Grant Agreement No. 611373

FP7-ICT-2013-10

D4.1. Cooperative control and navigation with diver in the loop - HIL simulation results

Due date of deliverable: 01/2015
Actual submission date: 03/2015

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

Organization name of lead contractor for this deliverable: CNR

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 describes the cooperative motion functionalities provided by the companion robot. Methodologies definition and initial algorithms for robotic buddy "observer", "slave" and "guide" features are reported.
Simulation of the different functionalities carried through Hardware-In-the-Loop (HIL) simulator and test of the switching conditions between the functionalities are reported and evaluated.

The idea developed in the framework of the CADDY project to assist and monitor the diver operations refers to three main functionalities that the robotic system has to provide to comply with the desired tasks:

- dive buddy ``observer'' - the system observes the diver at all times during the dive and interprets her/his behavior by assessing for example the body state, detecting the onset of nitrogen narcosis and signs of panic, and interpreting symbolic gestures communicated by the diver. 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;
- dive buddy ``slave'' - the system affords the diver a ``helping hand'' to examine the environment; e.g. hovering over a spot indicated by a laser beam operated by the diver and taking photos of the location, following the diver and acquiring a series of overlapping photos for mosaic making, illuminating a site from different angles upon request from the diver, and carrying a payload with tools and equipment;
- dive buddy ``guide'' - the system is in charge of actually guiding (upon request) the human diver from one spot to another, along a predefined search path, or steering the diver safely (in case of an emergency) to an appropriate point at the surface without violating basic diving rules and acting as an intelligent communication router in situations where the diver loses line-of-sight to the surface vessel.

In order to provide agile manoeuvring capabilities and maintain formations, such that diver safety and situational awareness is ensured even in unpredictable situations, a suitable management and supervision architecture is developed to fulfil these objectives.

2 Software & communication architecture

The CADDY software architecture, which is based on the ROS system, is mainly composed by the following five interconnected elements:

- diver;
- AUV;
- USV;
- remote control and supervision station;
- environment.

The ***diver*** node can actively interact with the architecture, in particular dialoguing with the AUV (companion/buddy autonomous vehicle - RECUV) in two ways: sending commands through the underwater tablet or performing gestures in front of the AUV camera.
Within the CADDY architecture, the diver node can be simulated through a simple kinematic model (commanded by the user or programmed to execute specific tasks). The node produces all the

navigation state variables (namely absolute position and velocity, body-frame velocity). Being the diver equipped with an acoustic modem, the communication channel is used to send **commands** (generated through the tablet) and **status** data structure which is filled with biological measurements (if available) for instance obtained by heart-beat reader, breath sensor, body temperature, etc.

The ***AUV*** is one of the two completely autonomous agents in the framework. Three of the main sensors equipping the AUV are: *i*) the video-camera which is essential to interact on one side with the diver, allowing the gesture recognition, and on the other side with the environment in order to track or avoid collisions with objects in the operative area; *ii*) the USBL system which is used to detect the relative position of the USV and (theoretically) also of the diver (it will strongly depend on the mounting configuration of the devices, the quality of the acoustic communication/tracking depends on the relative position of the pingers/beacons), *iii*) the sonar system which can be used as a counterpart of the video-camera for detecting the diver and obstacles when visibility is impaired. Through the acoustic channel the AUV transmits the current diver position (if available) and her/his known status, also the body-frame velocity of the AUV itself (the velocity information can be used from the USV to ease the task of cooperative motion or tracking, the AUV position is already known by USV thanks to the USBL measurement and thus it has not to be dispatched) and the operating mode; this latter data is generated by the AUV's mission control system in function of the received commands/gestures.

The ***USV*** is the other autonomous agent of the architecture and its framework-related characteristics are similar to the AUV's ones. It senses the position of the AUV and the diver via the USBL measurements. The USV is directly connected through a wi-fi link to the remote control station, thus the USV can be also exploited as a communication relay to forward information or commands to the underwater segment. The information sent through the acoustic channel are the position of the diver (obtained by the USBL) and the diver status (obtained by information sent by the tablet), the USV also sends it body-frame velocity and operating mode.
The USV and the AUV can dispatch additional information (to be defined) in order coordinate the evolution of the planned mission or to adapt to unexpected situations.

The ***remote control station*** is a supervision point that is used to monitor, first of all, the status of the diver and to track the state of advancement of the mission and/or desired tasks for the robotic platforms. Information can be forwarded to the diver (in turn appearing on the tablet) and commands can be sent to the platforms in order to force a specific operating mode or to update targets, references, etc.

The ***environment*** is a node that has to provide some essential information for the consistency of the framework, as for instance the GPS coordinates of the local origin in such a way that all the nodes can refer their positions to the same inertial frame. A shared clock or time data structure is also needed to synchronize all the nodes and all the variables of the architecture.
Within a simulative framework, the environment will also contain additional nodes and/or data structures in order to represent objects in the area, sea-bottom morphology, physical characteristics involving for instance the quality of the acoustic communication and so forth.

The proposed overall CADDY software architecture is reported in Fig. 3.1.

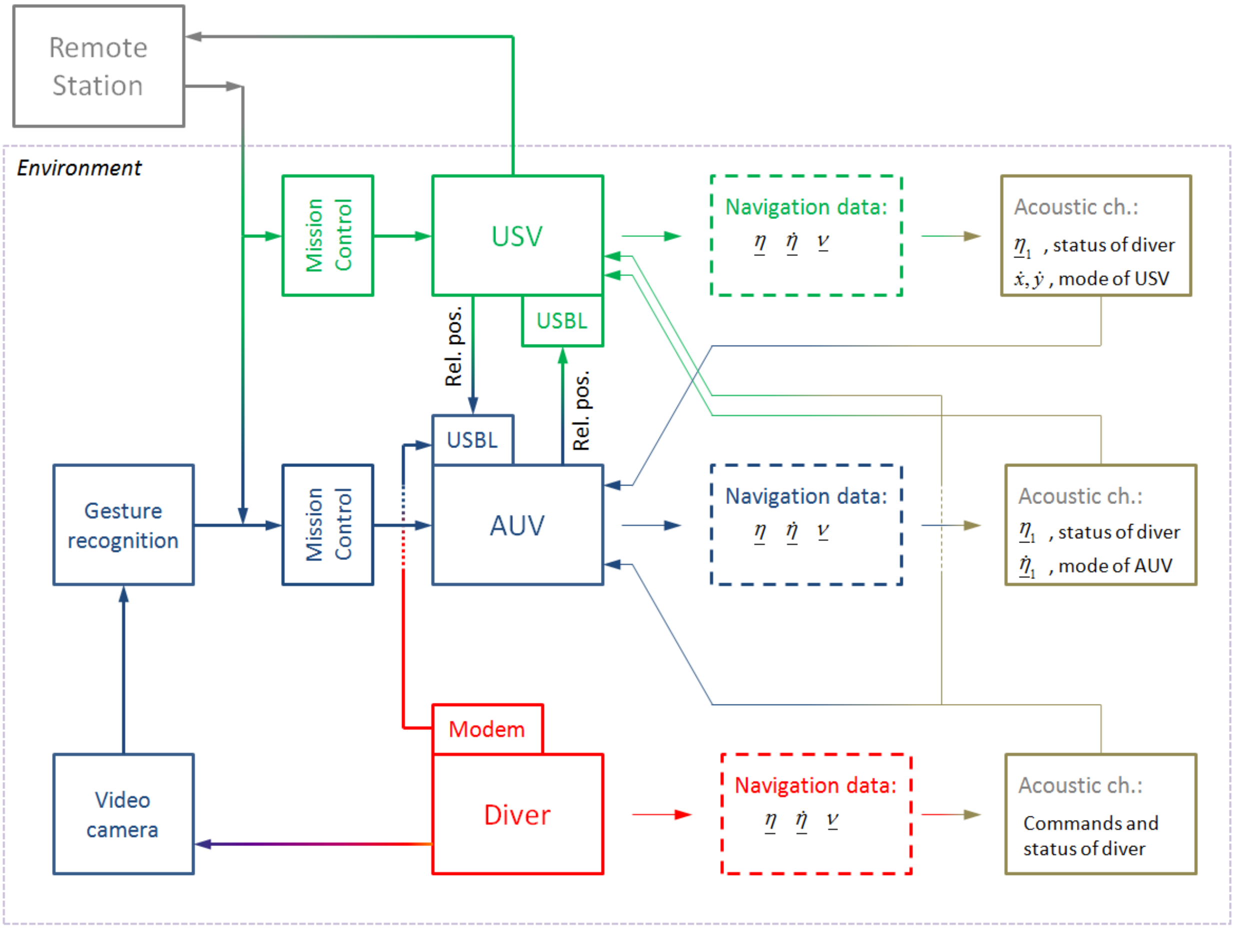


Fig. 3.1. Overall software architecture

The diagram reported in Fig. 3.2 represents the basic set of software modules to be instantiated and tailored for each particular scenario. The “CADDY Vehicle Wrapper” block represents a generic vehicle to be used for the CADDY project wrapped with the necessary interfacing software such that it complies to the standard interface adopted for CADDY.

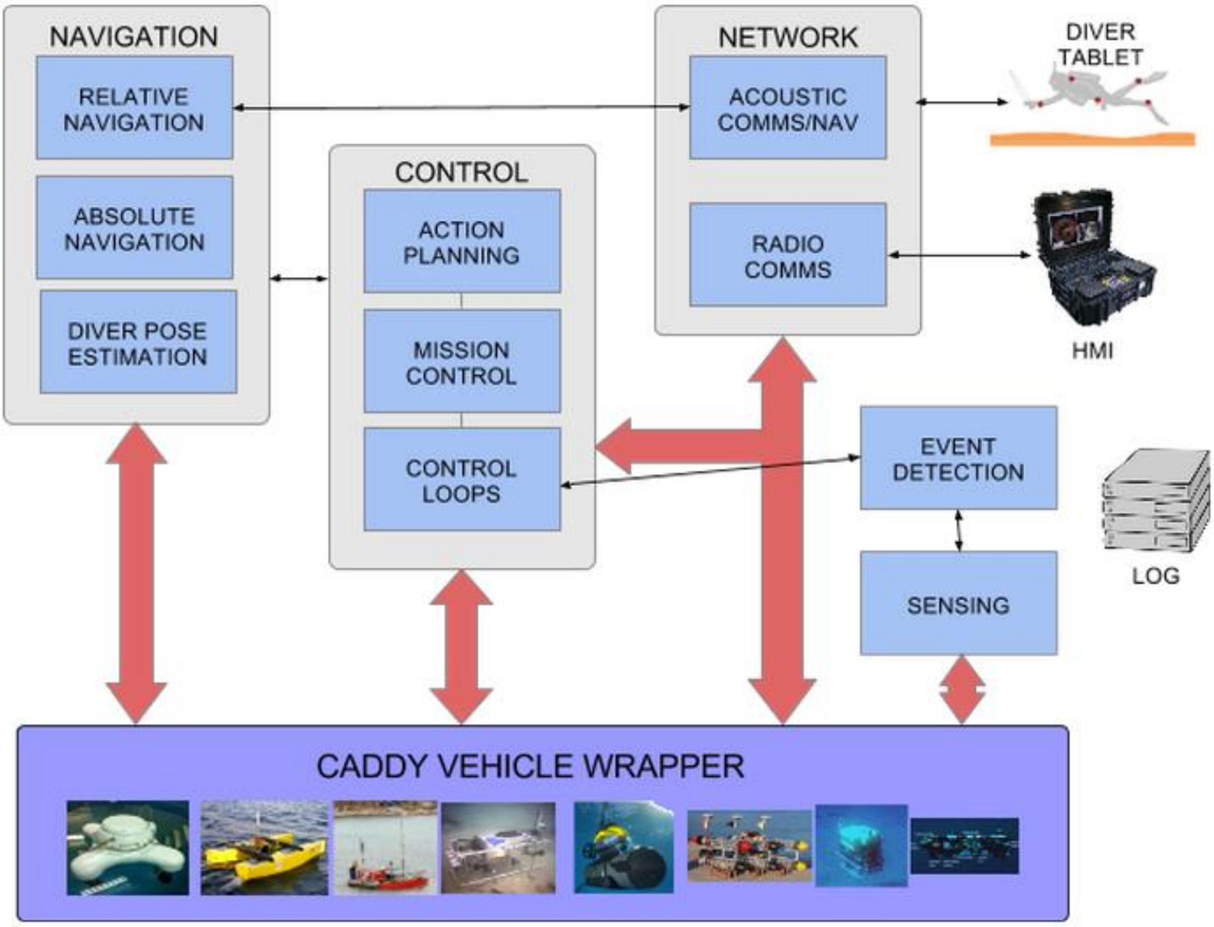


Fig. 3.2. Basic software module scheme

3 Dive buddy functionalities

3.1 Observer

The ***diver observer*** functionality is one of the three key functions needed to approximate the human diving buddy. As a diver "observer", the system observes the diver at all times during the dive and interprets his/her behaviour by assessing for example the body state, detecting the onset of nitrogen narcosis and signs of panic, and interpreting symbolic gestures communicated by the diver. 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 functionality addresses the issue of diver safety that has been identified as the most important issue during cooperative diving with autonomous vehicles. The ***diver observer*** is always close to the diver, it can interpret the diver behaviour (based on posture, heart rate, temperature, inhalation rate of the lungs etc.), detect anomalies, and promptly report any deviations from a normal condition to the diving supervisor in the command centre (on-board a support vessel or on-shore). Another aspect of safety is considered through ensuring that the diver-robot interaction is safe for the diver at all times by maintaining a safe perimeter around the diver.

The main technical challenge the observer functionality has to overcome is positioning the Buddy vehicle in an efficient way to enable use of the available sensors for detecting diver behaviour and recognizing gestures. This requires integration of as much sensor measurements as possible to receive an accurate diver position and orientation estimate. Good knowledge about diver position is required to keep the diver safe and maintain the vehicle outside of the safety operational radius around the diver. Alternatively, safety radius violation has to be detected by the observer in order to stop the vehicle operation. The diver observer functionality can be extended on the surface vehicle in order to have additional security in case the underwater Buddy fails during operation. The autonomous surface vehicle, ASV, has to follow the diver to ensure the best acoustic channel for data transmission and diver position updates.

Sections 5.3 will present a step-by-step hardware in-the-loop simulation and results about the ASV diver observer functionality. Available results from simulations as well as the validation results during filed trials with a human diver are presented. Section 5.5 will present the simulation scheme for the Buddy vehicle focusing on the observer aspect and the pointer concept. The pointer concept extends the observing functionality with passive guidance where the diver decides when to follow the Buddy which can point him towards the desired location.

3.2 Slave

When acting as ***dive buddy "slave"*** the system affords the diver a "helping hand" to examine the environment and perform all the dive-related tasks. For instance command the autonomous buddy can be commanded to hover over a spot indicated by a laser beam operated by the diver and taking photos of the location, following the diver and acquiring a series of overlapping photos for mosaic making, illuminating a site from different angles upon request from the diver, and carrying a payload with tools and equipment.
Moreover, in challenging underwater operations, such as excavation or documentation of archaeological sites, the most sophisticated methods used in underwater archaeology include the use of side-scan sonars and magnetometers to detect and survey underwater sites with high precision. Underwater site surveying is usually performed through documenting (recording) and excavation. Even though recording (mapping) of the site is nowadays commonly performed by using autonomous (or remotely operated) underwater vehicles, the excavation phase still remains a task that only divers can perform. It must also be stressed that during the recording phase, the structures at the site are often buried beneath the sediment, eroded, broken up, and scattered thus making them difficult to see by resorting solely to underwater vehicle recording. In addition to this, visibility may be extremely poor.
The most common practice when performing underwater excavation or documentation of an underwater site with divers is as follows. Firstly, a grid consisting of multiple rectangular frames is placed above the site, thus allowing for proper referencing of site objects in the generated frame (Fig 1.1c)). This grid is carefully levelled above the site and is used by divers to communicate the location of a specific object among them. Once a diver has finished the particular mission underwater (due to limited dive time), (s)he must report to another diver at the surface where the documentation task was stopped. The second diver must then descend to the reported area to continue documentation/excavation of the site. The point of diver entry into the water is often not exactly above the place where the underwater operations should take place. This means that the diver has to search for the locality and waste precious air and time (s)he is allowed underwater. More than often, the second diver misses the section and simply continues operation at a different point. The documentation of a site is traditionally done by measuring, drawing sketches, and taking photos of objects found at the site. A problem that has been reported by experienced divers is that of poor illumination while taking photos. Even though diver cameras are equipped with powerful flashes, the

problem is in the overall illumination of the object from different angles. The common practice while filming an underwater site is to have multiple divers around the object of interest, holding flashlights from different angles. The coordination of the illumination is a tedious task that is more than often accomplished in an unsatisfactory way, especially when currents are present.

It is also acknowledged that since divers have limited time available underwater, they will often decide to change the mission plan on the go, e.g. if the diver decides that (s)he will not have enough time or strength to excavate an object, (s)he can decide to move over to another part of the site, thus changing the mission.

CADDY contributes significantly to the quality and effectiveness of underwater operations that require human attention by enabling the ***dive buddy "slave"*** functionality, simultaneously with the dive buddy "guide" capability described afterwards. As a consequence, the need to setup reference frames will be overcome, thus reducing significantly the time of operation. CADDY will enable precise navigation of the diver to the archaeological site using an optimal route. In addition to this, the cognitive buddy system will be able to interpret diver's symbolic commands and assist her/him in underwater operations by executing compliant tasks (the dive buddy "slave" capability). The operations envisioned include photo and video taking upon diver's request and illuminating a selected area. If the diver changes the mission plan on the go, CADDY will ensure interpretation of the altered mission plan reported by using hand gesticulations, commonly used in the diving community. CADDY will also ensure immediate reporting of the changed mission plan to the command centre (on-board a vessel or on-shore).

3.3 Guide

In its function as a dive buddy ``guide'', the overall CADDY system is in charge of guiding (upon request) the human diver from one place to another, possibly along a predefined search path, or steering the diver safely (in case of an emergency) to an appropriate point at the surface without violating basic diving rules and acting as an intelligent communication router in situations where the diver loses line-of-sight to the surface vessel. To this effect, the diver can either be guided directly by the accompanying autonomous surface vehicle (the surface segment of CADDY), or the underwater robotic dive buddy. In this report, as a first step towards meeting the functional objectives of the CADDY system, we address the situation where the diver is guided by the underwater robotic buddy but focus, as a stepping stone towards achieving the guide functionalities, on the system that allows for cooperation between the surface and underwater vehicles.

The system, henceforth called Leader Tracking System (LTS), allows for one vehicle (playing the role of a follower) to track the motion of another vehicle (that plays the role of a leader). The LTS is at the core of cooperative maneuvers whereby *the underwater vehicle (the robot companion) is guided by the surface vehicle along desired trajectories.* In this situation, the autonomous surface vehicle (ASV) trajectory acts as a reference or leader (in 2D) and the autonomous underwater vehicle (AUV) must track this reference in the horizontal plane (albeit with a desired x-y offset, if required), while undergoing independent motion in the vertical plane (e.g. staying at a constant depth or constant altitude above the seabed). This technical problem is sufficiently rich in that its solution sheds light into the solution of other cooperative motion problems that are key to the implementation of the CADDY concept. Furthermore, the problem can be simply motivated by an interesting missions scenario that can be referred to as the "guided tour": one or more divers are interested in visiting an archaeological site, and to this effect they wish to be guided by an underwater "tour guide" that acts as a reference for them to follow visually, at close range. It is therefore up to the AUV to maneuver along a desired, pre-determined "tour path". *Because of stringent navigational constraints underwater, this is done by having the AUV track the reference trajectory set out by the ASV.* This calls for the installation of an ultra-short baseline (USBL) unit on-board the AUV capable of measuring its relative position with respect to the surface vehicle.

The LTS systems allows also for the realization of missions whereby the leader is the AUV and the follower (tracking the leader) is the ASV. This functionality becomes important in situations where the AUV takes over the task of guiding the diver directly (e.g. in response to foreseen events detected on line), and seeks navigation help from the surface vehicle that must track the AUV as the mission unfolds. In this case, the burden of determining the relative position from the AUV to the ASV falls on the ASV, that can either carry an USBL unit (therefore reducing the cost of the AUV) or perform sufficiently exciting maneuvers while localizing the AUV by resorting to range-based localization strategies. In both cases, the ASV is required to transmit updates about the AUV position to the latter vehicle using an acoustic modem.

4 Algorithms for cooperative tasks and simulation results

4.1 Surface Leader and Underwater Leader Experiments: Design and Development Framework

The ability of two or more agents, either vehicles or human divers, to maneuver in a cooperative manner at close distances is critical for the applications envisioned in the scope of the project. To achieve this, the vehicles should use the acoustic channel to exchange motion-related information. Given this setting, the *Leader Tracking System (LTS)* consists of a set of control and navigation-related blocks that, when combined with a strategy for exchanging information, enables one or more agents (followers) to track (follow) the position of a specific agent (leader) on a horizontal plane, with optional x-y offsets defined in a convenient path-dependent manner. The path of the leader agent is unknown a-priori by the follower agents. Motion in the vertical direction is considered to be handled independently by a depth or altitude controller.

The setup of the LTS is general enough for applications in a large variety of scenarios. In this section, after a brief technical description of the system, the results of applications to two such scenarios are presented. The first consists of an underwater vehicle tracking a surface vehicle; the second illustrates a surface vehicle tracking an underwater vehicle. Note that the results on these two scenarios are a solid contribution towards achieving the necessary functionalities in terms of cooperative maneuvers envisioned in the project, since it should be possible to replace one of the vehicles with a human diver with only slight modifications to the system.

The general scheme adopted to run a Leader Tracking maneuver can be best explained by referring to the block diagrams in Figs. 5.1.1 and 5.1.2, illustrating the navigation, control, and inter-vehicle information flow architectures adopted by IST. The illustrations concern the case where the leader vehicle moves at the surface (ASV), tracked by an underwater vehicle (AUV). Later, an extension to the setup is introduced so as to enable the underwater agent (AUV) to play the role of leader.

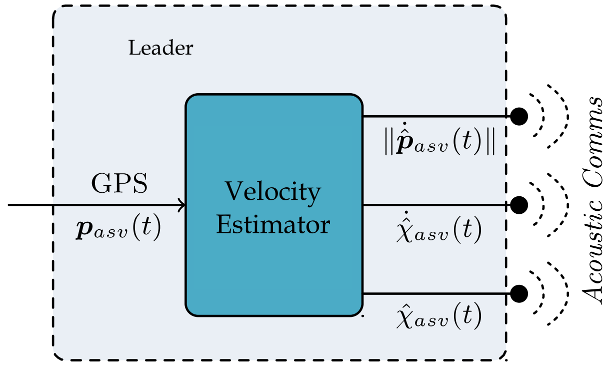


Fig. 5.1.1 Leader tracking system: the leader (ASV) architecture.

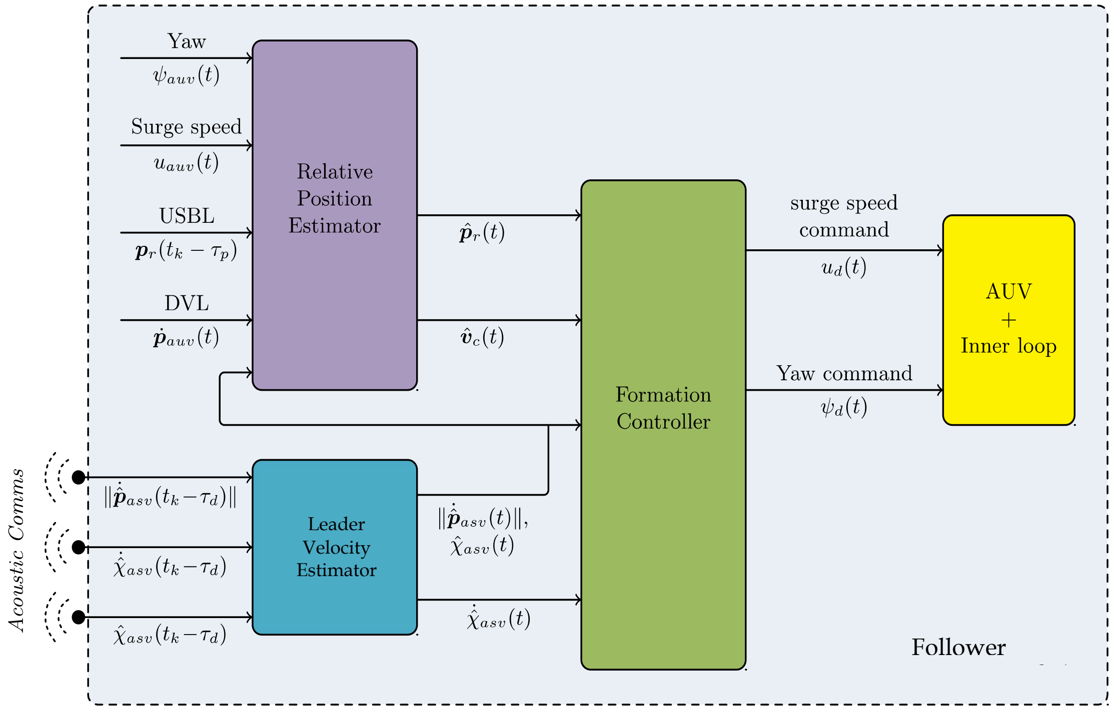


Fig. 5.1.2. Leader tracking system: the follower (AUV) architecture.

ASV Architecture. In the set-up adopted, the leader (ASV) is equipped with a GPS and runs a filter to estimate its inertial speed, course angle, and course angle rate. This information is transmitted to the AUV via an acoustic modem. In its present form, this system running on the ASV is mechanized as a Kalman Filter (KF). It uses the position measurements obtained from a GPS receiver, in an ENU (East, North, Up) reference frame, to estimate the inertial velocity of the surface vehicle in polar coordinates (norm and course angle) and the rate of the course angle. Both the norm of the velocity vector and the rate of the course angle are assumed to be constant in the model used for this KF, therefore the latter embodies in its design model piecewise constant-velocity and constant-curvature trajectories. As an alternative to this filter, when the leader vehicle (in this case the ASV) is moving along a pre-planned trajectory, the *nominal values* of its velocity, course angle and rate of course angle can be broadcast instead. This is typically the case, as the leader vehicle usually performs path-following on a planned trajectory. This is also the case in the experimental results of the system shown in later sections.

AUV Architecture. The system running on a follower vehicle (in this case the AUV) involves four main subsystems:

1. ASV velocity estimator – the follower (AUV) receives the information broadcast by the leader at discrete, possibly asynchronous instants of time (with a time delay) and runs an internal filter to generate estimates of the ASV´s inertial speed, course angle and rate at a rate fast enough to be used for motion control.

2. Relative position estimator – this block is in charge of fusing data available from different sources: i) the ASV's speed, course angle, and course angle rate broadcast by the ASV; ii) the (delayed) relative position of the ASV with respect to the AUV obtained using an Ultra-Short Baseline (USBL) system installed on-board, iii) the velocity of the AUV with respect to the seabed using a Doppler log (this is the case in shallow water; in deep water, the unit can yield both the velocity with respect to the seabed and to the water), iv) Heading, provided by an Attitude and Heading Reference System (AHRS), and v) surge speed with respect to the water, where the latter is estimated using a quasi-static propulsion model that relates the speed of rotation of the vehicle propellers with the vehicle's forward speed. Its output consists of the estimate of the relative position of the AUV with respect to the ASV, together with the estimate of the underwater current, both at a sufficiently fast update rate.

3. Formation controller – this block is in charge of generating commands for the AUV surge speed and yaw angle (tracked by the AUV inner loops) so as to make the AUV track the position of the ASV with a properly chosen, possibly time-varying offset, as per the requirements of the maneuver being performed. In fact, the formation controller can be viewed as the cascade composition of two operations: i) generating a virtual target (determined by the trajectory described by the leader and the requisites of the leader tracking maneuver) and ii) tracking the virtual target. The generation of the virtual target (its position and velocity) relies on the fact that the follower (AUV) has access not only to the relative position and velocity of the leader (ASV), but also to the curvature of its trajectory. In the tests illustrated in later sections, this block is configured so that the virtual target is positioned at a point defined by desired along- and across-path distances with respect to the path defined by the ASV (which, we assume, is either a straight line or a segment of a circumference, or a combination thereof). This allows for the characterization of the trajectory of the virtual target, both in terms of its position relative to the underwater vehicle (follower) and its inertial velocity. These parameters are then fed to a trajectory-tracking controller that forces the actual vehicle to track the virtual one.

4. Inner loops – this block consists of simple PI(D) controllers that attempt to make the surge speed u and heading ψ of the vehicle track the references u_d and ψ_d.

Shifting the role of leader to the AUV. In order to enable the AUV to play the role of leader, additional information exchange over the acoustic channel is required (e.g., to allow the ASV to perform path-following along a pre-planned trajectory without having to resort to an overly expensive navigation system). Specifically, the ASV (which we assume plays the role of follower, but is not necessarily the case) should have access to its position in an earth-fixed frame via GPS, and its position relative to the leader vehicle using an Ultra-Short Baseline (USBL). Based on these two inputs, the ASV can then compute the position of the AUV (leader) vehicle in the earth-fixed frame and broadcast it. The underwater vehicle can now perform path-following based on this broadcasted position. For this scenario, the remainder of the architecture resembles the one shown above, obviously now with the AUV as leader and the ASV as follower.

The work done towards the development of the guide functionalities have progressed well beyond the stage of simulations. In fact, the LTS was fully implemented at tested with two vehicles of the MEDUSA class playing the roles of ASV and AUV. The results of the tests are described next.

4.2 Surface leader experiment

In what follow we summarize the results of practical experiments that illustrate the performance of the LTS in the first scenario: one ASV as leader and one AUV as follower. During the tests, the ASV was requested to perform a U-shaped path-following maneuver at the surface. In the set-up adopted, the virtual target (to be tracked by the AUV) is positioned at a point defined by desired along- and across-path distances with respect to the path defined by the AUV (which, as explained before, is either a straight line or a segment of a circumference, or a combination thereof). The along and cross- path distances were set to -17 and +5 meters, respectively (intuitively speaking, this means that the AUV was requested to stay 17 meters behind along the path and 5 meters to the right). Throughout the maneuver, the AUV was commanded to remain at a fixed depth. The nominal speed of the leader vehicle (ASV) was set to 0.3 m/s.

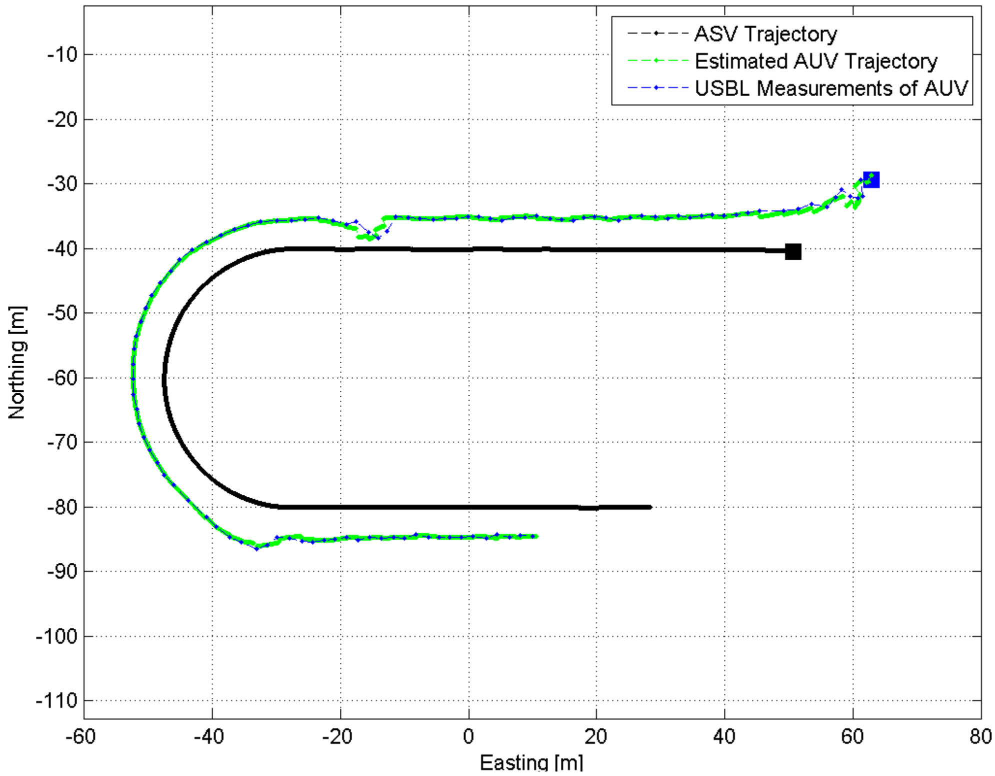


Fig. 5.2.1. Leader Tracking System with ASV as leader: ASV and AUV trajectories.

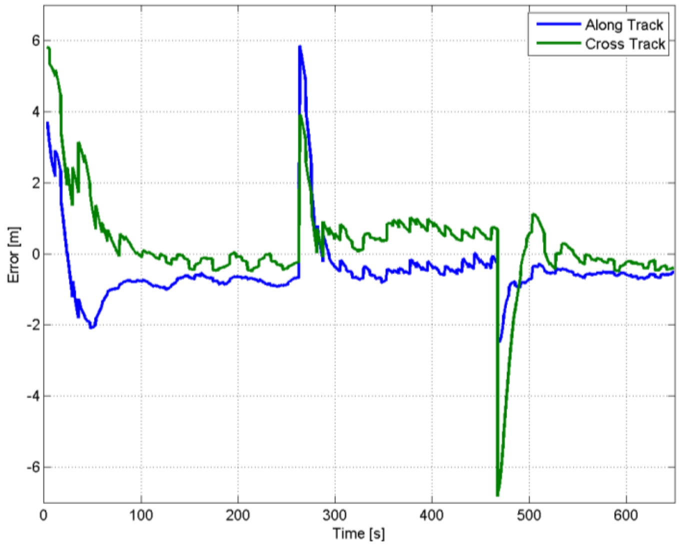


Fig. 5.2.2. Tracking error of the AUV

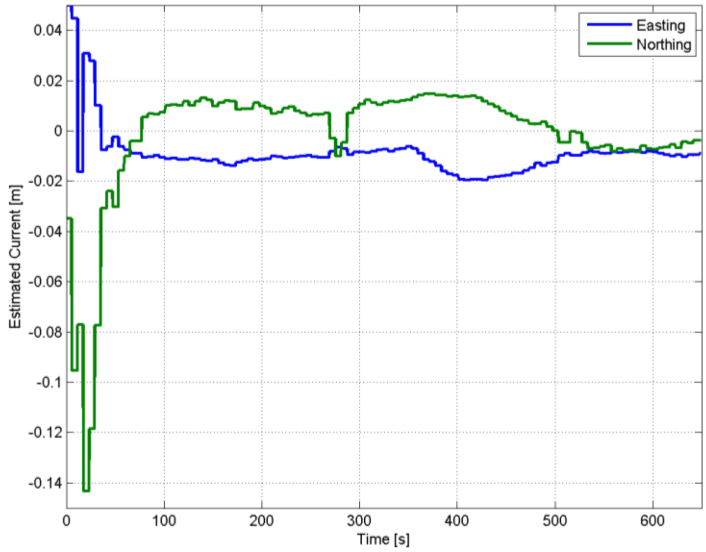
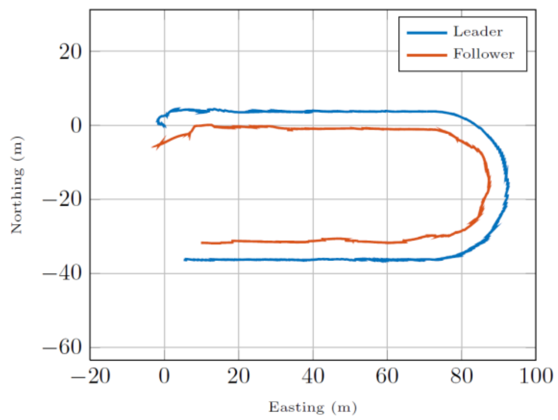


Fig. 5.2.3 Estimate of ocean current on-board the AUV

Fig. 5.2.1 shows the trajectories of both vehicles, and Figs. 5.2.2 and 5.2.3 show the position error (with respect to the virtual target that should be tracked) and the estimate of the ocean current. The performance of the Leader Tracking System illustrated by these figures is visibly good. The deterioration in performance that occurs when the ASV enters or leaves the circular part of the maneuver is simply due to the fact that the along- and cross track position specification for the virtual vehicle (to be tracked by the ASV) are done considering that the circular part of the path is extended backward as a circumference (upon detection that the ASV actually entered the circular path). This was done at the time when these tests were conducted to simplify the implementation of the Leader Tracking system. Meanwhile, this problem has been overcome by extending back the path taken by the AUV taking into consideration the actual path traversed, stored in memory. This is illustrated in the results shown in the next section, which no longer exhibit this problem.

4.3 Underwater leader experiment

The second scenario is illustrated in Fig. 5.3.1 with results obtained with one AUV playing the role of leader, performing path-following on the same pre-defined U-shaped mission, and one ASV playing the role of follower. The ASV was configured to follow 5 meters behind along the path of the leader, and 5 m to the right. The nominal speed of the leader vehicle (AUV) was set to 0.3 m/s.



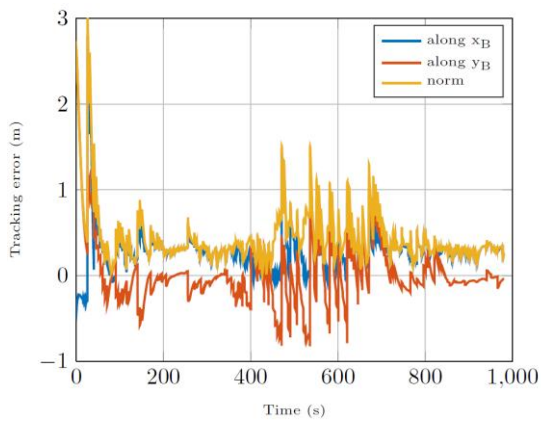


Fig. 5.3.1. Leader Tracking System with AUV as leader.
Left: Trajectories of AUV and ASV. Right Tracking error of the follower (ASV)

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

4.4 Diver leader - ASV follower experiment

The scenario implements the concept of a private diver satellite that enhances the diver's safety. It can be analyzed as the surface version of the ***diver observer*** functionality as the ASV is essentially trying to follow the diver to the best of its abilities in order to observer the diver position and messages sent by the diver. The scenario depends on an autonomous surface vehicle, preferably omnidirectional, that has the ability to localize the diver. The ASV takes the role of a follower (slave) and tracks the diver, positioned above the diver at all time as shown in Fig. 5.4.1. Three main functionalities are performed by the ASV during diver following:

1. the ASV carries the international dive flag and marks the exact location of the diver thus increasing the diver safety. Acoustic communication allows removing the tethering required with static bouys
2. reliability of the acoustic communication and localization is maintained due to the vertical communication path. The communciation is used to forward the diver his geodetic position.
3. the ASV acts as a relay between the surface station and the diver to allow communication between the station and the diver and diver monitoring at the surface station.

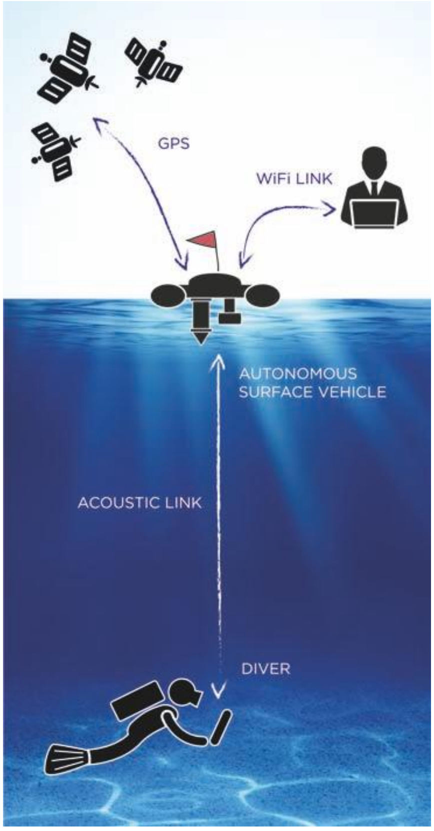


Figure 5.4.1 Diver leader – ASV follower concept

Acoustic diver localization requires the use of an acoustic positioning system, e.g. USBL, where one node is located on the diver and the interrogation node is located on the autonomous surface vehicle. The ASV is knowledgeable about its geodetic position and during the USBL interrogation it acquires the relative position of the diver and by extension the diver's global position. This information is used for dynamic positioning above the diver and for positions updates sent to the diver.

4.4.1 Simulation setup

The simulation setup consists of three separate sub-systems: *a*) the ASV platform, *b*) the acoustic localization and c) the diver. The simulation is implemented in the Robot Operating System (ROS) where the diver and ASV have each their own ROS master. The ROS masters communicate through an acoustic modem simulation that corrupts the diver position information with noise and randomly creates dropouts in the communication. Using this setup the concept can be tested and proven using pure simulation experiments. This was already done in (Miskovic, et al. 2013). However, switching directly from pure simulation to human in-the-loop operation is not advised. Therefore the simulation experiments are refined using the hardware in-the-loop simulations. The experiments are made increasingly complex by introducing new hardware agents instead of simulated ones. In the case of diver leader ASV follower two such iterations are needed:

1. ASV hardware in-the-loop – the diver and acoustic interogation are simulated but the real vehicle is used

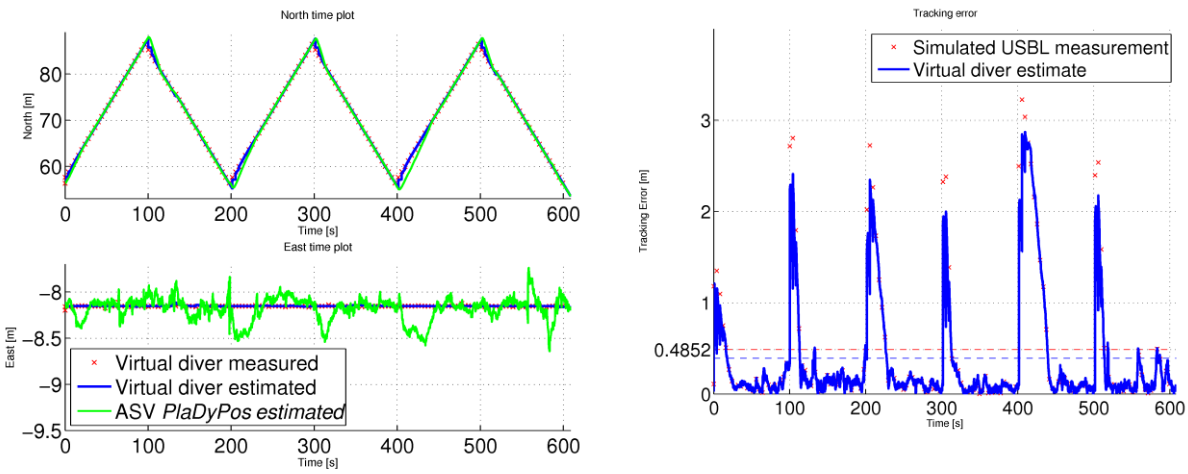
2. ROV hardware in-the-loop – the diver is simulated using a remotely operated underwater vehicle. The acoustics is performed in a real-environment but without any diver interference or diver related noise

The third iteration would introduce a real diver at which stage the experiments no longer contain simulated parts. This experiment can then be used as validation.

Experiments are designed to be repeatable therefore in all scenarios the diver is simulated as moving between two points. This provides an idealized, but easily analyzed, version of the diver movements underwater. On the borders of the transect the diver abruptly switches the course of his movements thus showing the amount of overshoot that can be expected due to slow update rates of the diver estimation filter.

4.4.2 ASV hardware in-the-loop

This experiment replaces the simulated ASV with an ASV in a real environment which follows the virtual diver that is simulated using a kinematic model and operated using a joystick by a user or programmatically for repetitive experiments. While this experimental setup eliminates acoustic sensor and diver related uncertainties, it also allows reliable testing of the ASV behaviour under different measurement update rates and performance evaluation of the diver estimator onboard the ASV in real environmental conditions. Fig. 5.4.2.1 shows the full experiment with virtual diver tracking in duration of around 10 min. While the results given in Fig. 5.4.2.1(a) indicate that the ASV was following the same path as the virtual diver, the real virtual diver tracking quality is observed from Fig. 5.4.2.1(b). Since this experimental setup is influenced only by environmental and uncertainties caused by unmodelled dynamics, we conclude that these uncertainties cause the mean error of about 0.5 m. This error is mostly due to transients that occur when the virtual diver is changing the direction of transect following, as shown in Fig. 3.5.2b.



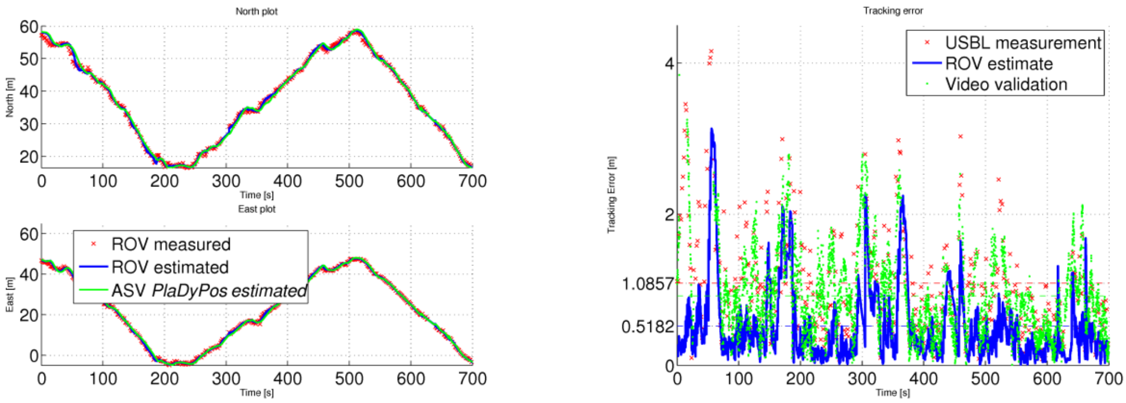
(a) *(b)*

Figure 5.4.2.1 Experimental results obtained from ASV hardware in-the-loop

4.4.3 ROV hardware in-the-loop

This experiment simulates the human with a remotely operated vehicle (ROV) equipped with the acoustic transponder. The ASV carries the USBL thus introducing the real acoustic channel uncertainties but eliminating those caused by the diver. This simulation is designed to identify potential deterioration in system performance due to the acoustic channel characteristics and the overall influence of the acoustic positioning system in the diver following scenario. While in the earlier simulation there was a ground truth diver position to compare the tracking error in this experiment it is unavailable. The ROV system has no localization of its own that could be used. To alleviate the lack of ground truth a camera is added on the ASV to have the option of detecting the diver position from direct observation. Although the video does not represent an absolute ground truth it provides better precision than the USBL system in shallow water with good visibility. The ROV approach allows testing of the complete system without unnecessarily endangering divers with an untested acoustic positioning system. The ROV does not carry the tablet which is used to decode and display the diver underwater position. However, the tablet can be utilised on shore by the ROV operator or diver in-training by connecting the underwater modem and tablet through the ROV tether.

Results in Fig. 5.4.3.1 show 10 min. of the experiment, for the sake of clarity. Result show that the mean tracking error based on acoustic measurements in this setup is about 1 m which lets us conclude that the inclusion of the acoustic sensor uncertainty increases the tracking error by 0.5 m.



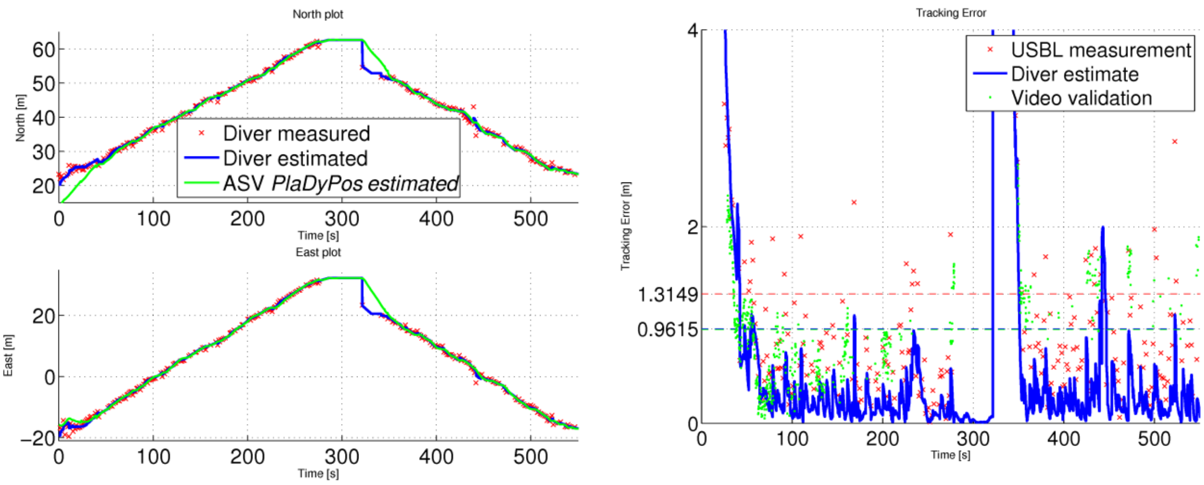
(a) (b)

Figure 5.4.3.1 Experimental results obtained from ASV+USBL+ROV hardware in-the-loop

4.4.4 Validation experiment

Once the hardware in-the-loop simulations are successful the final iteration is full runtime validation of the system without simulated components, i.e. in real conditions. This includes the human diver with disturbances like breathing, unpredicted variations from the path, non-zero roll and pitch, etc.

Fig 5.4.4.1 shows results of diver following during the same transect as in hardware in-the-loop simulations. The mean tracking error across validation experiments is calculated to be about 1.8m.



(a) (b)

Figure 5.4.4.1 Experimental results obtained from the validation experiment

4.5 Cooperative ASV-Buddy Experiment

The cooperative ASV-Buddy experiments, relying on a strict motion coordination between surface and underwater segment systems, is envisioned in the scope of the *Buddy Guide* functionality, where the autonomous systems are responsible for a correct leading of the diver throughout the dive activities.
The main task of this experiment is to develop and exploit a technique to coordinate the motion of the surface and underwater vehicle in such a way to: *i*) command each vehicle to follow a same predefined motion path; *ii*) adapt the vehicles' speed in order to match with a desired cruise speed, while at the same time maintain a formation, i.e. keep the vehicles in a vertical configuration in such a way to guarantee the reliability of the acoustic tracking and data exchange between the surface and underwater platforms.
The possible limitations of the communication availability can constrain the inter-vehicle information exchange, thus for this reason distributed controllers using only local information are desirable, as well as to reduce the quantity of navigation data exchanged in order to overcome the bandwidth limitations.
From a technical point of view, the proposed cooperative motion procedure is based on:
1. a Lyapunov-based virtual target path-following algorithm that allows a single vehicle to approach and follow a generic reference path in the horizontal plane;
2. a distributed coordination scheme allowing the motion synchronization of the two vehicles, using a minimum data exchange (i.e. the values of the virtual target curvilinear abscissae, as described afterwards).

4.5.1 *Single vehicle path-following*

The design of a virtual target based guidance system is reported in *Bibuli et al. (2009)*, a brief description of the guidance approach is given in the following.
Given a reference path on the horizontal Cartesian plane, the along-track and cross track errors defined between the path and the actual position of the vehicle, namely s_1 and y_1, and the orientation error β are computed as follows:

$$s_1 = -(x_f - x)\cos(\psi_f) - (y_f - y)\sin(\psi_f)$$

$$y_1 = (x_f - x)\sin(\psi_f) - (y_f - y)\cos(\psi_f)$$

$$\beta = \psi_e - \psi_f$$

The point (x,y) and ψ_e are the actual position of the vehicle and the direction of its motion. (x_f,y_f) and ψ_f respectively denote the position and orientation of a virtual target that moves on the reference path. The nomenclature framework is reported in Fig. 5.5.1.1.

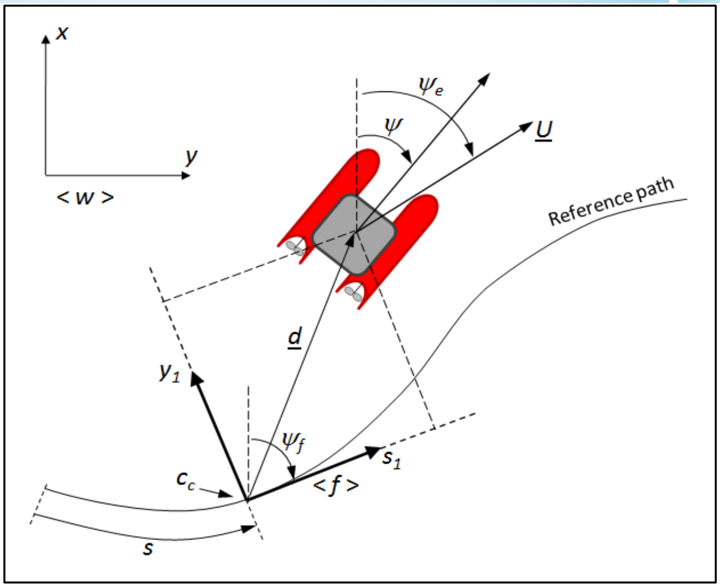


Fig. 5.5.1.1. Single vehicle path-following framework

On the basis of the kinematic error dynamic system expressed by:

$$\dot{s}_1 = -\dot{s}(1 - c_c y_1) + u\cos\beta$$
$$\dot{y}_1 = -c_c \dot{s} s_1 + u\sin\beta$$
$$\dot{\beta} = r - c_c \dot{s}$$

$\dot{s}$ is the speed of the virtual target along the reference path, c_c the local curvature of the path (equal to the inverse of the radius, for the circle-following case), r is the control input i.e. the yaw-rate of the vehicle. The zeroing of the kinematic error, i.e. the convergence to and the following of the reference circle, is achieved through the implementation of two guidance laws: (1) one which regulates the evolution of the virtual target motion over the path, and (2) one computing the reference yaw-rate that the vehicle has to track in order to converge to the desired path. The virtual target and yaw-rate laws have the following expressions:

$$\dot{s}_r = u\cos\beta + k_s s_1$$
$$\dot{r} = \dot{\varphi} - k_1(\beta - \varphi) + c_c \dot{s}$$

k_s and k_1 are tunable parameters, while φ is a suitable approach angle defined with the following form:

$$\varphi = -\psi_a \tanh(k_y y_1)$$

with k_y as a tunable gain and ψ_a the maximum angle of attack, with respect to the local path tangent that the vehicle can assume to converge to the path.

4.5.2 *Vehicles' coordination scheme*

The goal for this task is develop a cooperative behaviour in order to perform a path-following execution along a predefined reference path, maintaining a fixed position configuration, i.e. a certain horizontal offset that can be set and updated online by the human operator.

In the case of coordinated path-following there is not a definition of l*eader* and f*ollower* vehicles like in many other coordination schemes (an extended description can be found in *Bibuli et al. (2010)*); in the proposed framework, the vehicles are "equal", they know in advance the reference path they have to follow, and they share a few basic navigation information that are used to coordinate their motion, i.e. properly setting their own surge speed in order to reach the desired position configuration.

The basic idea for the coordinated path-following problem resolution is to enable all the vehicles involved in regulating their own speed in order to fulfil the cooperative goal.

For a two-vehicles framework the curvilinear distances are defined as $\Delta s_1 = s_2 - s_1$, for Vehicle-1, and $\Delta s_1 = s_1 - s_2$, for Vehicle-2, with reference to Fig. 5.5.2.1.

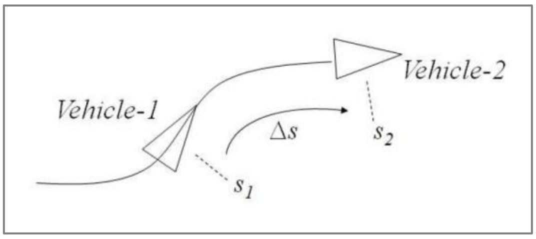


Fig. 5.5.2.1. Cooperative framework representation

Defining the distance error for each vehicle as $e_{si} = \Delta s_i - D^*$, with $i = 1, 2$ and D^* as the desired horizontal curvilinear distance between the vehicles, a smooth regulation law for the surge speed adaptation can obtained thanks to:

$$u_i^* = C + (C - u_{\min})\tanh(k_u e_{si})$$

with $C = (u_{max} + u_{min})/2$ and where u_{min} and u_{max} are used-defined speed limits and k_u is a controller gain.

It can be easily noticed that to allow the cooperation between the two vehicles, the only information that has to be shared to achieve the coordination of the motion is the value of the curvilinear abscissa s_i of the virtual target of each vehicle. This turns into a reliable scheme when the robotic framework includes underwater vehicles: the constraint of a very reduced acoustic communication band-width is not problematic, if a single information value has to be sent and received.

4.5.3 Simulative results

The simulation environment is set up employing the HIL simulators of the surface and underwater vehicles, both properly connected to the ROS environment through their relative wrappers, that allow the basic data exchange for the coordination task.

A common reference path is defined and sent to the vehicles; in a first totally virtual framework, the vehicles execute the path-following task and at the same time they exchange the virtual target curvilinear abscissa values in such a way to coordinate their speed and thus fulfilling the cooperative task. A 3D representation of the simulated experiment is depicted in Fig. 5.5.3.1, where the vehicles, after independently reaching the reference path, coordinate their speed in such a way to maintain a vertical configuration, with the ASV navigating on the surface and the dive buddy maintaining a constant depth.

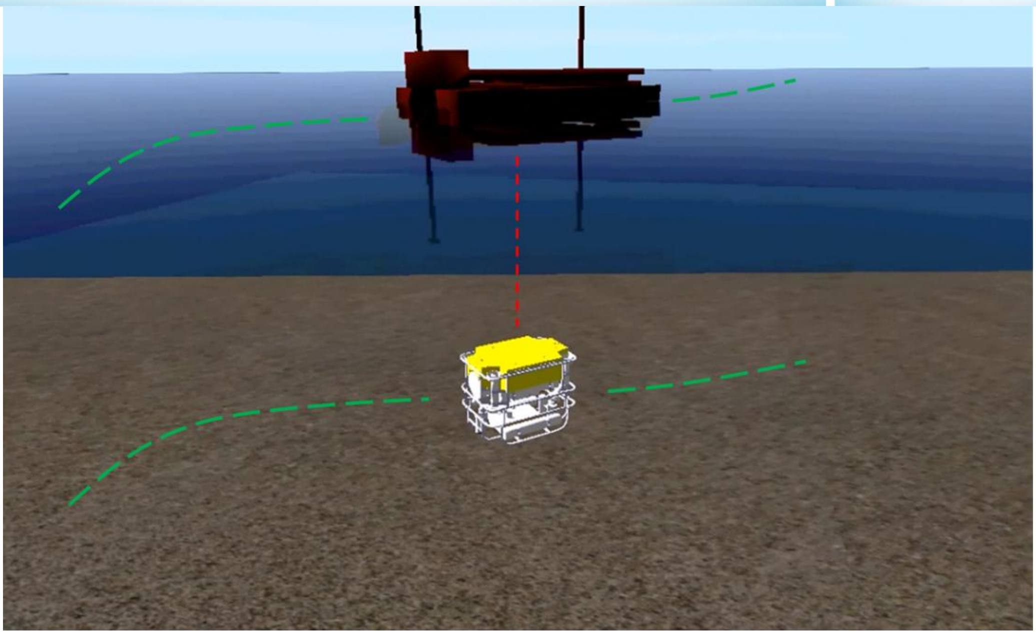


Fig. 5.5.3.1. Simulated cooperative guidance experiment

The horizontal motion of the vehicles during the experiment is reported in Fig. 5.5.3.2 where the different phases can be observed. Firstly, the vehicles perform the approach manoeuvre to the path; once on the path, they cooperatively regulate their surge speeds in order to reach and maintain the vertical formation. In the proposed simulation, at a certain time the dive buddy is required to force its speed to zero (triggered by any unpredicted event), thus losing the vertical formation with the ASV, that slows down to the minimum cruise speed trying to wait for the underwater vehicle to join back the formation. Once that the nominal operating condition is restored, the dive buddy accelerate to gain its formation position re-establishing the vertical configuration with the ASV.
In Fig. 5.5.3.3 the speed profiles of the two vehicles during the simulation are reported.

The simulative framework is made more complicated by the addition of the environmental uncertainties and disturbances as well as the communication delays introduced by the acoustic devices responsible for the data exchange. Another simulation run is executed and the result is reported in Fig. 5.5.3.4, where the perturbed motions of the vehicles can be noticed; such motion behaviours don't impact the functionality of the cooperative guidance, anyway leading to the coordination task fulfilment.

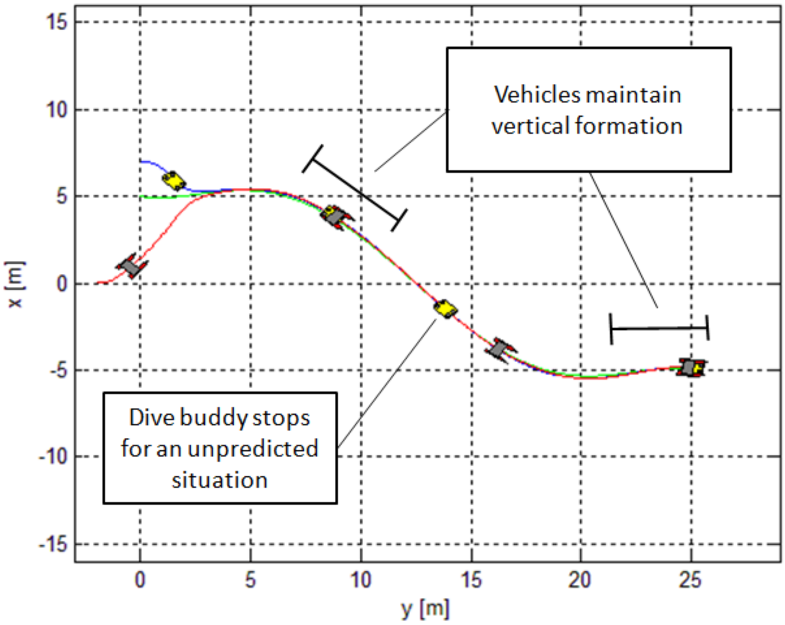


Fig. 5.5.3.2. Horizontal motion of the vehicles during the simulation

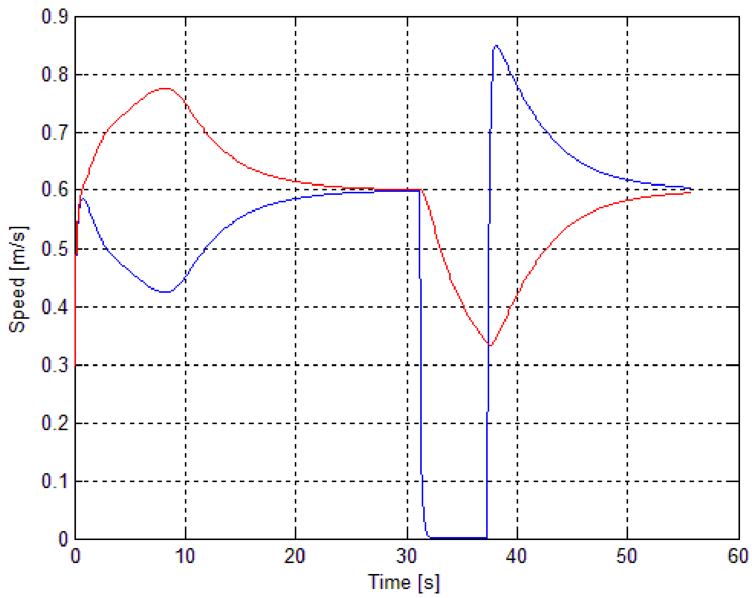


Fig. 5.5.3.3. Vehicle speed profiles during the simulation

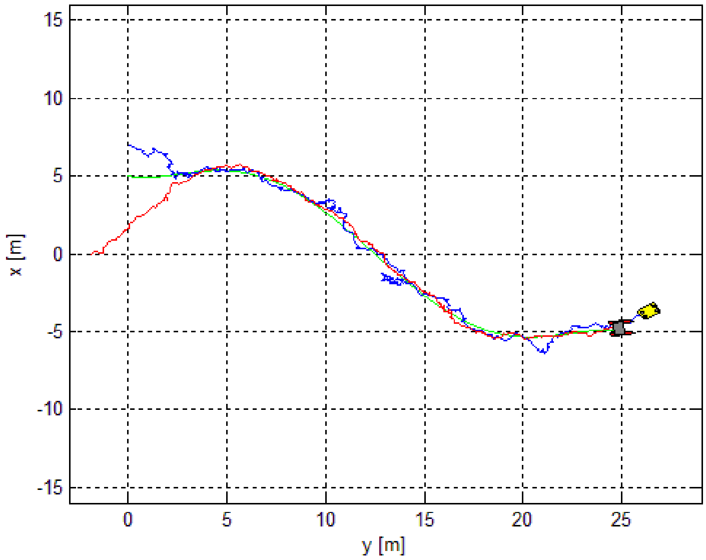


Fig. 5.5.3.4. Cooperation simulation corrupted by disturbances and delays

4.6 "Pointer" experiment

The pointer experiment is envisioned as an augmented realization of the ***diver observer*** functionality. The underwater vehicle, Buddy, has to stay in the field of view of the diver in order to perform sonar or visual sensor observation of the diver. With this concept the diver can make easy visual contact by a simple forward glance and verify the position of his "diving buddy". No limitations are put on the whereabouts of the surface vehicle, ASV, since the Buddy vehicle has at least USBL acoustic localization to determine the diver position. Note that the diver heading has to be known by the Buddy vehicle in order to determine the best position for frontal diver observation. The diver heading is assumed to be transmitted during the acoustic communication of the group.

Diver behaviour observation will be performed by a stereo video-camera and/or a sonar device for murky waters. These sensors can provide a faster update and more precise information about the diver orientation, depth and relative position. First experiments will employ only the USBL device to realize the ***diver observer*** functionality. However, the video and especially sonar information will be added to improve the diver estimate on the Buddy vehicle and allow for smoother positioning relative to the diver. Improved diver position allows augmenting the ***diver observer*** functionality with simultaneous ***diver guide*** functionality. The pointer concept is depicted in Fig 5.6.1. The Buddy vehicle, depicted in blue, has two objectives: a) observing the diver from the ideal monitoring position and b) positioning itself between the target and the diver. Here the target point is where the diver should be guided. The operating radius is the safety distance from the diver. Creating an artificial balance between the two points on the operating circle the vehicle will position itself either to the right of the monitoring point. While the diver performs other tasks the vehicle performs observation of the diver by staying near the monitoring point. Once the diver decides to follow the Buddy vehicle he will start swimming towards the vehicle. The vehicle will continue moving right from the diver towards the guidance position. With his intention to follow the Buddy vehicle and turning to swim in its direction the diver will actually steer the Buddy vehicle to the guidance position. When this happen the ideal frontal monitoring position and the guidance position become the same point and the vehicle will be in front of the diver directly.

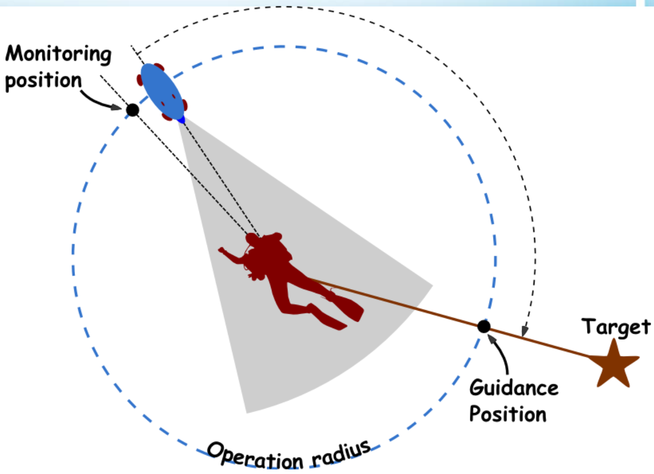


Figure 5.6.1 Pointer experiment concept

The ASV is the sole provider of absolute position data and for improved overall operation it should be included in the formation. To keep the ASV close in the formation it can operate in three ways: a) Buddy follower, b) diver follower, c) cg follower; where the cg point is defined as the artificial centre of gravity of the diver-Buddy cluster. Note that c) virtually positions the ASV on a line connecting the diver and Buddy positions. For the experiments the diver and Buddy weights will be identical, i.e. the ASV will be in-between the diver and Buddy surface projections.

4.6.1 Simulation setup

The simulation consists of three main agents: a) diver, b) buddy and c) ASV. The ASV is included as the communication infrastructure will have to take into account that two USBL devices and one modem are operating in a predetermined three agent interrogation cycle. Hardware will be integrated into the simulation similar as in section 5.3. Four iterations can be defined:

1. Diver tablet hardware in-the-loop – all systems are simulated, except the diver tablet that is fully operational as if used underwater to validate the diver application
2. ASV hardware in-the-loop – the ASV is operated in a real-life conditions
3. Buddy hardware in-the-loop – the ASV and Buddy vehicles are operated in real-life condition while the diver remains simulated
4. ROV hadware in-the-loop – the ROV mimics the diver in real-life operation

Additionally, iterations allow for following combinations in experiments:

1. Buddy operated only in observer mode
2. Buddy operated in pointer mode
3. ASV operated in Buddy follower, diver follower or CG follower

As of writing of this document only the first iteration of hardware in-the-loop simulations was performed, while other iterations are scheduled for field trials in May 2015. The following sub-sections will present the first simulation step and describe the final ROV simulation step. Simulation steps with integrated ASV and Buddy vehicle follow a similar pattern as the ASV integration in section 5.3 and will be skipped due to lack of field-trial results.

The acoustic localization is simulated with measurements each 2 seconds, but without the transmission delay. Transmission delay will be introduced in future simulations to fully model the acoustic localization pings.

4.6.2 Diver tablet hardware in-the-loop

From the control point of view this simulation step is identical to the complete system simulation. The simulation layout is shown in Fig 5.6.2.1. The simulations are done in the Robot Operating System with same control and navigation algorithms that will be used during real-life operation. Each agent is simulated as an individual ROS system with its own core. In addition to the agent two additional systems are added, namely, the User and Sim systems. The User system encapsulated the diver interaction with the simulation. The diver operates the simulated model, and later the ROV, via joystick while he is receiving feedback through the diver tablet and through the 3D visualization camera mounted in the diver model head.

The Sim system has absolute awareness about all agents and simulates the 3D world including the acoustic medium. Other agents receive updates about the environment only through the acoustic link or potentially through video or sonar processing. This layout has the advantage that the simulation for each agent can be executed on a separate computer, i.e. on vehicle computers.

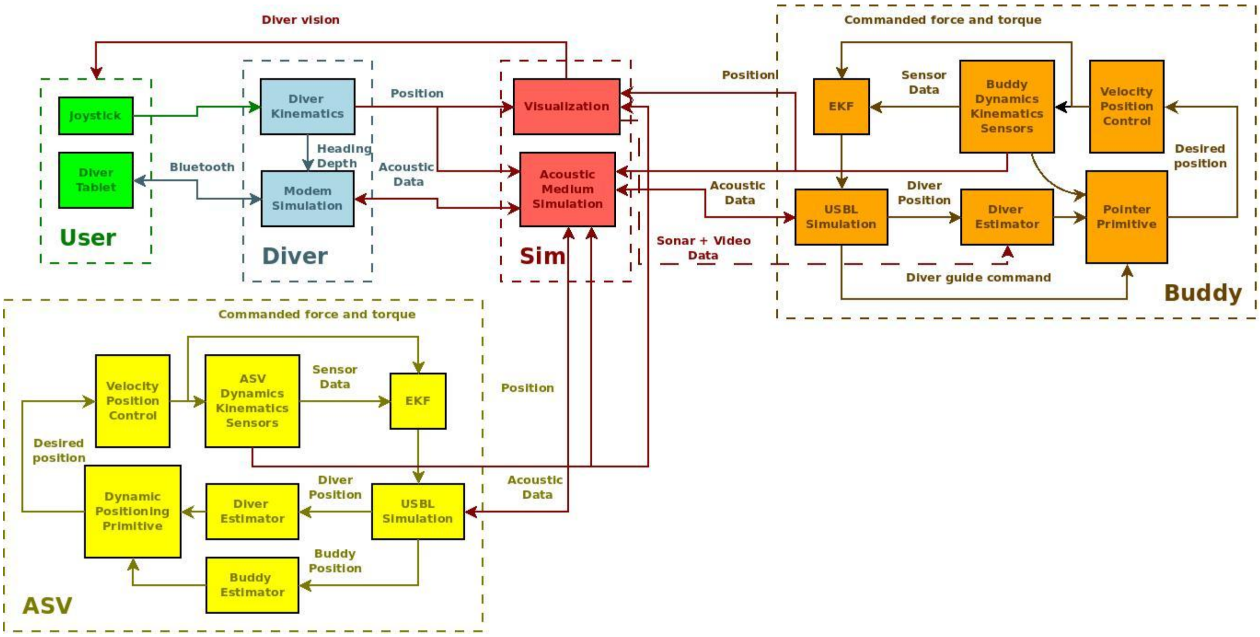


Figure 5.6.2.1 Simplified full simulation setup

Simulation results are shown in Fig. 5.6.2.2 shows a dive observer scenario with a random path taken by the simulated diver. Fig. 5.6.2.2(a) and Fig. 5.6.2.2(b) show the ASV and Buddy position relative to the actual diver position. In case of the ASV the desired position is to be on-top of the diver during the dive. It can be seen that the ASV tracks the estimate diver position. The estimator is a kinematic model that assumes linear motion. Considering that the diver usually moves from A to B the linear motion model makes a good starting model. However, during the diver turns the estimator will lag behind until the actual diver course is estimated. Fig. 5.6.2.2(d) shows the horizontal distance in comparison to the desired distance from the diver. The Buddy vehicle range is offset by the operation radius. The second plot compares the heading of the Buddy vehicle against the heading of the diver. Although the Buddy vehicle is always looking towards the diver position, when the diver turns the vehicle has to pass along the arc that the diver turn forms on the operational circle. During these transient the Buddy vehicle is unable to directly face the diver. Errors up to 100° are observed on sharp diver turns. Further testing is needed to analyze methods of reducing the maximum error during in-place turns of the diver.

Fig 5.6.2.3 shows the pointer experiment where the diver is moving along the transect and requests Buddy to lead him back to the origin when required. In Fig. 5.6.2.3(a) it can be seen that initially the Buddy vehicle is positioned directly in front of the diver. Since the diver is already at the origin he is not pointed towards it. The diver starts moving and the vehicle moves to the left in order to point-out the direction of turn towards the target. Once the diver decides to get back to the transect he starts to turn towards the Buddy. In Fig. 5.6.2.3(b) larger turn radius is observed. The turn radius will depend on the maximum speed the Buddy vehicle can achieve and on the forward speed of the diver. The angle between the diver and Buddy heading can be observed in Fig. 5.6.2.3(c) where the same behaviour is shown. Initially Buddy is in sync with the diver heading and later it deflect at the maximum of 20° from the diver view. Around 80s in the simulation the diver start to follow the Buddy vehicle. The angle is decreased as the diver starts going in the right direction.

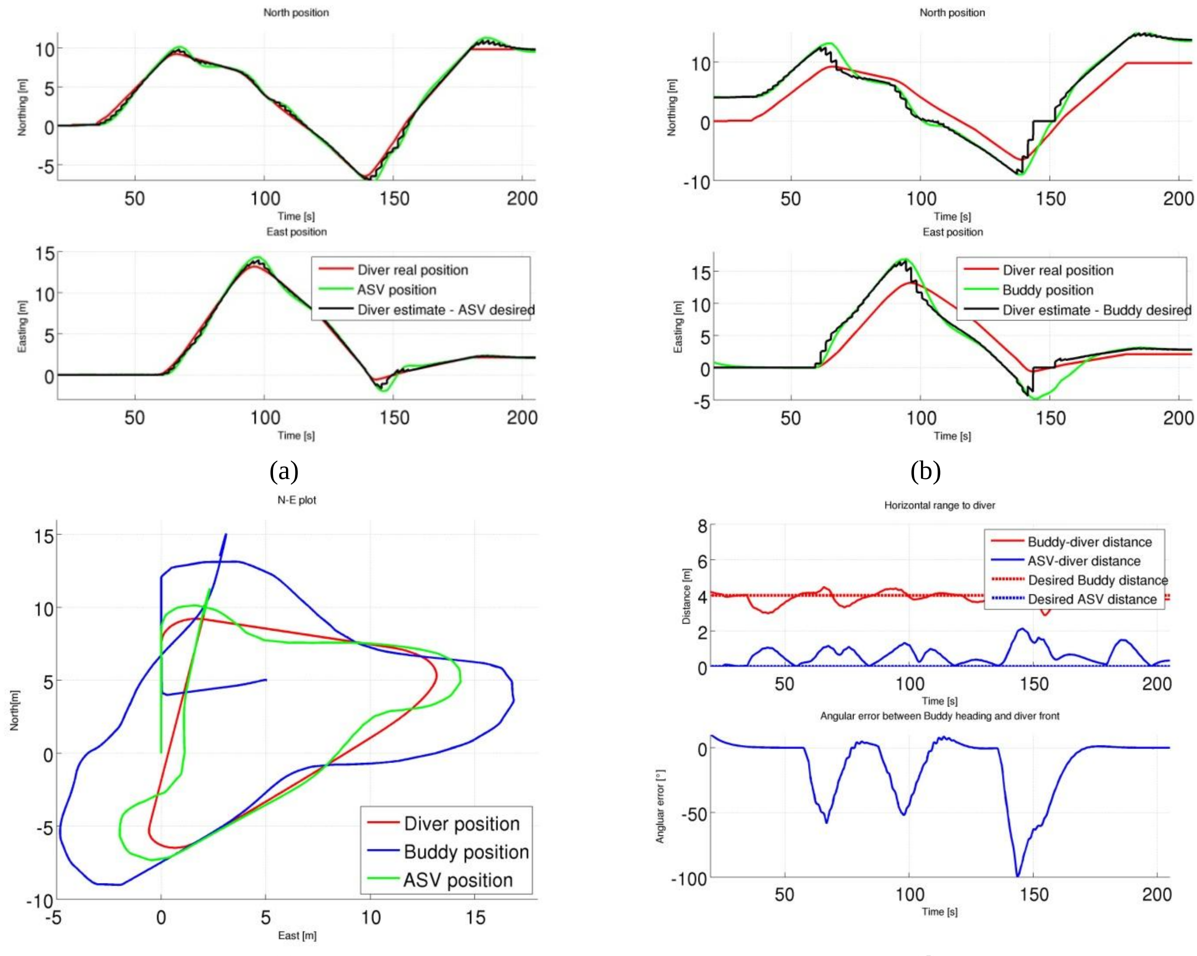
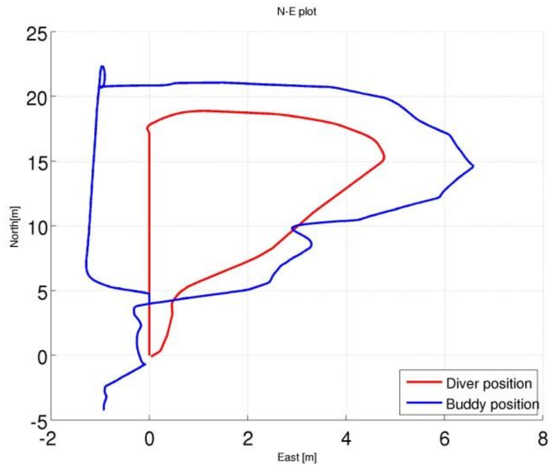
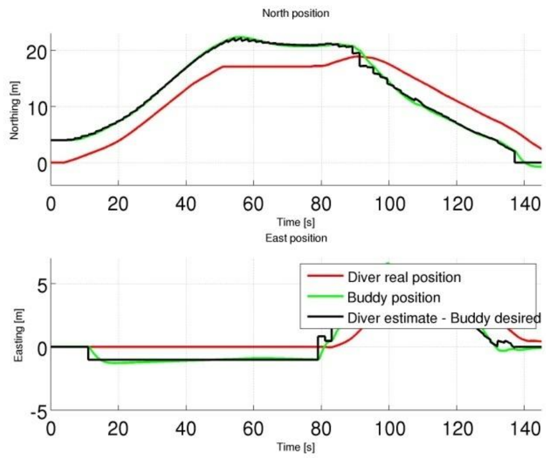


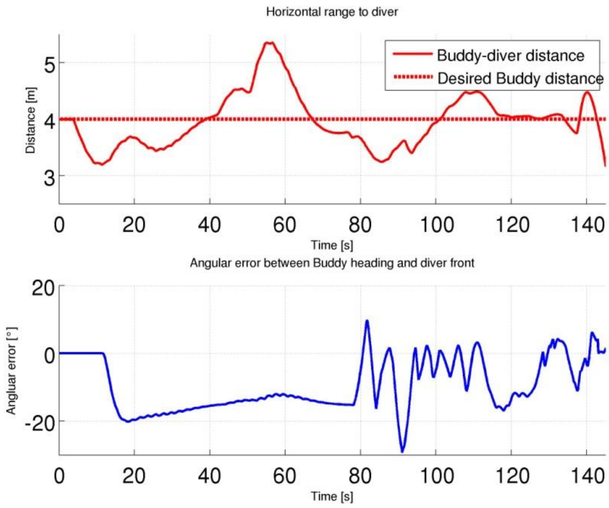
Figure 5.6.2.2 ASV diver follower and buddy observer



(a)



(b)



(c)

Figure 5.6.2.3 Buddy pointer

4.7 How experiments connect to functionalities

The following Table 5.7.1 briefly summarise the matching between the CADDY functionalities and the proposed algorithms/experiments.

Table 5.7.1

functionality	type	experiments	comment
guide	switched guiding	5.1 + 5.2	
	cooperative guiding	5.4	(diver must track the buddy with arbitrary speed)
	pointer guiding	5.5 + 5.2	
		5.5 + 5.3	
		5.5 + position midway	
observer	surface observing	5.3	
	underwater observing	5.5	
slave		5.2	

5 Conclusions

This deliverable has described the different functionalities that the CADDY system enables in order to support the different dive operations and tasks. In order to meet the requirements and specifics of each functionality, different procedures and (simulative) experiments have been developed and exploited.
The results reported in this deliverable prove the feasibility and the reliability of the overall system in operative conditions.

6 Literature

Miskovic, N., D. Nad, N. Stilinovic, and Z. Vukic. "Guidance and control of an overactuated autonomous surface platform for diver tracking." *Control & Automation (MED), 2013 21st Mediterranean Conference on.* 2013. 1280-1285.

Bibuli, M., Bruzzone, G., Caccia, M., Lapierre, L. "Path following algorithms and experiments for an unmanned surface vehicle" Journal of Field Robotics 26(8), pp.669-688, 2009.

Bibuli, M., Caccia, M., Lapierre,L. “Virtual Target Based Coordinated Path-Following for Multi-Vehicle Systems”, Proc. of the IFAC Conference on Control Applications in Marine Systems (CAMS), Rostock (Germany), September 15-17, 2010.