COOPERATION

Grant Agreement No. 611373

CADDY

Cognitive Autonomous Diving Buddy

FP7-ICT-2013-10

D1.1 - Technical and performance characteristics of the robotic diver assistance system consisting of three agents

Due date of deliverable:
Actual submission date:

Start date of project: 01 January 2014 Duration: 36 months

Organization name of lead contractor for this deliverable: UNIZG-FER

Revision: version 1

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)	

Contents

1 Outline of the deliverable

This deliverable provides detailed technical description of all the systems that comprise the overall robotic diver assistance system. In particular, the different robotic platforms made available by the partners and the related modifications and upgrades to fit with the project specifics are described. Basic performance characteristics of the vehicles are provided, based on initial experiments.

PlaDyPos by UNIZG-FER (Fig. 1.1a)), MEDUSA$_S$ by IST (Fig. 1.1b)) and Charlie by CNR (Fig. 1.1c)) are the autonomous surface vehicles that have been refurbished to act as the diver's "private satellite". In addition to changing the hardware and testing all the developed software (control architectures and mission planners), all partners modified their vehicles to enable ROS-based heterogeneous systems integration.

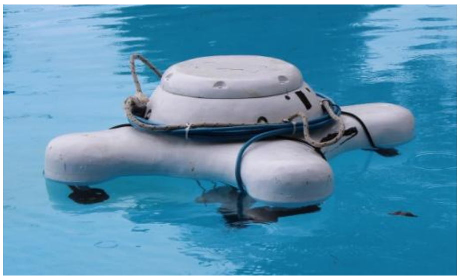


Fig. 1.1a) PlaDyPos by UNIZG-FER

Fig. 1.1b) MEDUSAS by IST

Fig. 1.1c) Charlie by CNR

While UNIZG-FER is almost finished with the prototype of the new BUDDY AUV (Fig. 1.2a), Fig. 1.2b)), CNR has upgraded their ROMEO ROV (Fig. 1.2c)) for the purposes of CADDY project and IST is using their existing MEDUSA$_D$ AUV (Fig. 1.1b)). The initial BUDDY version was successfully tested during in water trials in Split. BUDDY is the first AUV with diver interface in a form of an underwater tablet.

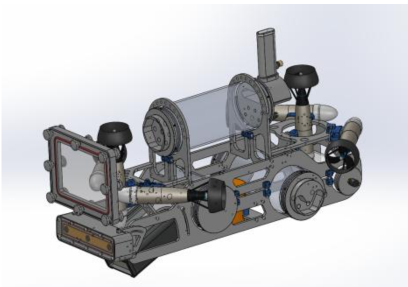


Fig. 1.2a) BUDDY AUV components

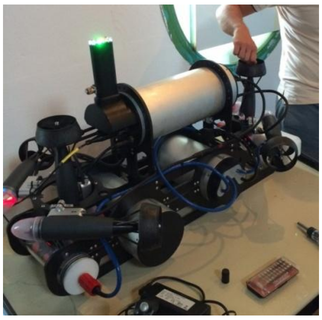


Fig. 1.2b) BUDDY AUV prototype

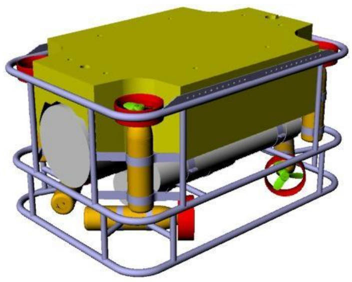


Fig. 1.2c) ROMEO by CNR

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

A new underwater tablet casing has been designed and produced (Fig. 1.3). The case allows the diver to use commercially available tablets to exchange data with the vehicles.

Fig. 1.3 The underwater tablet case.

2 The surface segment

The availability and adaptation of existing/under development surface platforms is described in this section. The main characteristics of the surface vehicles made available by each partner involved in the task, are described in terms of mechanical structure, sensor suites, navigation and guidance abilities, communication systems, integration with the overall framework.

2.1 PlaDyPos (UNIZG-FER)

UNIZG-FER efforts are mainly directed on the modification and enhancement of the autonomous surface marine platform, which will be referred to as *PlaDyPos* (short for Platform for Dynamic Positioning, which was its original functionality).
Hardware modifications and refurbishment on the existing surface vehicle include the following items:

- Appendix on the back of the platform for cables (Fig. 2.1.1a))
- Ubiquiti Bullet M2 HP WiFi for platform and ground station (Fig. 2.1.1b))
- Mount for new WiFi antenna on platform (Fig. 2.1.1.b))
- universal mount for USBL and DVL (Fig. 2.1.1c))
- Charging and powering without opening the lid

a) b) c) d)

Fig. 2.1.1 Modifications and refurbishment of the UNIZG-FER PlaDyPos.

The electrical configuration of PlaDyPos is shown in Fig. 2.1.3a). The following set of electrical modifications and enhancements have been made: ethernet relay has been added thus allowing the possibility to turn on/off: every motor separately, USBL, DVL, CPU over WiFi from ground station; ethernet switch is added and USB drive for logging; new wiring has been integrated.
New battery which is also used in the Buddy vehicle is integrated in the platform, shown in Fig. 2.1.3b). Installation of the new battery requested new electrical configuration of the PlaDyPos (Fig. 2.1.3c)): 5, 9, 12 and 24 V DC-DC converters were added to supply electronic components with required voltages. With new motors which will be installed in next three months, both speed and autonomy of the platform will be increased. Failure of one motor driver for Seabotix thrusters demanded construction of new drivers capable driving brushed DC motors up to 60 V and 3 A.
Additional activities on the refurbishment of PlaDyPos in immediate future include signaling lights, new paint job, and new motors.
Since we wanted to ensure that the platform will follow the diver even at higher speeds, a custom made brushless thruster prototype, shown in Fig. 2.1.4, was created for nominal voltage of 48 V and 3 A current which would give 150 W of power.
Thorough laboratory testing of the custom made thrusters showed that thruster performance was not as expected and according to requirements. It forced us to use existing Seabotix thrusters for the

current experiments. Long term solution for the thrusters PlaDyPos is still open. At this stage of the project team has focused on of-the-shelf VideoRay Pro4 motors in watertight housing with custom made integrated drivers designed by VideoRay and modified for our purpose by UNIZG-FER team for propulsion of the Buddy vehicle. Custom heat sinks (Appendix1_UNIZG Page_22-23) shown in Fig. 2.1.2a) are made for cooling the driver inside the thruster. Custom mounts (Appendix1_UNIZG Page_20-21) shown in Fig. 2.1.2b) are also made for mounting thrusters to the frame.

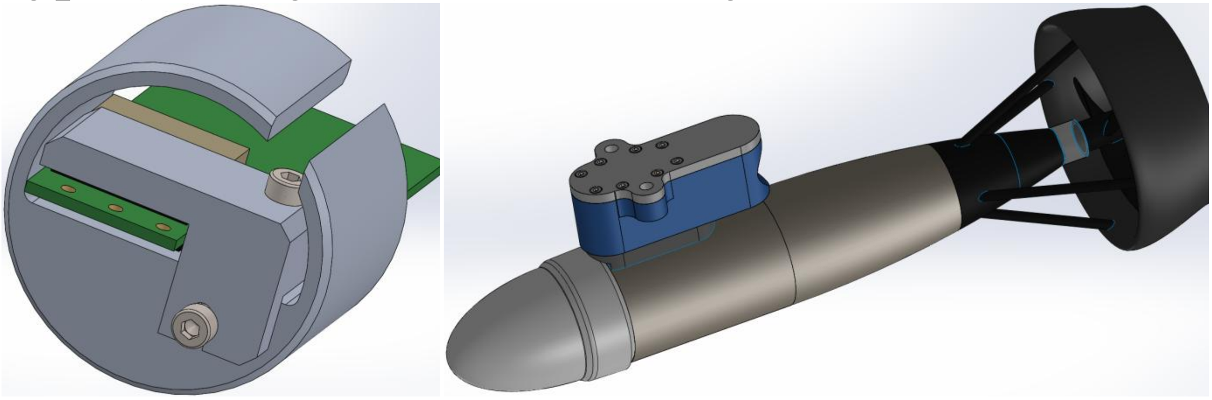


Fig. 2.1.2a) Motor driver heat sink and clamp, b) VideoRay Pro4 mount and mount cap

In the meantime the new SeaTrac USBL system, developed within the scope of the CADDY project by the Newcastle University, was integrated in the vehicle replacing the existing Tritech MicronNav USBL system. The main advantages of the new system are: smaller size, longer localization range, wider acoustic communication bandwidth and much easier interfacing with the control subsystem.

Fig. 2.1.3a) Electrical configuration of PlaDyPos, b) Custom made Li-Ion battery, c) New electrical configuration

Identification:

In order to achieve high quality low-level control, mathematical model of the platform has been identified. Thruster model has been identified using the classical steady state thruster mapping. We have applied the identification method based on self-oscillations to determine the dynamic model.

Software:

The control structure consisting of low-level controllers, high-level controllers, primitives and mission control has been established and documented. Control structure hierarchy is shown in Fig 2.1.4. Low-level controller and identification extensions have been implemented and pool testing has been successfully performed. State machine for control primitives execution which enables easier building and modifying of complex maneuvers has been implemented.

Mission is defined as a set of primitives that have to be executed. The primitives that comprise a mission are in fact states in a state machine. The mission control state machine example realized in ROS environments is shown in Fig. 2.1.5a).

Primitives are elementary parts that form a mission. They are uniquely defined by the structure of the low–level and/or high–level controllers that they engage, and a set of inputs.

As it is shown in Fig. 2.1.4, primitives can engage both high–level and low–level controllers. So, for example, the primitive go2point_FA engages the high–level heading controller (heading) in order to face the vehicle in desired direction, and the high–level fully actuated line following controller (LF_FA) which enables following desired line. The first implicitly engages low–level yaw rate controller, while the second implicitly engages the surge and sway low–level controllers. The primitive DP_primitive engages the high–level dynamic positioning controller (DP) in order to guide the vehicle to a desired point, and the high–level heading controller with full actuation (heading) and so on. The list of currently used primitives, their inputs, and high-level controllers they engage, is shown in Table 2.1.1.

All the primitives were tested on PlaDyPos, surface platform, during Split field trials in June/July 2014. Acquired results show that the proposed control structure ensures bumpless change in commanded signals when mission states change.

Table 2.1.1 List of primitives

Name	Inputs	Controllers
go2point_FA	T_1, T_2, ψ	LF_FA; heading
go2point_UA	T_1, T_2	LF_UA
dynamic_positioning	T_1, ψ	DP; heading
course_keeping_FA	course, ψ	LF_FA; heading
course_keeping_UA	course, ψ	LF_UA

The sensor drivers for the newly acquired Spatial IMU sensors have been custom-developed by UNIZG-FER, and they have been integrated on PlaDyPos.

Testing and performance evaluation of sensors, controllers and navigation was performed on the vehicle in real conditions on Jarun lake in Zagreb.

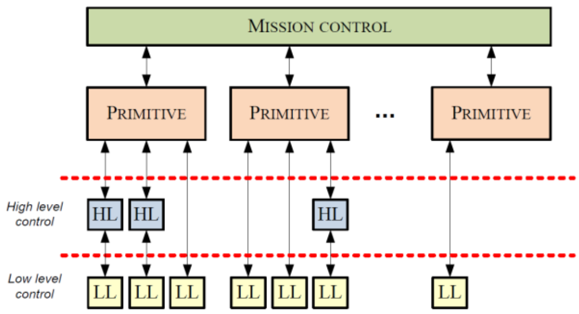
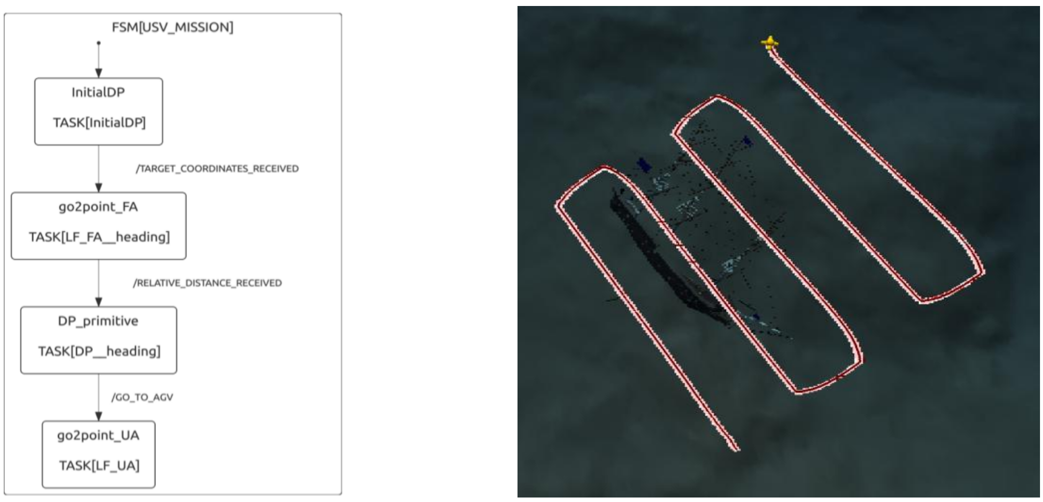


Fig. 2.1.4 Control structure hierarchy.



a) *b)*

Fig. 2.1.5a) Example of mission state machine, b) lawnmower mission executed in UWSim.

2.2 Charlie USV (CNR)

The Charlie USV (see Fig. 2.2.1) is a small catamaran shape-like prototype vehicle developed by CNR. Charlie is 2.40 m long and 1.70 m wide and weighs about 300 kg in air. The propulsion system of the vehicle is composed of a couple of dc motors (300 W at 48 V), with a set of servo amplifiers that provide a PID control of the propeller revolution rates. In the current release, the vehicle is equipped with a rudder-based steering system, where two rigidly connected rudders, positioned behind the thrusters, are actuated by a brushless dc motor. The navigation instrumentation set is constituted of a Trimble GPS and a KVH Azimuth Gyrotrac. Electrical power supply is provided by four 12 V at 40 Ah lead batteries, which can provide power supply for several hours of operation. The onboard realtime control system, developed in C++, is based on GNU/Linux and run on a single board computer (SBC), which supports serial and Ethernet communications and PC-104 modules for digital and analog input/output (I/O). A commercial wi-fi system provides the communication link, for commands and telemetry, between the vehicle and the remote control station.
The Charlie USV has been upgraded integrating an additional computing board in order to provide an interface with the ROS infrastructure. Moreover a secondary wi-fi system has been mounted on the USV allowing the communication among Charlie and the other vehicles, for the cooperative tasks, relying on the ROS architecture.
Regarding the payload side, the acoustic modem, needed to provide the communication channel for the surface/underwater robots' cooperation, has been mounted on the Charlie USV.
From the software side, the ROS infrastructure has been installed and set up on the secondary computing board. A software wrapper has been developed in order to integrate the custom Charlie control system with the CADDY framework, acting as a gate for command and telemetry dispatch.

Fig. 2.2.1 Charlie USV during operations

The integration of the Charlie USV software system with the ROS-based CADDY infrastructure requires the development of a software wrapper. Such a wrapper basically acts as a command/telemetry gate between the Charlie system and the ROS environment.
The wrapper developed for the Charlie system is based on two ROS nodes, namely *CommandSender* and *TelemetryReceiver*; the first one retrieves the desired guidance and control references and other high level directives, generated by the CADDY cooperative guidance modules, that the vehicle has to track/execute in order to achieve the coordinated motion tasks. In details, the *CommandSender* node collects the data that are published onto the */usv/command/...* topics and then forwards the commands to the Charlie system through a connectionless oriented socket.
On the other side, the CADDY framework requires the knowledge of the vehicles' navigation state; the second wrapper node *TelemetryReceiver* receives, through a second connectionless oriented

socket, the local 2D position, attitude, velocities reading from the vehicle navigation instruments, then translates these information in the proper ROS structure for vehicle pose definition.
The logical scheme of the Charlie-ROS wrapper is depicted in Fig. 2.2.2.

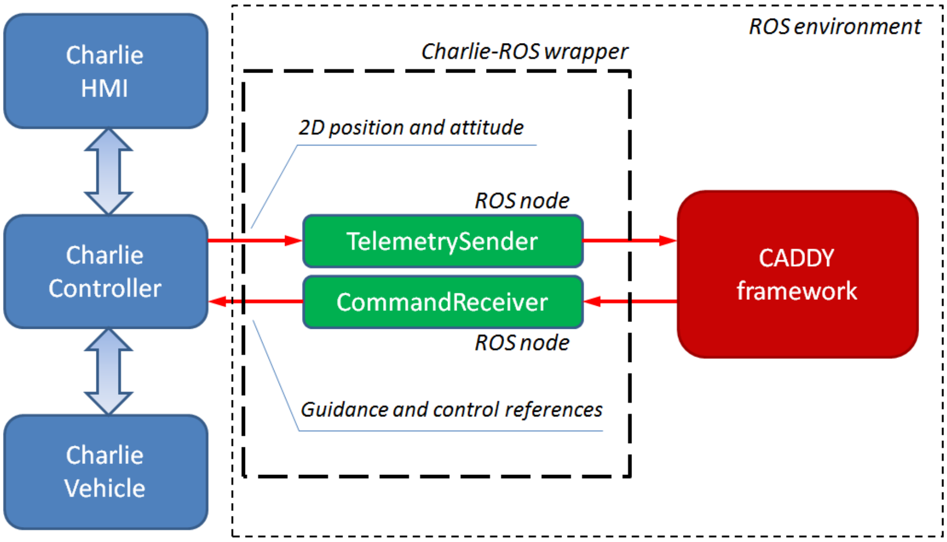
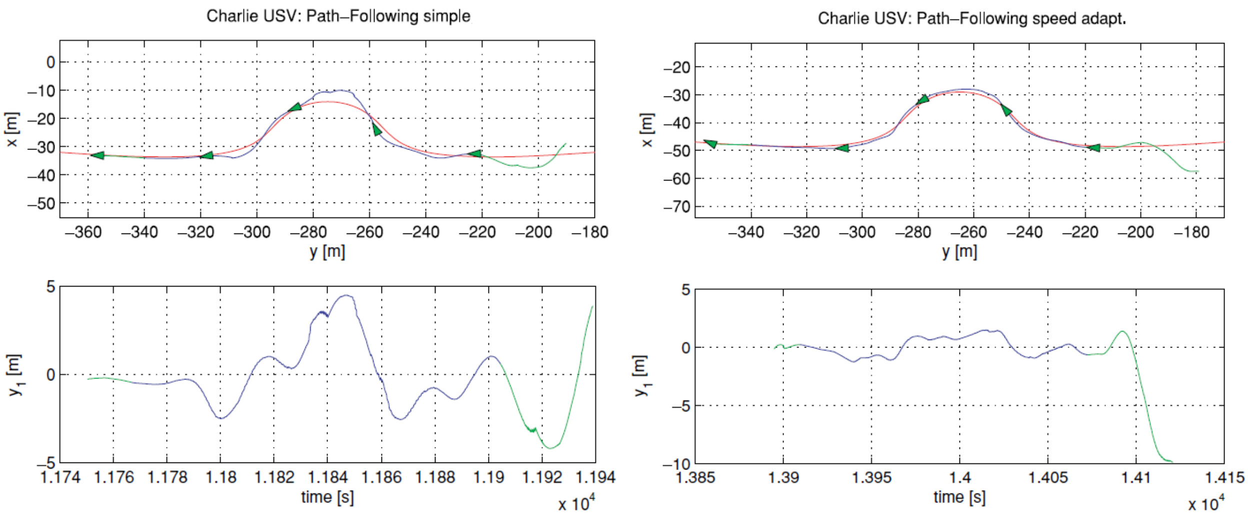


Fig. 2.2.2 Charlie-ROS software interface scheme

The Charlie USV capabilities in the exploitation of various at-field operations, at both low or high level of autonomy, in single or multi-vehicle frameworks are proved by a huge number of experimental results obtained in the last ten years of the vehicle employment at field.
The main features that are exploited within the CADDY framework are the general path-following guidance system and the high level mission control.
The path-following guidance system is based on a virtual-target based algorithm, ensuring global stability and robustness to disturbances and uncertainties. A complementary speed adaption scheme is integrated with the guidance module in such a way to improve the path-following performance. An exemplificative result set is reported in Fig. 2.2.3, where the difference between the simple path-following algorithm and the combined guidance plus speed adaptation can be evaluated. In the top plots the path reference and the vehicle motion are represented: in the top-right plot the vehicle performs a curve section closer to the reference in virtue of a speed reduction. Lower plots show the evolution of the cross-track error (i.e. the perpendicular distance of the vehicle with respect to the path), highlighting the lower values of the error during the motion in case of speed adaption exploitation.

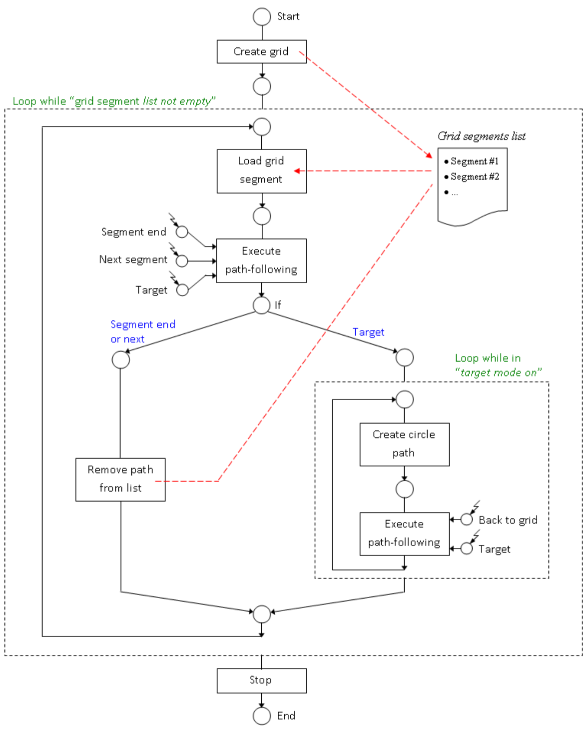
The goal of the high-level mission control system is the execution of predefined action plans, tracing and maintaining the consistency of the mission state, and allowing an online mission plan update by human operator interaction. The state of a generic mission evolves on the basis of occurrences of specific conditions, that can be related either to continuous-time or event-driver conditions; with the aim of making the state evolution handling homogeneous, from the point of view of the management of different notifications from different layers of the architecture, a logical interface based on *event* generation and dispatch has been developed. The need of defining the mission plan with a modular and top-down approach, complemented by the possibility of describing separately the management of emergencies and exceptions, usually field of intervention of the system engineer, from the planning of the specific mission, usually carried out by the end-user (or at least with his/her strong cooperation), brings to the definition of a sort of *programming language* for the mission plan description and automatic construction of the mission software structure. To this aim, the proposed mission planning and control system relies on a modular and recursive Petri net where

three main entities constitute the module base: *i*) execution actions, defining the semantics and state of actual action of the vehicle; *ii*) flow control modules, representing the topological interconnection of the execution actions; *iii*) data structures, needed to store and manage mission data like variables, counters, waypoint lists, etc.
A typical autonomous "explore and observe" mission for an USV can be designed as in Fig. 2.2.4; the resulting vehicle operations are depicted in Fig. 2.2.5.



(a) No speed adaptation (b) With speed adaptation

Fig. 2.2.3 Charlie USV path-following experimental results



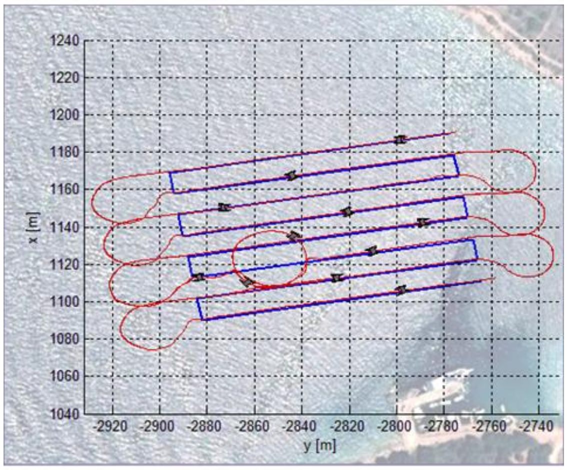


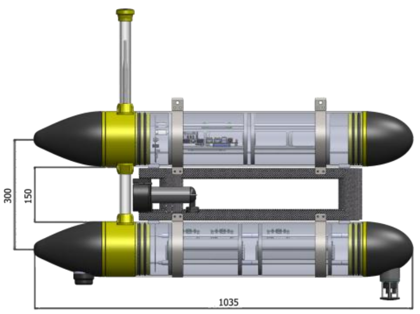
Fig. 2.2.4 "Explore and observe" mission plan *Fig. 2.2.5 Autonomous mission results*

2.3 Medusas (IST)

IST brings to the core of the CADDY project three autonomous marine vehicles of the MEDUSA-class, designed and built at the Institute for Systems of Robotics (ISR), a laboratory of IST. This class of vehicles was first designed, and prototypes were built, in the scope of the CO_3AUVs FP7 project (ended in January 2012). In the course of the latter project, the MEDUSA vehicles played the role of Autonomous Surface Vehicles (ASVs) in charge of guiding human divers. Since then, the MEDUSA vehicles have been used in the scope of the EC MORPH project to test MORPH Range-Only Formation control and navigation algorithms and to carry out data acquisition experiments.

As part of the effort to afford the members of the CADDY project marine vehicles to test and assess the efficacy of the methods developed for cooperative motion control, the vehicles were upgraded and fully tested, as explained below. *All existing MEDUSA vehicles can be used as ASVs*. In this mode of operation, they are simply referred to as $MEDUSA_S$ vehicles (where S stands for "Surface"). *Two of them have been upgraded in terms of sensors, actuators, power distribution, and control systems to be able to dive and can therefore be used as AUVs*. In this mode of operation, they are referred to as $MEDUSA_D$ vehicles (D stands for "Diver"). This was done in view of the goals to : i) develop and assess, in real operational conditions, the performance obtained with cooperative navigation and control systems for surface and underwater vehicles carrying joint missions (e.g., performing a leader tracking maneuver whereby the CADDY ASV plays the role of leader and the CADDY AUV tracks the trajectory described by the leader), and ii) to evaluate the performance of the navigation and control systems developed to allow for close diver / CADDY AUV interaction. In fact, it is envisioned that from a pure motion control and navigation standpoint, one of the underwater vehicles will act as a proxy for the diver during the first part of the project. Because of the role (as test beds) that the MEDUSA vehicles will play in the CADDY project, the *work done aimed also at adapting the software architecture of both the $MEDUSA_S$ and $MEDUSA_D$ vehicles according to the rules defined by the partner group for heterogeneous systems integration*.

The MEDUSA-class vehicles are approximately 1035 mm long and weigh 23-30 kg (depending on their configuration). The housings consist of two 150 mm diameter acrylic tubes with aluminium end caps, attached to a central aluminium frame. This design allows for a short length and better weight distribution (in terms of metacentric height), therefore the vehicles are easy to transport and launch and have good static stability. The upper body carries the light components, namely a single-board computer, an RTK-enabled GPS receiver, Wi-Fi 802.11 communications, a full navigation sensor suite, and a video acquisition system for an underwater camera. Most of the weight is concentrated in the lower body where the LiPo (Lithium Polymer) batteries and power management electronics are installed. Each of the $MEDUSA_S$ vehicles is propelled by two side-mounted, forward-facing thrusters that yield surge and yaw motion: the vehicle is capable of reaching speeds up to 1.5 m/s. The diving $MEDUSA_D$ vehicles are also equipped with two vertical thrusters for diving purposes.



$MEDUSA_S$ (Surface) Particulars	
Length	1035 mm
Height	875 mm
Tube diameter	150 mm
Weight in air	23 kg (Surface), 30 kg (Diver)
Energy	830 Wh LiPo
Endurance	11 h at 1.5 knot
Propulsion System	2 thrusters (Surface) 4 thrusters (Diver)

Fig. 2.3.1 The MEDUSA class of vehicles ($MEDUSA_S$): main particulars

Fig. 2.3.2 The 3 MEDUSA vehicles of IST

At the beginning of the project, the consortium agreed on a unified middleware to facilitate software development and integration. In accordance with this decision, the MEDUSA vehicles were upgraded to the middleware ROS (Robot Operating System www.ros.org), and some new modules were developed. Fig 2.3.3 illustrate the software architecture adopted for each vehicle. The diagram on the left shows the actual (physical) systems. The diagram on the right shows the structure adopted for Hardware-in-the-loop (HIL) simulations, whereby part of the systems (e.g. true vehicles) are replaced by simulations. The architecture adopted will allow for HIL simulations over the Internet, involving systems developed by the different CADDY partners.

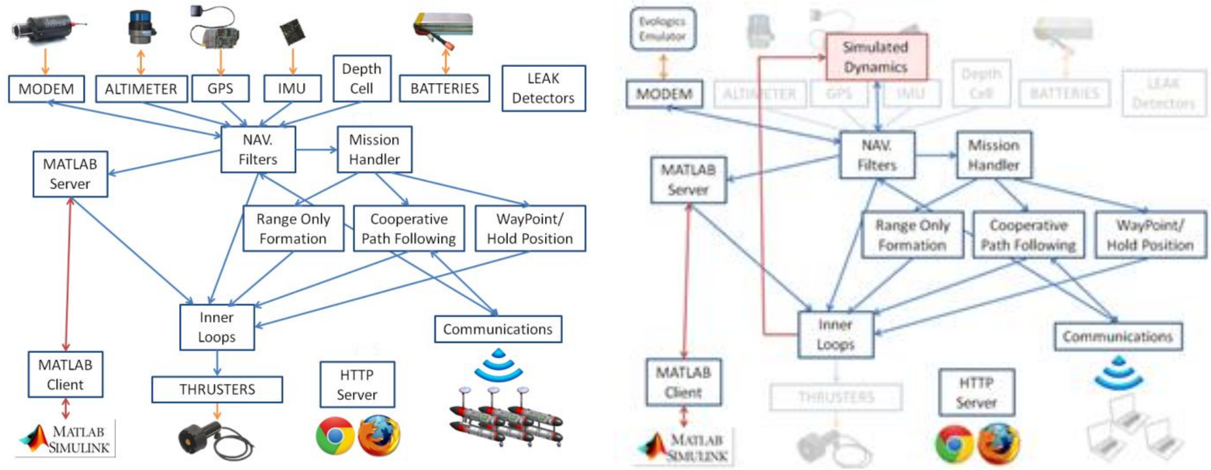


Fig. 2.3.3 The MEDUSA vehicles: Software Architecture (left: physical systems; right: set-up for Hardware-in-the-loop (HIL) simulations).

The following nodes/algorithms were developed (based in part on work done in previous projects) and are here emphasized because they will be helpful during the CADDY project.

Cooperative Path Following (CPF) – algorithms and related sensor/actuation systems responsible for making a group of marine vehicles follow predefined spatial paths while holding a desired formation pattern at a desired formation speed (constant or time-varying, according to a defined speed schedule).

Range Only Formation (ROF) – algorithms and systems for formation control, that is, to make a group of vehicles move in formation by using measurements of the ranges among them.

Waypoint Control /Hold Position (WCHP) – algorithms and systems to steer a vehicle to a given point and to keep its position in a small neighbourhood of that point in the presence of external disturbances such as currents.

Leader Tracking (LT) – algorithms to enable a marine vehicle (follower) to track the motion of another vehicle (leader) by using USBL and other proprioceptive data.

Mission Control - responsible for supervising and activating individual algorithms and systems upon detection of external or internal events.

Shore Console - allows the vehicles operator to visualize and monitor the state of the mission in real time, with interfaces for mission programming, data plotting, and multiple vehicle operation capabilities (see Fig. 2.3.4).

With the purpose of testing CADDY buddy-surface cooperative navigation and motion control algorithms (namely, those involved in the execution of Leader Tracking maneuvers), IST installed Ultra Short Baseline (USBL) units, acoustic modems, and a DVL on two of the MEDUSA vehicles, see Fig. 2.3.5. A description of the algorithms and field test results is available in Workpackage 4.

Fig. 2.3.4 Console Print Screen showing two MEDUSA$_D$ vehicles underwater (red and yellow) and one MEDUSA$_S$ vehicle at the surface performing a coordinated maneuver. The black vehicle (MEDUSA$_S$) is the leader, and the underwater vehicles are the followers. Cooperation is done using an USBL installed on the yellow MEDUSA$_D$ using a newly developed algorithm for acoustics-enabled Leader Tracking (LT).

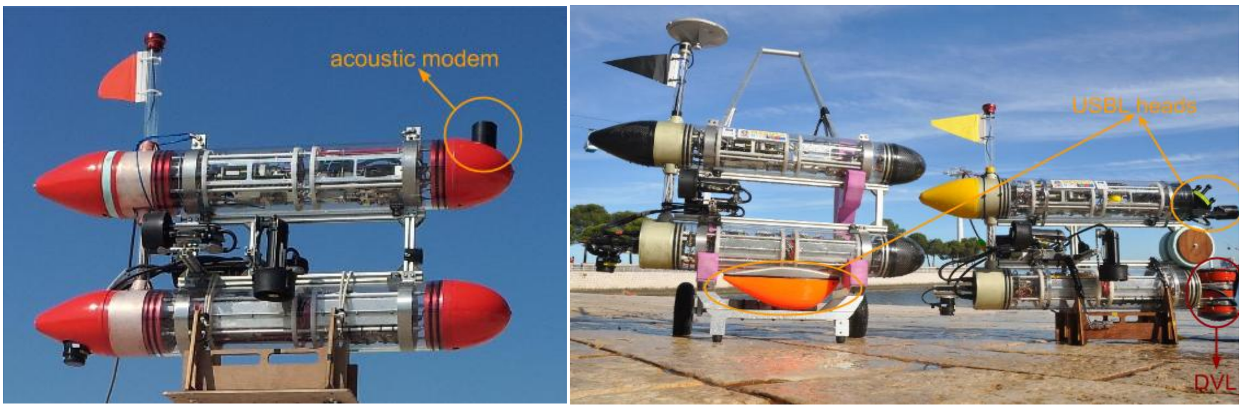


Fig 2.3.5 Two MEDUSA vehicles showing the installation of the USBL units, DVL, and acoustic modems.

3 The underwater segment

The availability and adaptation of existing/under development under-water platforms is described in this section. The main characteristics of the surface vehicles made available by each partner involved in the task, are described in terms of mechanical structure, sensor suites, navigation and guidance abilities, communication systems, integration with the overall framework.

3.1 BUDDY (UNIZG-FER)

UNIZG-FER is working on the development on the new autonomous underwater vehicle, **BUDDY**, specially designed for interaction with divers. BUDDY will be made of 3 canisters for electronic components. Besides, it will be equipped with high resolution sonar, DVL, stereo camera, low light camera and tablet for interaction with diver. It is equipped with four thrusters in X configuration for horizontal and two for vertical movement. All parts which are constructed as well as all electronic schemes are available in **Appendix1_UNIZG**. Electronic components are assembled in rack and are divided in canisters as follows:

- **Battery canister** - 46.8 V 24.8 Ah battery, (Fig. 3.1.1a)) (Appendix1_UNIZG Page_30). Three sets of batteries have been purchased to ensure uninterrupted execution of experiments with the vehicles. Battery is directly wired to 5, 12 and 24 V DC/DC regulators (Appendix1_UNIZG Page_1). Regulators are turned on or off via magnetic switch which is controlled by a magnet outside the canister (Appendix1_UNIZG Page_31-34). When On/Off pin of DC/DC regulators are short circuited to ground regulators are turned off. This is accomplished by putting the magnet over magnetic switch. When magnet is released, DC/DC regulators are turned on. 24V DC/DC regulator feeds two 9V DC/DC regulators (Appendix1_UNIZG Page_35-37). 5V DC/DC regulator turns on solid state relay which will in future be used for disconnecting the power to the motors via kill switch. Battery is bonded to one cap (Appendix1_UNIZG Page_4) of the canister with double sided adhesive tape to prevent movement and rolling inside the canister. Through other cap (Appendix1_UNIZG Page_5) four underwater cables exit to make connection with Master and Vision canister. Type of the cables is as follows:
    - 9 wire cable with 9 pin low profile connector connected to Master canister
    - 2 wire cable with 2 pin circular split connector (2/4) connected to Master canister
    - 2 wire cable with 2 pin circular split connector (2/4) connected to Master canister
    - 9 wire cable with 2 pin low profile connector connected to Vision canister

  Wires 6 and 7 are short connected to enable the Battery Management System (BMS) of the battery. If in any case it's needed to completely turn off the battery or reset it if BMS shuts itself down due to over current, low voltage, etc. protection, user can just disconnect 9 pin connector from Vision canister.

  For charging the battery it is required to disconnect the 9 pin connector from Vision canister and connect it to charging cable. Wires 1-5 from charging cable are all isolated for safety reasons and wires 6 and 7 are short connected to turn on the battery, i.e. BMS. Battery will not charge if BMS is not turned on.
- **Master canister** - this canister (Fig. 3.1.1b)) includes:
    - fiber optic converter for communication with the surface (Appendix1_UNIZG Page_38-39)
    - gigabit switch (Appendix1_UNIZG Page_40-43)
    - Ethernet relay board for powering up thrusters (Appendix1_UNIZG Page_44-51)
    - Ethernet relay board for powering CPU, DVL and acoustic modem (Appendix1_UNIZG Page_44-51)
    - PC104 embedded PC (Appendix1_UNIZG Page_52-53)
    - IMU (Appendix1_UNIZG Page_54-55)

- GPS - u-blox LEA-5 (Appendix1_UNIZG Page_56-57)
- Wi-Fi antenna - Belkin USB Wi-Fi adapter (Appendix1_UNIZG Page_58-60)

Inside the canister is rack connected to one of the caps of canister for easy assembly or disassembly of whole canister (Appendix1_UNIZG Page_2). On the same cap (Appendix1_UNIZG Page_8) there is Wi-Fi antenna with GPS module for communication and localization while on surface. Embedded PC is responsible for control of the BUDDY vehicle:

- gathering and processing data from DVL, USBL, IMU, GPS
- responding to commands and sharing telemetry data through fiber optic cable with the ground station for testing purposes
- sending commands to the motors

End cap (Appendix1_UNIZG Page_8) of the canister which has antenna mounted on it contains six bulk connectors:

- 9 pin low profile bulkhead for connection with Battery canister
- 4 pin circular split bulkhead (2/4) for connection with Battery canister
- fiber optic bulkhead for connection with ground station for testing purposes
- 8 pin bulkhead for DVL
- 8 pin bulkhead for USBL
- 8 pin Ethernet bulkhead for communication with Vision canister

Antenna on the end cap also has bulkhead which will be used for kill switches and other auxiliaries, e.g. Bluetooth for tablet, LED lights, etc.

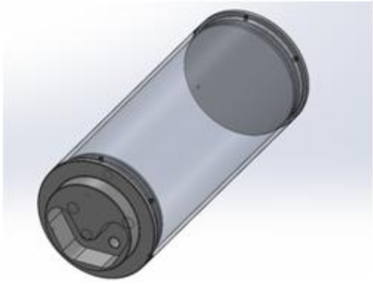
Fiber optic cable is connected to fiber optic converter which is then connected to gigabit Ethernet switch. Overall intention is to have as much equipment as possible to have Ethernet connection. This makes things easier to use because every member of a team can independently use any part of equipment regardless of the other team members. If some part of equipment is not on Ethernet network, it is connected to an embedded computer via some kind of serial connection.

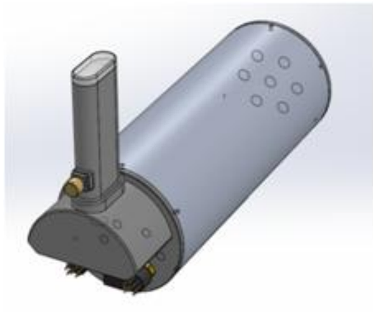
End cap on the other side (Appendix1_UNIZG Page_9) has three 8 pin bulkheads, and three 8 wire cables with cable glands and polyurethane rubber for fixing and sealing cables. Those bulkheads and cables feed power and communication to thruster.

- **Vision canister** - this canister (Fig. 3.1.1c)) includes:
  - Intel NUC Mini PC for acquisition of sonar, stereo and mono camera image (Appendix1_UNIZG Page_61-64)
  - gigabit switch (Appendix1_UNIZG Page_40-43)
  - Ethernet relay board for powering up CPU, sonar and cameras (Appendix1_UNIZG Page_44-51)
  - 24/31 V DC/DC regulator for multibeam sonar (Appendix1_UNIZG Page_65)

Electronics inside of canister is assembled on rack which is connected to one of the end caps for easy assembly (Appendix1_UNIZG Page_3). One of the end caps (Appendix1_UNIZG Page_4) has 9 pin low profile bulkhead. Through other end cap (Appendix1_UNIZG Page_11) four cables fixed with cable gland and sealed with polyurethane rubber exit the canister:

- 8 wire Ethernet cable for communication with Master canister
- 8 wire Ethernet cable for power and communication with low light mono camera and power and communication with tilt control of the camera
- 10 wire Power Ethernet cable for power and communication with multibeam sonar
- 8 wire Ethernet cable acting as FireWire cable for power and communication with stereo camera


a)


b)

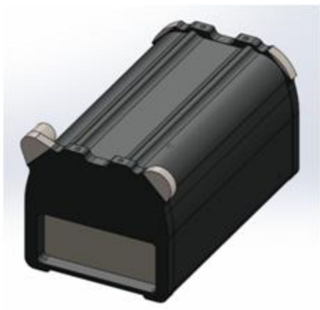

c)

Fig. 3.1.1 CAD model of three canisters comprising the BUDDY AUV.

All three cylinders are made of 5 mm thick Aluminum 6082 alloy. Diameter of the cylinder is 170 mm and lengths are 410, 410 and 300 mm for Battery, Master (Appendix1_UNIZG Page_6) and Vision (Appendix1_UNIZG Page_10) canister. End caps are made of POM-C polyacetal, as well as supporting frame of the vehicle (Appendix1_UNIZG Page_25). Hinges, lock nuts, flanges and mounts are made of Aluminum alloy. All bolts which are in contact with water are INOX A2. Overall dimensions of the vehicle are 1150x700x750 mm.

The public procurement of the ARIS Explorer 300 high resolution multibeam sonar (Fig. 3.1.2a)), that will be integrated in the BUDDY vehicle, is finished, and the sonar is available at UNIZG-FER. Fig. 3.1.2b) shows the CAD model of the DVL provided by UNIZG-FER that will be integrated in the vehicle. We performed pool tests for identification and navigation using the DVL sensor.

The initial distribution of the canisters, sensors and thrusters are shown in Fig. 3.1.3, in the form of a CAD model. The BUDDY vehicle will be equipped with a commercial tablet in a custom made waterproof casing in order to achieve efficient visual-based communication with the diver.

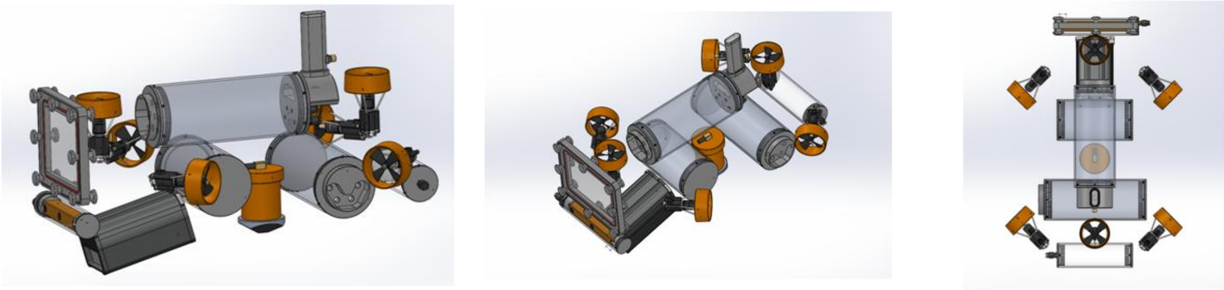

a)


b)

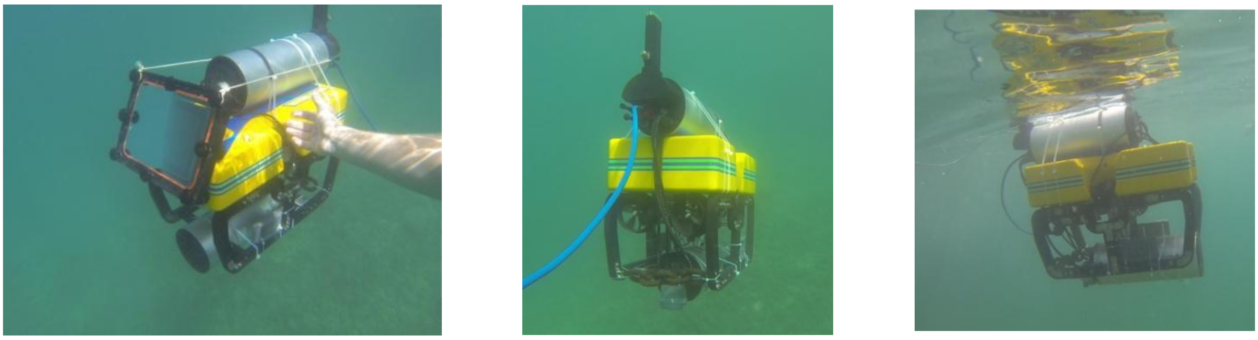
Fig. 3.1.2 - CAD models of a) ARIS Explorer 3000 and b) DVL.

The **first version** of the vehicle has been integrated and tested during the summer field campaign in Split (Fig. 3.1.3). We have successfully tested the functionality of the main and battery cylinder. The developed components were mounted on an existing frame (from Seamor ROV). It is needed to add and test vision cylinder and the sensors (sonar, DVL, stereo camera, low light camera, etc.). The vehicle will communicate with the surface via 150 m fiber optic cable in non-autonomous mode and acoustic modem in autonomous mode.

The **second version** of the vehicle has been integrated and tested during the autumn field campaign in Split and Biograd na moru (Fig. 3.1.4). This time functionalities of all three cylinders were successfully tested. Cylinders and payload were mounted on the new frame. This frame will be the final BUDDY frame, some minor modifications are possible. Payload which was tested during autumn trials are DVL, low-light camera, ARIS sonar and stereo camera. Pending hardware tasks are integration of the tablet, integration of diver safety system, depth sensor (already integrated from the hardware point of view), acoustic USBL transponder/modem, diagnostic sensors (e.g. cylinders internal temperatures, leak sensors), GPS, floating block and wet hull.



a)

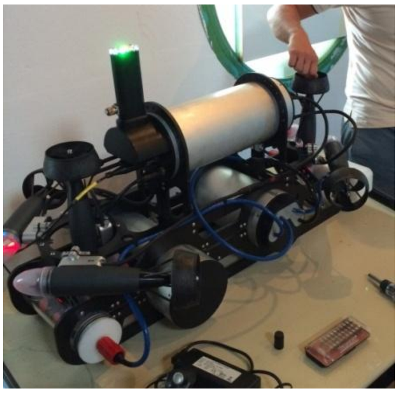


b)

Fig. 3.1.3 First version of BUDDY vehicle: a) CAD model, and b) real vehicle during trials.

a)

b)



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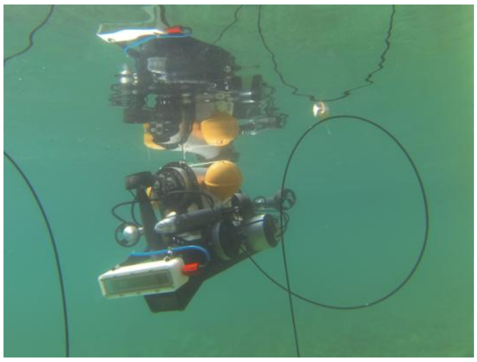


d)

Fig. 3.1.4 Second version of BUDDY vehicle: a) CAD model, and b) assembled vehicle, c) vehicle during trials.

BUDDY AUV safety mechanisms:

In order to ensure diver safety, a couple of safety switches will be mounted on outer shell of the vehicle. Two types of switches are possible:

- **Positive Action Switches** are designed to give a continuous signal when the switch is activated. Various configurations are available including Rotary and Push and Pull (Kill Switches)
- **Proximity Switches** use magnets, either in attraction or repulsion, to open or close an electrical circuit.

After agreement with partners responsible for diver safety, we will converge to the best solution of which type of switches we will use and how many of them is needed to keep divers safe.

3.2 R2 (CNR)

The **R2 ROV**, developed by CNR, is a fully actuated underwater robotic platform characterized by the dimensions of 1.3 (length) x 0.9 (width) x 1.0 (height) m, rated up to a depth of 500 m. The redundant allocation of 4 horizontal and 4 vertical thrusters allows the vehicle to a complete motion capability as well as the hovering skill. The integration of a fiber optic gyro (FOG) for attitude measurement with a Doppler velocity logger (DVL) provides a precise navigation system, needed for underwater operations. The availability of a fiber optic link between the vehicle and the surface control station allows the exploitation of high-rate data measuring devices on-board the ROV, such as cameras, multi-beam or side-scan sonars. The integration of USBL / acoustic modems on board the ROV and the USV provides the relative position sensing / communication between the robotic platforms, allowing the cooperation of the vehicles in the scope of coordinated robotic actions.
The vehicle can be exploited for the initial development of algorithms and preliminary trials.
A 3D representation of the vehicle is depicted in Fig. 3.2.1 and the vehicle during operation is shown in Fig. 3.2.2.

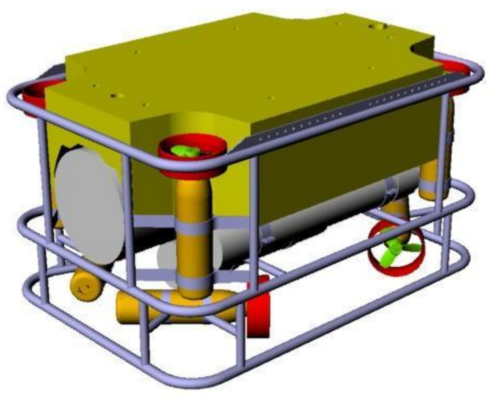


Fig. 3.2.1 3D representation of the R2 ROV

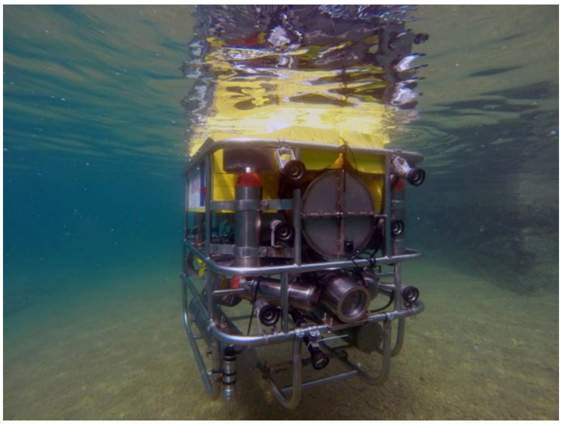


Fig. 3.2.2 R2 ROV during operations

The electronic upgrade of the R2 ROV is almost complete and it is focused on the installation of a new computing unit relying on a PCM-3362 Single-Board-Computer complemented by additional I/O boards to provide analog, digital and serial communication channels. Table 3.2.1 reports the number of channel needed and the association with physical devices.

A fiber optic link is provided by the ROMEO ROV system for the development & test phases. The tether used for Romeo contains two single-mode fibers and a pair of copper wires used to transfer power from the surface in order to have the maximum possible autonomy. This cable is part of the kit of optical fiber communication system Focal Technologies 903 Video/Data multiplexer.
The system is composed by:

- 1 channel Ethernet 10 Mbps,

- 5 x RS 232 @ 115 Kbps,
- 5 x 422 @ 250 Kbps,
- 4 videocomposite analogic signal channels.

Table 3.2.1 ROMEO ROV channels

Sensor/Actuators/Devices	Dig Input	Dig Output	Analog Input	Analog Output	RS 232 channels
Thrusters	9	16	8	8	0
IMU + GPS	0	0	0	0	1
IFZ camera	0	6	0	0	0
CTD	0	1	0	0	1
PA500 sonars	0	2	0	0	2
Lights	0	3	0	0	0
Temperature	0	0	1	0	0
Batt. Voltage	0	0	1	0	0
Batt. current	0	0	1	0	0
Total	**9**	**28**	**11**	**8**	**4**

The Romeo's power supply system is constituted by source of batteries charged by a pair of ac/dc converters fed from a 220V AC source through the tether. The battery block is composed of a certain amount of cells Cyclon 2V and 5 Ah. Each block contains 64 cells divided into two parallel 32 placed in series between them, with a total voltage of about 64V 10 Ah. The choice of this voltage is due to the value of the nominal voltage of 60V required by the electric motors mounted in the thrusters.
Romeo can install up to three cylinders (30Ah), one next to the master cylinder and two in the slide, or 1 (only 10Ah) in the case that the slide is dedicated entirely to the payload. Each cell must be charged at constant voltage of 2.45V and constant current to be determined in relation to the charging time, there are no limits of charging current. Then, blocks of 32 cells will be charged at a constant voltage of 78.4V. The value of a cell charge without load is 2.13 V, then each cylinder without load will present at its terminals a voltage of 68.5V. During the discharge the voltage of each cell must not fall below 1.5V, 48V for each cylinder. A brief description of the ROMEO's Cyclon battery is depicted in Fig. 3.2.3.
The thrusters of Romeo contain a DC brushed motor, its shaft is connected to a tachometer dynamo and in the other side to the propeller through a flexible coupling and a system of dynamic seal with mating-type graphite / ceramics.
The three-bladed propellers were designed to take full advantage of the characteristics of the employed electric motors. Its physical characteristics are the following: weight in air: 8.7 kg; weight in water: 5.7 kg; volume: 3 liters.

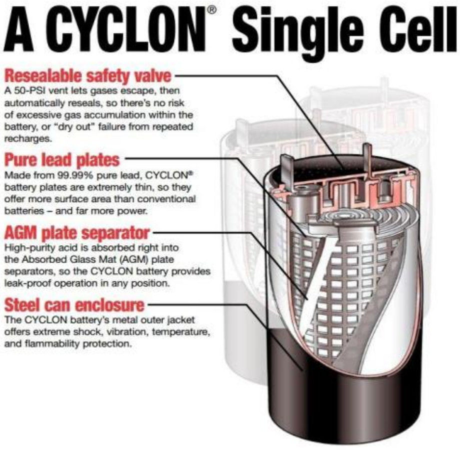


Fig. 3.2.3 ROMEO's Cyclon battery description

The thrust curve is depicted in Fig. 3.2.4.

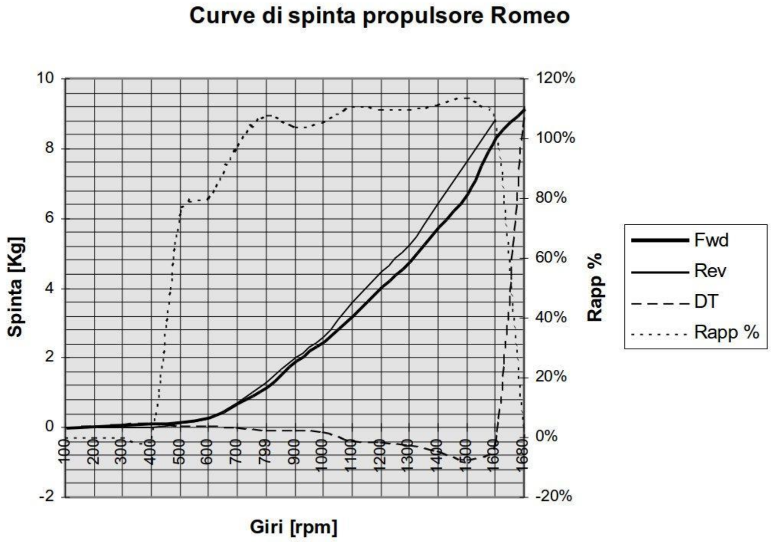


Fig. 3.2.4 Thrust curve

The navigation package is composed by an integrated GPS and Attitude Heading Reference System (AHRS), providing absolute position fix (when surfaced) combined with attitude measurements and IMU-based linear and angular velocity readings. The GPS-AHRS system is a Microstrain 3DM-GX3-35. The R2 ROV is also equipped with a Tritech PA200 altitude sensor with a range of 0.7 - 100 m and resolution of 0.025% of the range.

The custom software architecture developed for the control of the R2 ROV is linked to a ROS wrapper (as already described previously for the Charlie USV in section 3.2) in order to share telemetry and commands with the other nodes of the framework. In Fig. 3.2.5 a preliminary test of surface and underwater autonomous vehicles cooperation is represented.

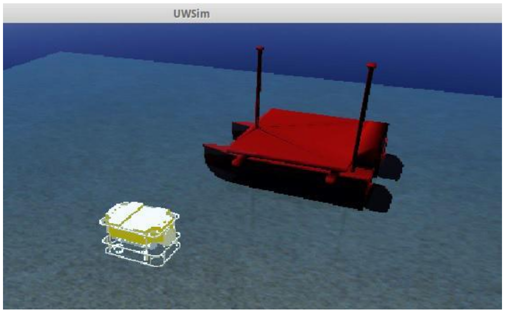


Fig. 3.2.5 Surface and underwater segments cooperation

The R2 guidance and control system allows the use of the vehicle in: *i*) manual mode, directly driving the surge, sway, heave forces and yaw torque, usually employed when the vehicle is command through a joystick; *ii*) velocity control mode, the vehicle tracks the commanded velocity profile along surge, sway, heave directions and rotational velocity, i.e. yaw-rate; *iii*) position control, the vehicle can execute go-to/station-keeping actions, as well as auto-heading, or (as for the Charlie USV) general path-following guidance.

Fig. 3.2.6 reports the time response of the angular position control, underlining the good tracking performance of the regulation system. Fig. 3.2.7 shows a go-to/station-keeping execution, where the vehicle is commanded to keep the position on one desired location and then to move towards another reference point. Fig 4.2.8 reports the time response of the positioning control of the two separated Cartesian coordinates.

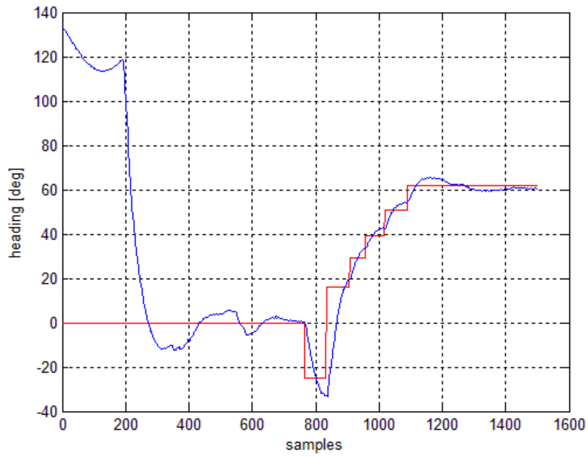


Fig. 3.2.6 R2 heading control system response

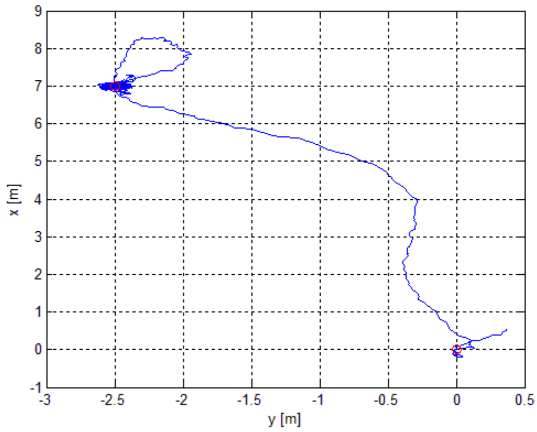


Fig. 3.2.7 Horizontal position control behavior

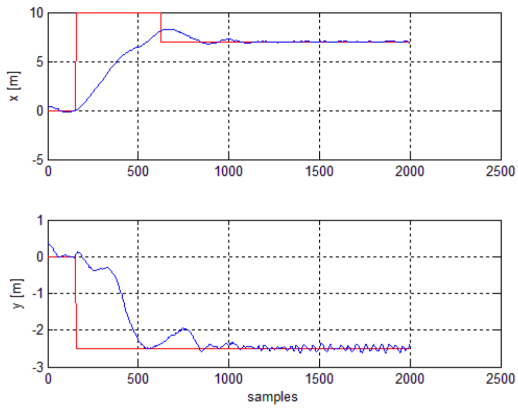


Fig. 4.2.8 Time response of position control

The mission planning and control system described for the Charlie USV is integrated in the R2 overall software architecture, allowing the execution of high level autonomous operations.

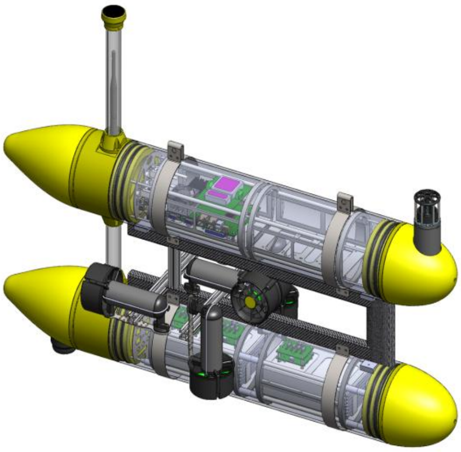
3.3 Medusas (IST)

As described in Section 2.3 (Surface segment) the MEDUSA$_D$ vehicles (diving version) not only have the same functionalities/capabilities of the MEDUSA$_S$ but also the capability to move vertically in the water column using vertical thrusters.

For the CADDY project the "BUDDY" vehicle needs to maintain itself in the human diver field of view (to allow the diver to see it) while simultaneously i) keeping the human diver in its own field of view (for camera/ sonar based diver tracking) and ii) following arbitrary paths or illuminating the seafloor in an arbitrary direction. To be able to perform these manoeuvres the "BUDDY" vehicle is required to have lateral actuation. As such, with the objective of contributing to the pool of vehicles available for tests in the scope of the project, the MEDUSA$_D$ vehicles are being modified to accommodate a new additional thruster with custom mechanical parts developed in-house.

Moreover, the leader tracking and underwater path-following controllers are being redesigned to take advantage of the vehicle sway motion.

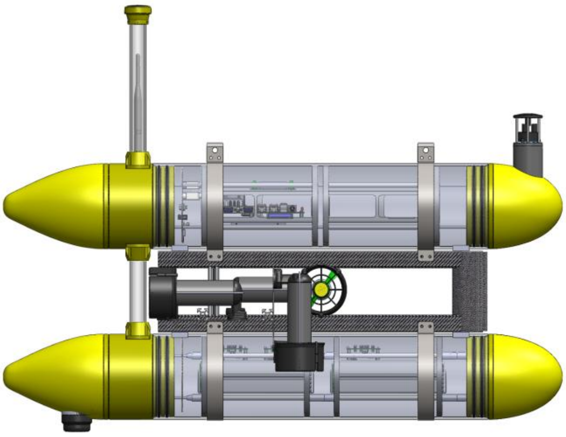
Fig. 3.3.1 and 3.3.2 shows the 3D model of the modified vehicle with the modem/USBL developed by Newcastle University and an extra lateral thruster.

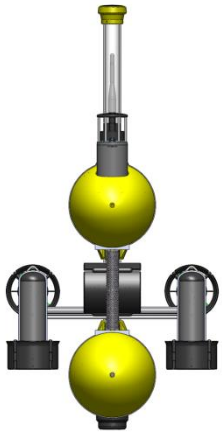


MEDUSA$_D$ (Diver) Particulars	
Length	1035 mm
Height	875 mm
Tube diameter	150 mm
Weight in air	30 kg
Energy (LiPo)	830 Wh
Endurance	9 h at 1.5 knot
Propulsion System	5 thrusters

a) b)

Fig. 3.3.1 The MEDUSA$_D$ vehicles: a) isometric view, b) main particulars





a) b)

Fig. 3.3.2 The MEDUSA$_D$ vehicles: a) side view, b) front view

4 Interfacing the diver - Underwater tablet

This section provides the description of the dedicated devices needed to interface the diver with the robotic platforms. UNIZG-FER have developed an underwater tablet case made of Polyacetal (POM-C) (Appendix1_UNIZG Page_19) and tempered glass (Appendix1_UNIZG Page_17-18). The main purpose of the casing is to hold a commercially available tablet that is used by the diver as an interface to the vehicles. The tablet case is designed in symmetrical form to implement 5 mm thick transparent tempered glass lids onto both sides of the housing (Fig. 4.1). This will allow use of the rear camera on tablet, and also due to stiffness of tempered glass, less sagging caused by external pressure. O-ring groove is identical on the both sides and accommodates silicone rubber o-ring seals from 5.7 to 6 mm in section diameter. It will use DIN6336 star-grip M8 threaded knobs for clamping. Rear lid will be fastened and independently sealed with the housing frame via 8 DIN7380 M5 screws with rounded head. All additional brackets, supports and equipment will be bolted to the sides of the frame (holes will be drilled and tapered once all the brackets and extras are defined). For testing purposes 5mm lid thicknesses are used. In this configuration weight of the housing (in air) should be around 3900 grams with tablet and fasteners. This setup is tested successfully at 25 meters (Fig. 4.2).

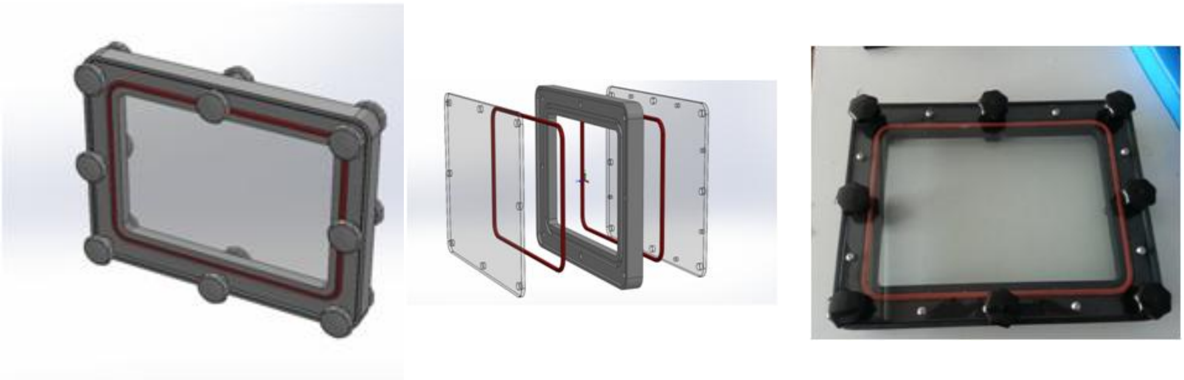


Fig. 4.1 Computer model and manufactured tablet case.

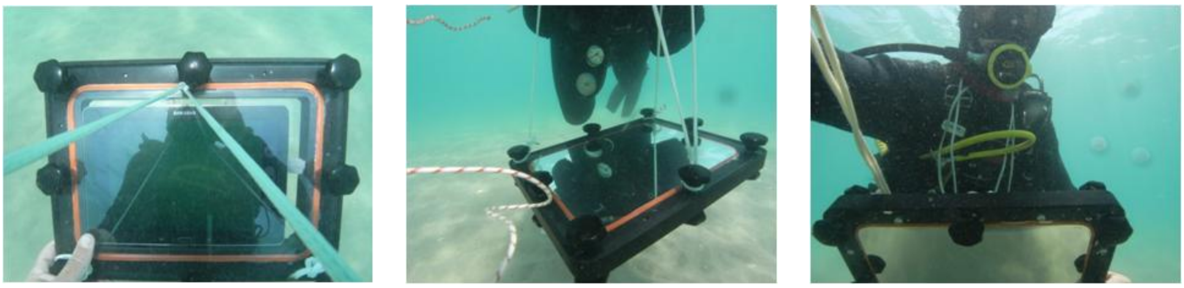


Fig. 4.2 First pressure and functionality tests underwater

5 Data distribution network

The different robotic platforms and the diver tablet are able to communicate among themselves thanks to an acoustic link which relies on the modem/USBL devices developed by UNEW.
The devices, depicted in Fig. 5.1, are detailed described in Deliverable D1.2.1 "Initial communication transceiver units, protocols and software".

a) b) c)

Fig. 5.1 X110 Modem Prototype, b) X150 USBL Prototype, c) X150 Modem Line Drawing

6 Integration, experiments and performance evaluation

6.1 UNIZG-FER

UNIZG-FER has carried out a number of experimental trials focused on the integration of instruments onboard its robotic platforms, as well as early

- **Experiments on lake Jarun, Zagreb**

Experiments on Jarun lake in Zagreb have been performed to test the DVL and the new PlaDyPos control architecture and modifications.

- **Experiments in Israel, 19-25 May 2014**

These experiments were not charged on the CADDY project. However, we managed to use this campaign to test the PlaDyPos control architecture and performance of algorithms in real life scenarios.

- **Experiments in Split, 20 June - 5 July 2014**

These extensive experiments took place at the venue where the validations trials will be performed. The UNIZG-FER team made preparations for the validation trials and tested the diver tracking abilities of the platform. Structured experiments where PlaDyPos followed the virtual diver, an ROV and the real diver were successfully executed. In addition to that, first trials with the BUDDY AUV were performed. This was a major step towards the completion of the BUDDY AUV (Fig. 6.1.1).

Fig. 6.1.1 Photo taken during the Split trials in June 2014.

- **Experiments in Split and Biograd, 21 September – 10 October 2014**

First round of these experiments took place at the same venue in Split while second round took place in Biograd na Moru during the BtS workshop organized by the UNIZG-FER. The UNIZG-FER team tested again the diver tracking abilities of the platform, this time with the new USBL system developed by the CADDY partner, University of Newcastle. Initial results showed comparable tracking quality performance with significantly improved bandwidth of the communication channel. Main goal of the experiments was testing of the BUDDY AUV. Functionality of the presently integrated payload, DVL, both cameras and ARIS sonar as well as manual motion control of the vehicle were successfully executed.

6.2 CNR

A full week of experiments of the R2 ROV was carried out in Biograd (Croatia) during the BtS workshop organized by UNIZG-FER, in the period 5-12 October 2014. The experiments were mainly focused on the vehicle performance characterization, navigation guidance and control modules tuning, adaptation of the software architecture towards the CADDY framework. During the trials, early work focused on the human-robot interaction was performed, collecting images of a diver executing gestures in front of the vehicle. In Fig. 6.2.1 the R2 ROV during guidance test is shown, while Fig. 6.2.2 reports human-robot interaction trials.

Fig. 6.2.1 R2 ROV during guidance test

Fig. 6.2.2 Early human-robot interaction test

6.3 IST

- **USBL experiments at the Oceanarium dock, Lisbon, PT**

The USBL and acoustic modem units, manufactured by EvoLogics GmbH, Germany are property of IST and were brought into the CADDY project to test cooperative navigation and control algorithms at an early stage of the work program. At the beginning of the second year of the CADDY project, the units will be replaced by the new, highly performing communication and USBL systems under development by the University of Newcastle (CADDY partner). Nevertheless, it was judged useful to test the existing units and assess their performance, with a view to better understand the type of performance that can be achieved with navigation and control. The units achieve data transmission rates of 9600 bps, range measurements with a standard deviation of 100 mm, and angular measurements with standard deviations of 5 deg. These figures were computed based on data acquired during experiments conducted at the *"Oceanarium dock",* in Lisbon, Portugal, using one $MEDUSA_S$ vehicle doing path-following manoeuvres in the neighbourhood of another MEDUSA vehicle "sitting" at the bottom of the dock on a "tripod", see Fig 6.3.1

Fig. 6.3.1 A MEDUSA vehicle "sitting" on a tripod, ready to go in the water for USBL calibration purposes.

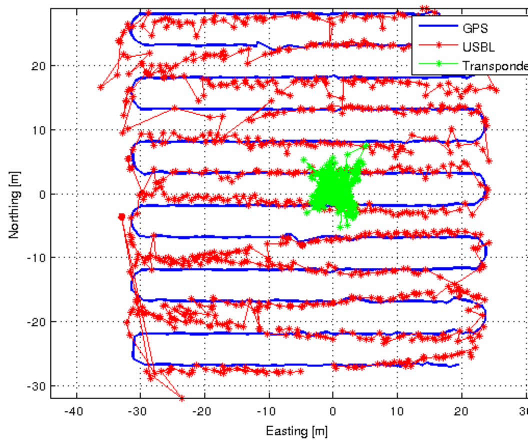


Fig. 6.3.2 USBL data acquired data with two Medusa vehicles

Fig. 6.3.2 shows the results obtained during one of the trials with a USBL unit, whereby the stationary MEDUSA acts as a proxy to an acoustic transponder. The “transponder” position estimated by the USBL+GPS of the moving vehicle is plotted in green. Assuming that the location of the transponder is known *à priori* it is possible to calculate the position of the moving vehicle, plotted in red. From the data obtained it was concluded that an accurate attitude unit calibration is needed and the navigation algorithms should handle large periods of time without USBL fixes. Most certainly these periods will be even longer in the presence of air bubbles resulting from the air exhaled by the diver. It must be stressed that the data shown were obtained under very “harsh” conditions: because the maximum height of the water column is approximately 4 meters, acoustic propagation is plagued with severe multi-path effects. The performance of the USBL is expected to improve substantially when the depth of operation increases (and the slant range decreases). Nevertheless, it is important to explicitly address the situation where diving operations take place in very shallow water and to carry out a thorough analysis of the USBL unit that will be provided by the Univ. Newcastle.

- **Surface-Leader tracking experiment at the Oceanarium dock, 29 May 2014, Lisbon**

This experiment was conducted to validate the leader tracking controller: one vehicle at the surface performed a path-following manoeuvre using GPS while the other vehicle underwater tracked it using its own USBL, see Fig. 6.3.3.

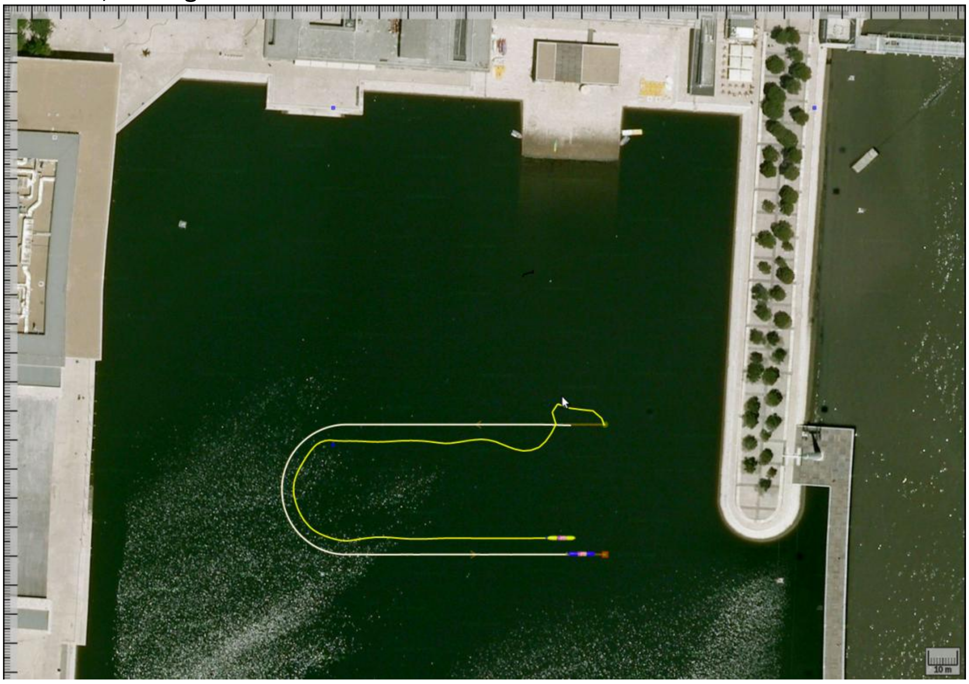


Fig. 6.3.3 Surface-Leader Tracking Experiment (leader in blue and tracking diver in yellow)

- **Underwater-Leader tracking experiment at the Oceanarium dock, 28 November 2014, Lisbon**

To achieve the diver guidance scenario where the “BUDDY” diver vehicle must follow a path underwater while it maintains the human diver in its own field of view, experiments were done using two MEDUSA vehicles. Fig. 6.3.4 shows a path-following mission executed by an underwater vehicle (represented in yellow) while a surface vehicle (in blue) tracks its movement using an USBL; red dots denote the acquisition of USBL fixes.

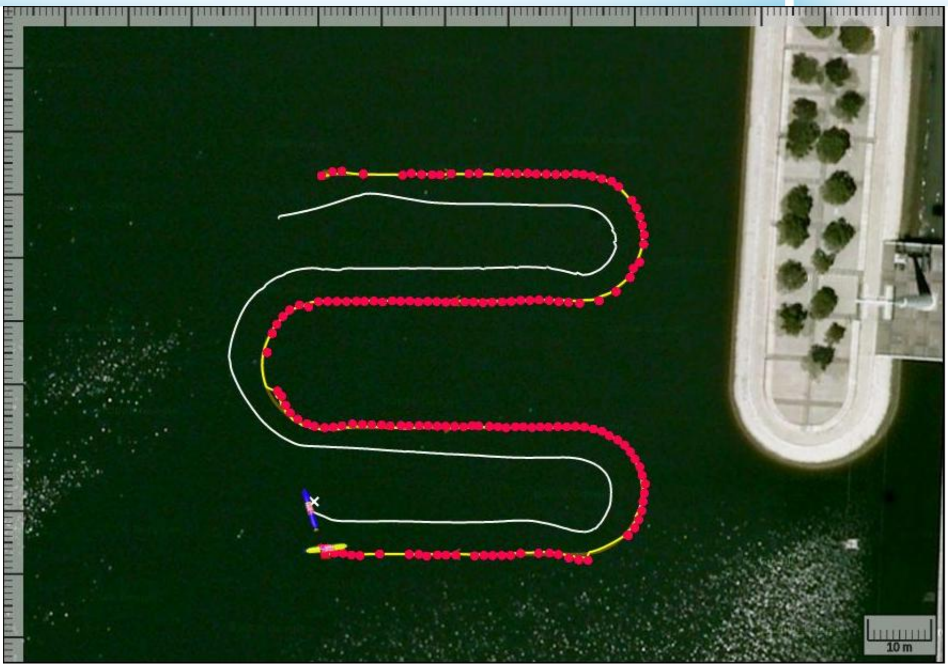


Fig. 6.3.4 Underwater-Leader Tracking (leader in blue and tracking diver in yellow)

6.4 Multi-vehicle integration

Different scenarios for the evaluation of the cooperative robotic capabilities are proposed as follows:

1) **First scenario** - is envisioned only as a test for guidance and navigation tasks.

MOCOS leading -> it executes a single-vehicle path-following (i.e. it explores an area)
RECUV follows -> it executes path-following tracking the master (MOCOS) vehicle
DIVER follows RECUV -> he/she executes LOS on RECUV position (LOS seems to be, in our opinion, the only way a human pursues a target)
It is supposed that the DIVER always remains in proximity of RECUV.

2) **Second scenario**, cooperative path-following:

MOCOS + RECUV -> cooperative path-following - they both regulate their speed to maintain a vertical configuration, moving together along the desired path.
DIVER follows RECUV by LOS.
In this scenario, if the DIVER gets lost (goes outside a boundary ball around RECUV), the path-following is stopped; then RECUV performs LOS toward the last known DIVER position and MOCOS tracks the RECUV position, until the DIVER is recovered within the formation.

3) **Third scenario** - RECUV guiding the DIVER and MOCOS tracking both.

RECUV: wants to stay within the field of view of the diver, so that a) it can observe the diver at all times, b) the diver can see the RECUV which is pointing in the direction where the diver should go to reach the goal.
MOCOS: positions itself at the surface, between the buddy and the diver, thus keeping a triangular formation
If the diver is going toward the specific location, then the RECUV positions itself at the intersection of the circle surrounding the diver (ensuring that safe distance from the diver is maintained), and a line connecting the diver and the target location. I.e. the buddy points toward the target, as shown in Fig. 6.4.1.

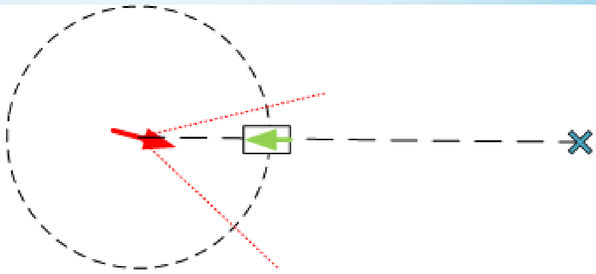


Figure 6.4.1 RECUV pointing the target spot.

If the diver has decided to follow another path, as shown in Fig. 6.4.2, buddy positions itself at the edge of the diver's field of view, pointing to the direction where the diver should be going.

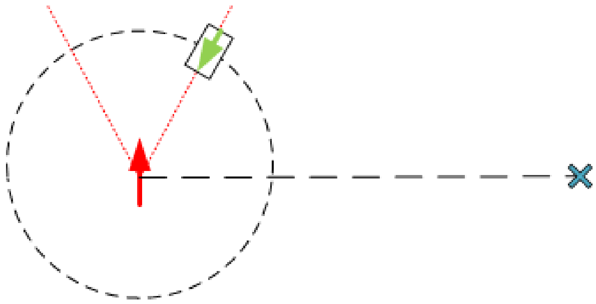


Figure 6.4.2 RECUV pointing in the direction to drive the diver.

7 Conclusions

The deliverable has described the different robotic platforms employed by the project partners and put at disposal of the CADDY cooperative framework. The adaptations performed to each robotic vehicle (both surface and underwater) related to the specific project requirements are reported. Sets of experimental trials report the vehicles capabilities and performances.
The description of the underwater tablet for the interaction with the diver is also reported.
The next steps are the integration of the acoustic communication infrastructure, in order to allow information flow among the agents composing the CADDY framework, and the development of the cooperative actions and procedures allowing the robotic system to coordinate its behavior with the diver needs during operations.

8 Appendix1_UNIZG

This appendix includes all electrical schemes, hardware schemes and datasheets of all equipment used in Buddy vehicle.