwater in a frequency set by the metronome
- diver swimming in a slow/fast rate in the swimming pool

6.2 Validation procedure

6.2.1 DiverNet experiments – dry tests with tethered DiverNet

Diver is underwater with DiverNet and breathing belt, tethered to the surface. The following data is processed on the tablet and acoustically sent to the surface every 5 s: breathing rate (calculated based on last 5 s of data), status based on breathing rate, speed of flippers.

Validation procedure:	Validation output:	Result:
5.1. Diver on dry land with tethered DiverNet, NO flippers, paddles in defined set of frequencies (slow to fast)	Obtained paddling frequency corresponds to the metronome frequency	COMPLETED Raw data captured at ‘flipper rates’ of 0.4, 0.8, 1.2 and 2.4Hz via tethered Divernet. Paddle rate extracted through frequency domain analysis in Matlab.
5.2. Diver on dry land with tethered DiverNet, WITH flippers, paddles in defined set of frequencies (slow to fast)	Obtained paddling frequency corresponds to the metronome frequency	COMPLETED Raw data captured at rates of 0.4, 0.8 and 1.2Hz on dry land with flippers. No degradation observed in paddle rate detection.
5.3. Diver on dry land with tethered DiverNet, breathing in a defined set of frequencies (slow to fast), breathing recorded via breathing belt	Obtained paddling frequency corresponds to the metronome frequency	NOT COMPLETED Using the belt it was impossible to isolate the divers breathing rate from other muscle movements (e.g. swimming). The breathing belt was therefore deemed unsuitable for future experimentation.

6.2.2 DiverNet experiments – wet tests, acoustic transmission of measurements

In this set of experiments, DiverNet is connected via BlueTooth to underwater tablet, while the tablet transmits the data to the surface via acoustic link. All the processing is performed on the tablet and the calculated frequency is transmitted to the surface.

Validation procedure:	Validation output:	Result:
5.4. Diver with feet in water, WITH flippers, paddles in defined set of frequencies (slow to fast), data processed on tablet and frequency	Obtained paddling frequency corresponds to the metronome frequency; package dropout rate	COMPLETED Integration of tablet, DiverNet and modems was completed. Frequency domain analysis was migrated to the tablet allowing flipper rate to be extracted in real-

of paddling acoustically transmitted to surface		time. Flipper rate was successfully transmitted to the surface terminal at a rate of approximately 0.5Hz. Minimal packet dropouts were observed in a highly reverberant communication channel
5.5. Diver breathing at different rates while breathing is recorded using a hydrophone and breathing rate is transmitted acoustically.	Obtained breathing frequency corresponds to the metronome frequency; package dropout rate	PARTIALLY COMPLETED Breathing data for different rates was collected using a hydrophone and post processed offline. Analysis was also performed in cases where interference from modem traffic was observed. In this scenario, with the current configuration, difficulty in detecting the inhalation of the diver was observed.
5.6. Diver in water, simulates using one of the flippers	detect loss of flipper by detecting different paddling frequencies	COMPLETED Disconnection of the IMU sensor from one of the legs was used to simulate the loss of a flipper. The system was able to detect the variation in rate between the two flippers.
5.7. Diver fully in water, swims slow and fast across the pool, data transmitted to the surface acoustically	Obtained paddling frequency corresponds to “slow” and “fast swimming”; package dropout rate	COMPLETED Flipper rate was observed at the surface in real-time while the diver swam multiple lengths of the 50m pool at different speeds: ‘steady’, ‘fast’ and ‘sprint’.

6.3 Results

6.3.1 DiverNet experiments – dry tests with tethered DiverNet

The first set of experiments were performed using the tethered DiverNet. Raw data from the IMU sensors was recorded and processed Matlab. Algorithms to detect the paddle rate of the diver were tested offline prior to their integration on the tablet. The following procedures demonstrate the performance of the algorithm in controlled scenarios (e.g. with timed / measured paddle rates).

- **Validation procedure 5.1. Diver on dry land with tethered DiverNet, NO flippers, paddles in defined set of frequencies (slow to fast)**

For all experiments during which the diver paddles with IMU sensors attached to his feet (with or without flippers), raw data processing was done using the following steps:

1 – Read x, y, z axis acceleration from sensor
2 – Remove DC drift using a recursive average method
3 – Use simple numerical integration method to calculate velocity
4 – Calculate FFT for basic frequency fs=10Hz with a widow length of 128 samples
5 – Set FFT bins 0 and 1 to zero and extract maximum energy bin from the remainder
6 – Calculate corresponding frequency in Hertz from retrieved bin

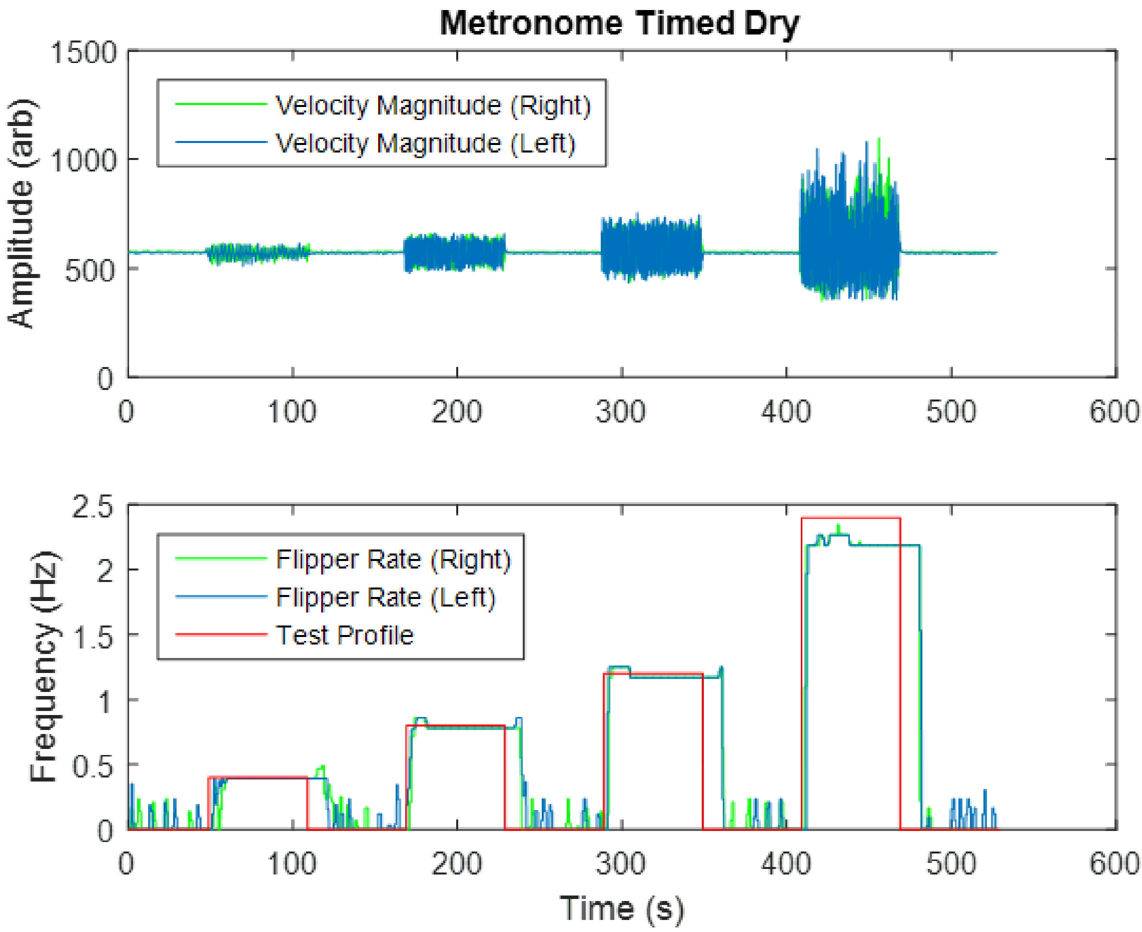


Fig. 6.2. Raw data from dry land experiment (top); Extracted flipper rate compared to metronome-timed test profile (bottom).

Fig. 6.2. shows the result of the diver's timed paddling in 60-second windows of activity over four chosen testing frequencies. There is a noticeable delay difference between rising response time (from 0 Hz to test frequency levels) and falling response time (from test frequency levels to 0 Hz). This behaviour is expected due to the relatively large length of the FFT window (and subsequently large number of required samples the system is buffering) and the ignoring of the low frequency bins. The presence of jitter during rest periods is also notable, but could easily be filtered out using standard noise removal and thresholding methods.

- **Validation procedure 5.2. Diver on dry land with tethered DiverNet, WITH flippers, paddles in defined set of frequencies (slow to fast)**

As mentioned above, data processing for tests done with IMU sensors attached directly to the diver's feet and attached to the diver's flippers was done using the same procedure.

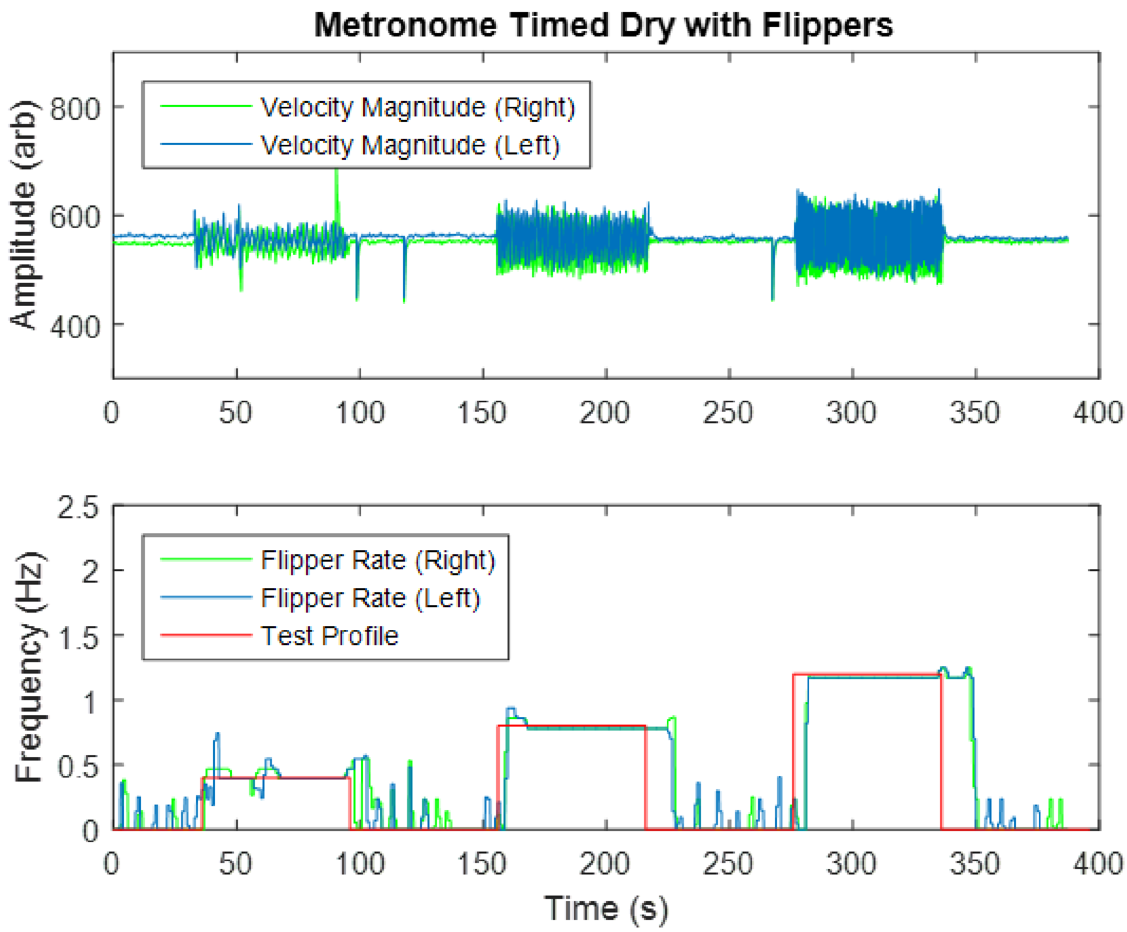


Fig. 6.3. Raw data from dry land experiment with sensors attached to flippers (top); Extracted flipper rate compared to metronome-timed test profile (bottom).

Fig. 6.3. shows the result of the diver's timed paddling using three testing frequencies. Results are consistent with ones from the experiments done without flippers, showing no significant degradation of performance and frequency detection quality, despite the sub-optimal mounting of sensors.

- **Validation procedure 5.3. Diver on dry land with tethered DiverNet, breathing in a defined set of frequencies (slow to fast), breathing recorded via breathing belt**

Initial monitoring of the breathing rate was performed using a modified Pneumotrace 2 breathing belt. Initially problems were observed with the reliability of the belt and modifications were made to the interface circuit and transducer element.

During further tests, the breathing belt was fitted around the chest of the diver and varying breathing rates were observed. It was immediately apparent that the belt had very low sensitivity to the divers breathing. Varying the position and tension of the belt was noticed to give a significant change in performance. Once an optimum position had been identified the test was repeated with the diver performing various upper body movements (e.g. replicating swimming / underwater movement). It was noted that the system had a much higher sensitivity to the diver's movements than to the breathing and that isolating the two variables would be impossible. It was also apparent that as the diver moved the position of the belt changed and the sensitivity to breathing degraded.

Although the system had been modified to try and enable its use underwater, it was agreed that any form of mechanical belt was unsuitable for this form of testing. The hardware was found to be easily damaged by shock movements and water ingress caused by the bending of the material. Additionally, the inherent sensitivity to body movement, made it unsuitable for this form of application where the diver would rarely be still. It was agreed that an alternative methods of measuring the divers breathing would be explored and that for the remainder of the trials focus would be given to extracting the paddle rate from the diver.

6.3.2 DiverNet experiments – wet tests, acoustic transmission of measurements

The following results, demonstrate the performance of the full system, encompassing the integration of the Divernet, modem and tablet (connected via the Bluetooth link). The results presented for procedures 5.4, 5.6 and 5.7 are the outputs from the surface terminal, collected remotely in real-time via the acoustic link. In this scenario, the proposed algorithm had been migrated to the tablet, allowing the raw data to be processed subsea. Continuous transmission of the processed paddle rates were achieved at upwards of 0.5Hz.

- **Validation procedure 5.4. Diver with feet in water, WITH flippers, paddles in defined set of frequencies (slow to fast), data processed on tablet and frequency of paddling acoustically transmitted to surface**

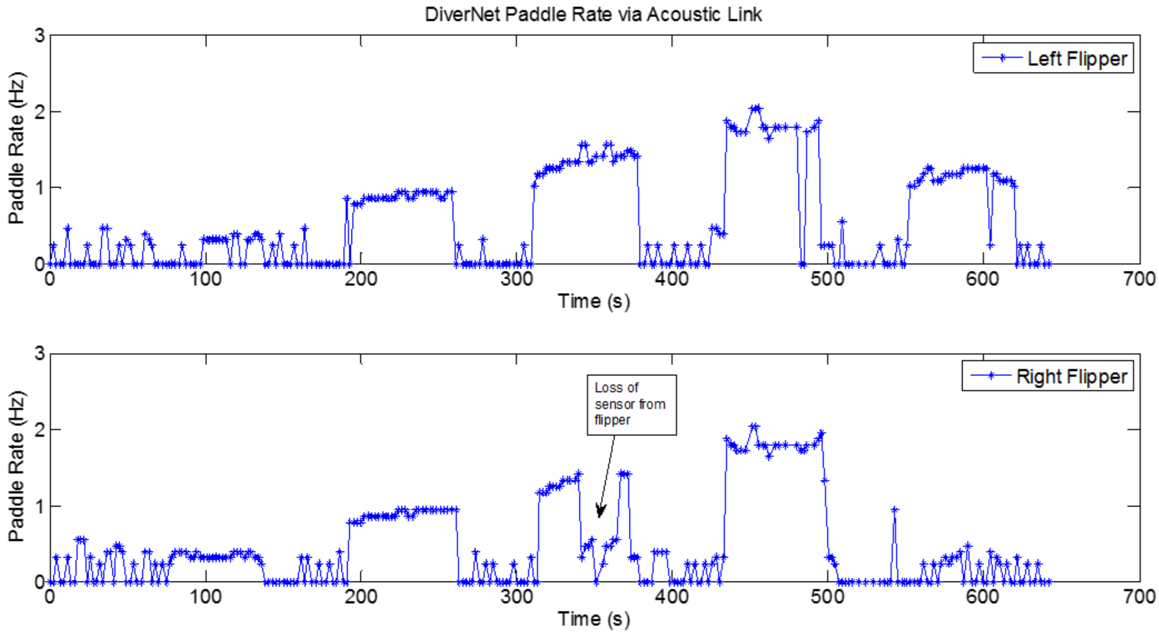


Fig. 6.4. Paddle rate frequency validation data from on-land experiment with diver's flippers in water, left flipper (top) and right flipper (bottom) shown separately.

Fig. 6.4. shows the paddle rate experiment results of on-land experiments during which the diver's feet and flippers, as well as the tablet doing data processing, were submerged in a small pool ("hot tub"). Of particular interest is the time window between 300 and 400 seconds, during which the IMU sensor fell off the diver's right flipper. This is clearly visible in the data output thanks to the still present but dampened physical link between the diver and the sensor, and will prove useful for further development of diver monitoring. Further corroborating this result is the end of the experiment (550 seconds and onward), during which the diver paddled at a fixed rate with the right flipper sensor once again detached.

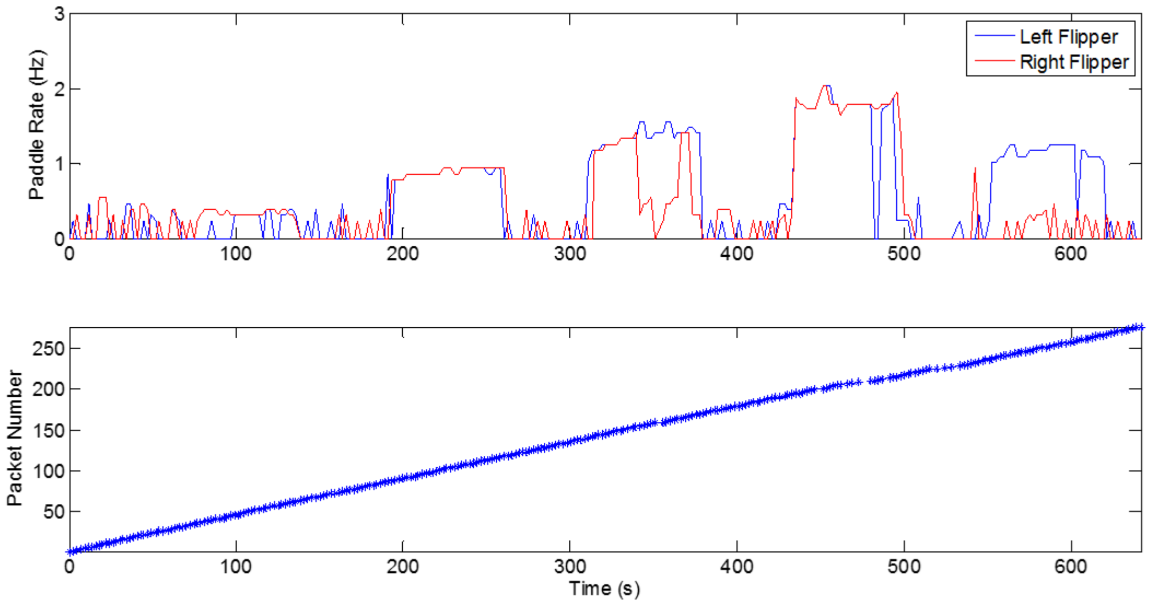


Fig. 6.5. Paddle rate frequency validation data from on-land experiment with diver's flippers in water (top) and acoustic packet reception plot (bottom).

Fig. 6.5. shows the reliability of the acoustic data transmission when it comes to packet loss. As can be seen, there are very few dropouts even in a highly unusual communication channel (a "hot tub").

- **Validation procedure 5.5. Diver breathing at different rates while breathing is recorded using a hydrophone and breathing rate is transmitted acoustically.**

Following on from procedure 5.3, it was agreed that an alternative method of identifying the breathing rate should be explored. Monitoring the acoustic emissions from the diver's regulator was proposed as a suitable none-intrusive method of detecting the inhale and exhale pattern. Using an off the shelf commercial hydrophone (Reson TC4032), the noise from the regulator was recorded for various breathing rates (timed by a metronome). During the recording, breathing rates of 30, 60 and 120 breathes per minute were captured over 1 minute periods, interleaved with 1 minute periods of 'normal' unregulated breathing.

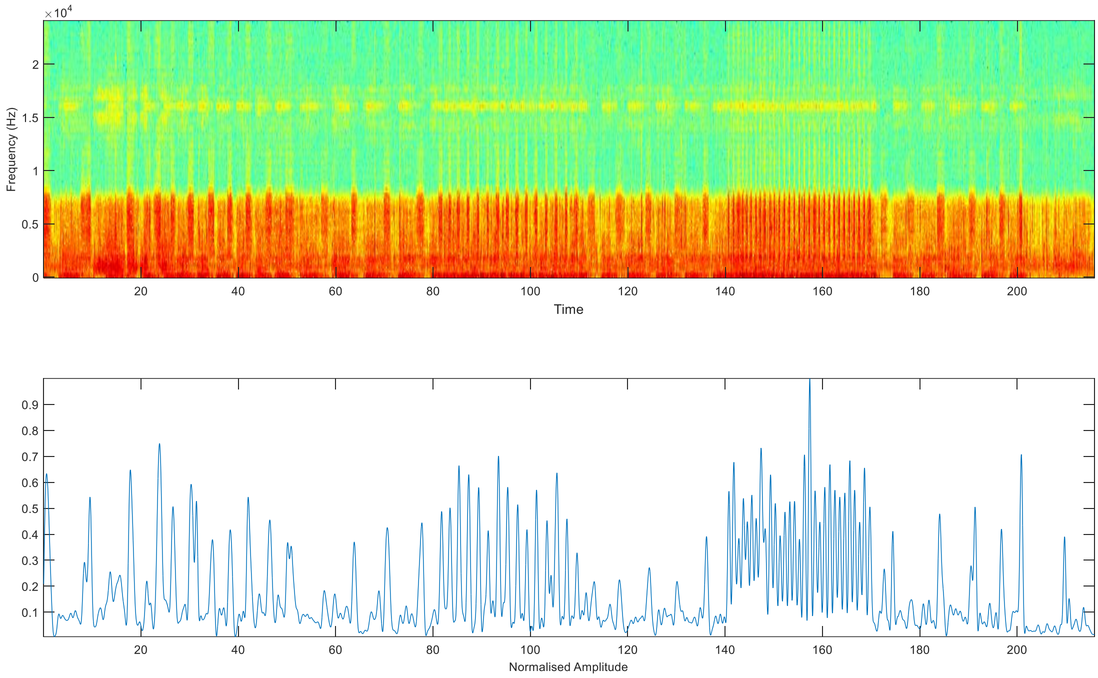


Fig. 6.6. Breathing rate detection through passive acoustic monitoring.

Fig. 6.6., shows the data for one recording. The first subplot presents the spectrum of the received acoustic signal. Several identifiable frequency components can be seen as the diver inhales and exhales, with significant contributions between 4kHz-8kHz and 15-17kHz. By filtering the received signal (bandpass 4-8kHz) and then passing it through an envelope detector the response of the respirator can be observed in the second subplot. The breathing rate can then be recovered with a threshold detector.

A second set of data was captured, examining the effects of the modem interference. In this scenario the modem was set to regularly send a ping transmission at 0.5Hz. In this case the acoustic output from the modem saturated the hydrophone pre-amps and minimal information, relating to the breathing rate of the diver, could be recovered. This problem could be resolved using a highly directional transducer, mounted onto the front of the respirator. Mechanical baffling would be used to isolate the transducer from the interference generated by the modem and tighter pre-amps would be used to isolate the breathing signature from the communication transmissions.

- **Validation procedure 5.6. Diver in water, simulates using one of the flippers**

Included in validation procedure 5.4.

- **Validation procedure 5.7. Diver fully in water, swims slow and fast across the pool, data transmitted to the surface acoustically**

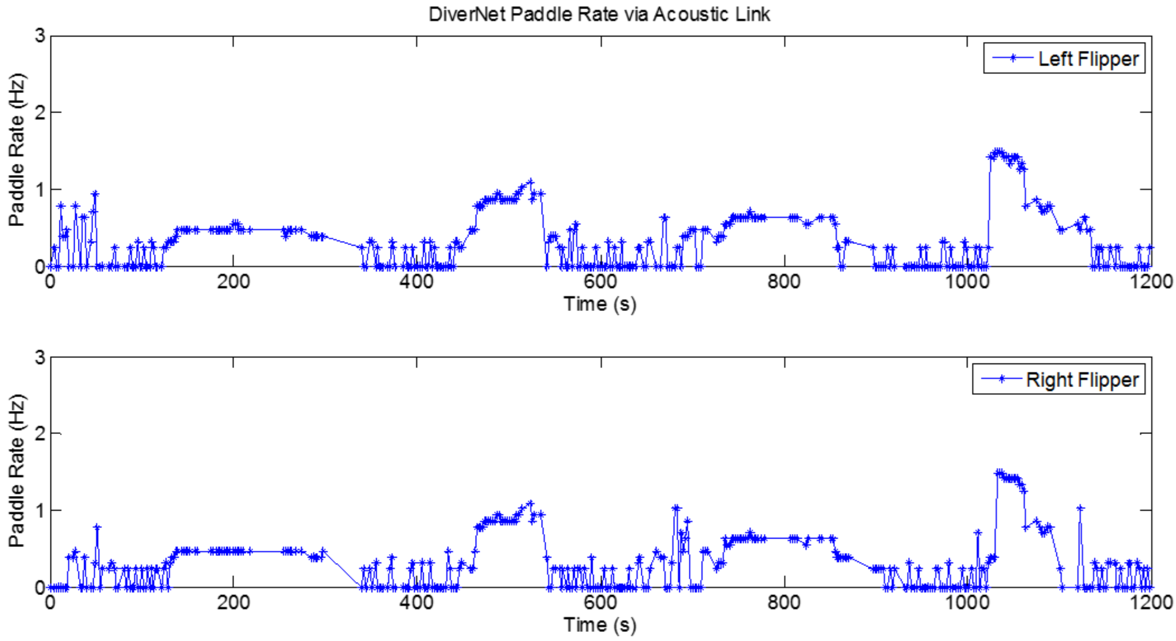


Fig. 6.7. Paddle rate frequency validation data from underwater experiment, left flipper (top) and right flipper (bottom) shown separately.

Fig. 6.7. shows the results of the more realistic underwater experiment. Base water-treading frequency is notably consistent, allowing for easier result analysis. An approximately double paddling rate seems to correspond to the halving of the time needed to swim a constant distance (in this case, the length of the pool). The activity window starting at around 1000 seconds shows the diver attempting to swim as quickly as possible, and the paddling rate clearly reflects him getting gradually tired during the run, which could prove beneficial for future diver health and safety monitoring.

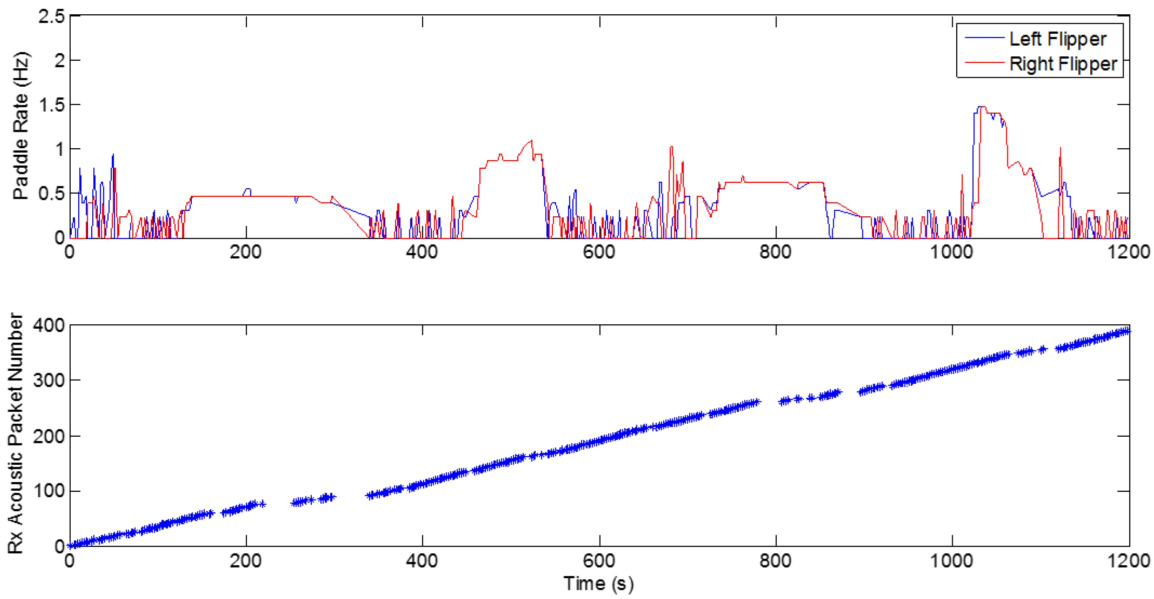


Fig. 6.8. Paddle rate frequency validation data from underwater (top) and acoustic packet reception plot (bottom).

Figure 6.8. shows the acoustic dropouts during the experiment. There is a marked increase in dropout rate on several occasions when compared to the on-land variant. Most notably, dropouts regularly occurred during transitions from the left hand side to the right hand side of the pool, which is likely caused by the positioning of the beacon on the diver's tank and possible brief shadowing during turning. Other occurrences can be seen during times when the diver surfaced but failed to remain on his back, thus allowing the beacon to exit the water and lose link with the shore station. Encouragingly, in case of link loss, communication is regained almost immediately upon the beacon once again becoming submerged. Packet dropout rates while the diver is actually underwater and swimming are consistently low.

6.4 To-do list

1. Implement a suitable method of collecting breathing data:

Two possible solutions have been identified and are currently being explored:

a) Construct a directional hydrophone (with mechanical baffling) and suitable signal conditioning circuitry. Mount hydrophone on regulator and ensure breathing pattern can be isolated from acoustic modem emissions. Test to see if inhalation can be detected accurately.
b) Interface the 'Nerites' unit (from Innovasub) into the DiverNet Hub, enabling real-time breathing patterns to be collected from a pressure sensor in-line with the BCD inflator.

2. Transmit the breathing rate through the acoustic link

3. Compare received parameters to a defined model / previous state for automated identification of divers 'state' (health and safety monitoring).

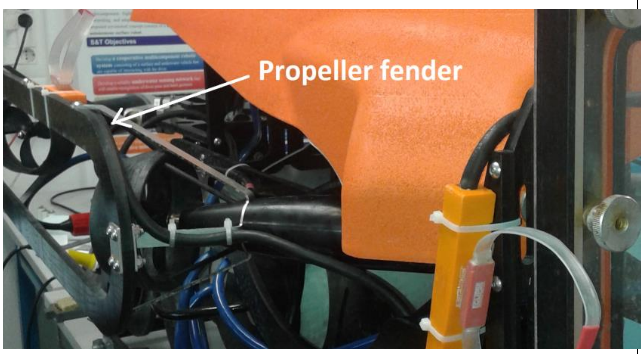
4. Utilise real world USBL position alongside paddle rate to identify efficiency of divers swimming: indicating the tiredness of the diver or tidal effect of the environment.

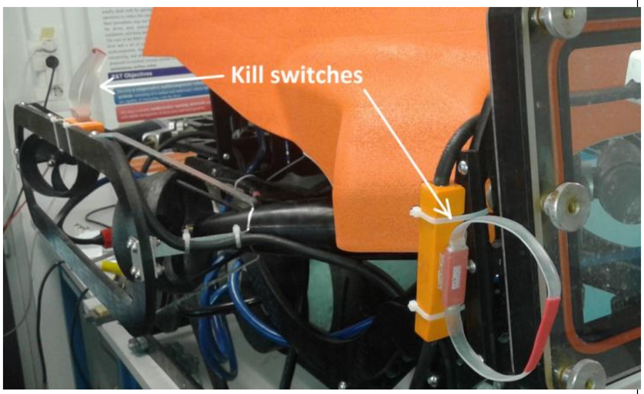
7 Validation Annexes

ANNEX A. CADDY Safety Validation Questionnaire

The purpose of this questionnaire was to assess the safety of CADDY autonomous vehicles. Vehicle compliance with each of the statements is indicated by placing an **x** in the appropriate box. Comment tab is filled out where necessary.

Vehicle: BUDDY AUV (UNIZG-FER)

No	Safety		yes	no	comment
1	Are the propellers of the AUV guarded in order to prevent injuries?		x		Propeller guard is not installed on the thruster itself, the fender is installed instead to disable the direct access to the propellers (see image below). 
2	Do acoustic devices installed on the vehicle (modem, Sonar, Doppler velocity log) meet the safety requirements from the D6.1.1.	Modem	x		According to requirements from D.6.1.1.
		Sonar	x		According to requirements from D.6.1.1. Sonar ARIS posses acoustic emission test certificate and approved permit to monitor protected and endangered species in the USA according to manufacturer.
		DVL	x		According to requirements from D.6.1.1.
3	Sound source with the frequency close to the human lung resonant frequency of 42 Hz is not used.		x		Yes, means that low frequency sound source is not used.

4	RECUV power supply is in compliance with IMCA code of practice.		x		The vehicle power supply is 46.8V DC battery. Vehicle is equipped with tripping device with a reaction time of less then 20ms. Consequently it is considered electricaly safe according to criteria set in D.5.1, D6.1.1 and "Code of Practice for The Safe Use of Electricity Under Water", IMCA document D 045, R 015, October 2010.
5	Activation of the kill switch stop the operation of the vehicle immediately.	Sw.1	x		All mechanical kill switches are tested. Their activation stops the operation of the vehicle immediately. Haptic kill switch is not operational at this stage and it will be tested during the next trials.
		Sw.2	x		
		Sw.3	x		
		Sw.4	x		
		Sw.5	x		
		Haptic	N/A		
6	Position and number of kill switches ensure safe stopping of the vehicle from all sides.		x		The five switches are evenly distributed around the vehicle (forward-left, foreword-right, left, right, back). It satisfies criteria set in D5.1. and D.6.1.1.
7	It is quick, simple and obvious to operate kill switches even for panicking user.		N/A		To activate the kill switch it is enough to pull off the stripe/handle from the switch. Furthermore kill switches are coloured red and orange to make them visible and to make their function obvious. Due to limited number of AUV dives with the diver, further testing with more divers is required during the second validation trials.

ANNEX B. CADDY First Validation Trial Questionnaire

The purpose of this questionnaire is to assess compliance of CADDY system with the validation plan. System compliance with each of the statements is indicated in the validation tab together with comments or recommendations when necessary.

TASK	DESCRIPTION	PROCEDURE	CRITERIA	VALIDATION
I. TESTING "GUIDE" FUNCTIONALITY				
I.a) vertical guidance down	buddy should be able to safely take the diver to a desired depth and lead him/her to the surface	specify desired depth; buddy keeps track of the diver; diver follows the buddy to a specified depth	• buddy keeps an eye on the diver constantly • final depth matches desired depth	Validation postponed for next trails and experiments in deeper water.
I.b) vertical guidance up		buddy keeps track of the diver; diver follows the buddy to a specified depth	• diver and buddy surface together • task accomplished without violating diving safety rules	Validation postponed for next trails and experiments in deeper water.
I.c) steering the diver, control of the diver orientation	buddy should perform automatic manoeuvre in order to steer the diver to take and maintain desired orientation		• buddy steers the diver to the desired direction • diver is oriented correctly	State of progress successfully validated Experiments 3.3.-3.6.(virtual diver) and 3.7.-3.10. (USV) present BUDDY automatic positioning in respect to diver Pending: automatic steering manoeuvre, validation with the ROV and then with the real diver

I.d) buddy maintains the "communication" and "observation" position	Buddy automatically positions itself in the middle of the divers field of view, defined distance away from the diver, to ensure optimal conditions for diver-buddy communication or monitoring	• buddy understands and follows the diver's orientation • buddy maintains desired position for this task	State of progress successfully validated Gradual progress towards full functionality through “buddy pointer“ experiments 3.3.-3.6.(virtual diver) and 3.7.-3.10. (USV) Pending: validation with the real diver, for more details see section 4.4.
I.e) surface vehicle maintains the "communication" and "observation" position	Surface vehicle automatically place itself in an optimal fleet position for enhanced underwater localisation, communication or fleet monitoring.	• Surface vehicle takes optimal formation position.	State of progress successfully validated Functionality validated through “underwater leader” experiment 1.8. and "extremum seeking" experiments 4.3 and 4.4. Pending: full fleet configuration
II. DIVER BUDDY NONVERBAL COMMUNICATION			
II.a) vocabulary for non-verbal communication	Check availability of the initial vocabulary of signs, gestures and syntax and check if it covers all the foreseen situation for topic "Understanding the Diver".	• vocabulary exist • it covers all foreseen situations	Validation successful Elaborated in details in D3.1.
II.b) diver-buddy communication	Validate diver-buddy communication using standardized static and dynamic hand gestures from the diver symbolic vocabulary as well as using symbols (or sequences of symbols) that are defined for the purpose of compliant robotic task execution. Test communication using all categories: standard diving set of signs and gestures, custom set of signs and other means of communication. At this stage only subset of symbols and gestures will be validated. Validation subset and communication success rate are to be	• successful diver-buddy comm. using standard diving vocabulary • successful diver-buddy comm. using custom vocabulary • successful diver-buddy comm. using other means of communication	State of progress successfully validated Functionality validated through experiments 1.10.-1.13. and 2.1.-2.4. New: introduction of CADDIAN slang, one gesture that represents the same message as complex structure Future: inclusion of more static, complex and slang gesture and syntax

		defined prior to first validation trial.		checker, for more details see "to-do" sections 2.4. and 3.4.
III. VALIDATION OF THE COMMUNICATION LINK BETWEEN THE SURFACE CONTROL CENTRE AND THE UNDERWATER AGENTS				
III.a) direct link diver - surface **III.b) diver - surface via buddy** **III.c) buddy - surface**	Test all available communication channels and quality of the communication interface	Initiate and test communication from both sides	• communication link is functional and provides reasonable flow of information.	State of progress successfully validated Experiments 1.1.-1.3. communication, interrogation scheme over the internet using the simulated agents. Experiment 1.6.-1.7. the same on real vehicles (with WIFi) Pending: to include acoustic communication channel, more details in section 2.4.
III.d) communication interface		Test and evaluate the interface	• Interface is easy and intuitive to use. Provide recommendations for potential improvements	
IV. POSE ESTIMATION BY LOCAL AND REMOTE SENSING				
IV.a) an online repository of diver pose datasets	Check availability of the online repository of diver pose datasets, obtained from remote (video, sonar) and local (DiverNet) sensing and check if it is relevant for the diver pose, behaviour, signs and gesture interpretation.		• an online repository of diver pose datasets exists • it is relevant for the purpose	Validation successful Deliverable D.2.4.
IV.b) Pose estimation by local sensing	Validate methods for pose estimation but not interpretation at this stage.	Assess performance of the local sensing method (DiverNet), for the diver pose estimation. Assess ergonomics and comfort of the DiverNet in real missions/operation.	• reliable diver pose estimation • comfortable for divers to wear it	State of progress successfully validated through the experiments 5.1.-5.7. Divers felt comfortable enough to wear DiverNet.

IV.c) Pose estimation remote sensing		Assess performance of a remote sensing for the diver pose estimation using: camera or high resolution sonar.	• reliable diver pose estimation using mono/stereo camera • reliable diver pose estimation using sonar	State of progress successfully validated Experiments 3.1. and 3.2. tracking ROV/diver in BUDDY sonar image
IV.d) Buddy interference in normal operation	The robotic buddy must manoeuvre safely around the diver in order to assume the best viewpoint for observation; at the same time, its presence should not interfere with the normal unfolding of the mission. The trial will answer the question what are the optimal distance and angle for different observation sensors.		• Buddy should not at all, or only insignificantly interfere with the normal unfolding of the mission	State of progress successfully validated Experiment 3.3.with the virtual diver. Distance of 4 meters and angle 0 were found appropriate for observation task. Pending: to be tested with the real diver
V. Slave				
V.a) take a photo	buddy takes a photo upon divers request		• buddy goes to the position • buddy takes a photo	Validation successful - experiment 2.11. State of progress: CADDIAN command by diver underwater, buddy takes a photo
V.b) take a video for the mosaic	buddy acquires a series of overlapping photos for a mosaic upon request from the diver	Diver orders the buddy to acquire a photos for a mosaic or simply guides the diver	• buddy covers the area following the diver's order or following the diver • buddy takes a video	State of progress successfully validated Experiments 1.16.-1.1.8. State of progress: CADDIAN command from the surface, underwater data acquisition, generated mosaic Pending: command from underwater and mission generation interface
V.c) move following my command	Buddy follows the ordered command	Diver orders the buddy to follow specific command	• buddy execute order correctly	Validation successful - experiments 2.9.-2.10. State of progress: CADDIAN command by diver underwater, buddy follows the command

V.d) carrying a tool or equipment	buddy carries a payload with tools and equipment upon divers request	• buddy understands the request • buddy carries a payload	Validation successful - experiment 2.12. State of progress: CADDIAN command by diver underwater, buddy executes the command