FREESUB: MODULAR CONTROL SYSTEM FOR INTERVENTION AUVS (IAUV)

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1 ABSTRACT

The last decade has witnessed the emergence of Autonomous Underwater Vehicles (AUVs) as tools *par excellence* to acquire ocean data on an unprecedented scale, especially in the field of oceanography. However, these vehicles are mainly used for survey purposes since interventions by a manipulator are still done by tethered vehicles physically linked to the surface. This situation is now being changed with a new class of AUVs under development, named Intervention AUVs (I-AUVs), capable of performing tasks with a manipulator on deep sea structures. In order for the new breed of robots to fulfil these missions, new methodologies and technologies are needed. The European Research Training Network "FREESUB" has as its key objective the study of new technologies for Autonomous Underwater Vehicles for Interventions down to depths of 3000 meters. The network consists of seven European organizations with an expertise in AUV technology that was acquired in the course of projects that led to the development of such vehicles as the INFANTE (PT), DELFIM (PT), SIRENE (FR), SWIMMER (FR) AUTOSUB (GB) or ALIVE (FR). One of the directions of research adopted within the network is the study of modular control systems that can be implemented on different types of AUVs. The modular architecture of this system allows either an integration of all system sub-units or only parts of it such as the modules for Obstacle Detection / Avoidance, the Simultaneous Localization and Mapping or the Dynamic Stabilization. The need to perform telemanipulation tasks impacts strongly on the architecture. The navigation and guidance capabilities are similar to those of survey AUVs. However, the possibility of using a robotic manipulator is a novelty. This paper seeks to explore how to merge the control of such a manipulator with the functions of the navigation, guidance and control systems. The telemanipulation system of such a robot must have access to the data of the navigation system and the sensors onboard. All systems must be merged while keeping the modularity of the global architecture. This paper will start by presenting a basic navigation, guidance and control system for Autonomous Underwater Vehicles. The implementation of other sophisticated functions into this base system will be described at a second stage. The integration of the functions of the control system for the sub-sea manipulator will be the last step in this process, effectively transforming the AUV into an I-AUV.

2 INTRODUCTION

Man has steadily increased the depth of deep sea intervention and research. Oil exploitation reaches depth down to 3000 meters while the exploitation of the seabed reached the deepest grounds on earth.

Human divers were replaced by remote operated vehicles (ROV), linked to the surface by an umbilical. The latest development goes to Autonomous Underwater Vehicles (AUV). These sub-sea robots are equipped with certain autonomy and are not controlled and supplied by the surface through a physical link. The control of the vehicle is generally realised by an acoustic modem between the vehicle and the surface which only allows a limited communication [1].

Autonomous Underwater Vehicles can be divided into three different classes.

- AUVs for survey : AUVs for surveying are already widely used by the oceanographic research society for the exploration of the oceans, cartography of the seafloor and probe sampling. These torpedo-like vehicles turn the disadvantage of the missing physical link into an advantage by executing missions over great distances in autonomous mode.
- Hybrid ROV/AUV : This is an intermediate solution between the ROV and an autonomous vehicle. In fact the proposed solution is to use an autonomous carrier vehicle (an AUV) to transport a ROV to the sea-bed. Once arrived there it docks automatically to a docking station which is linked to the surface with energy supply and communication links. At this stage the ROV can be launched from the carrier by using the energy and the real-time control from the surface. This concept was successfully tested on the SWIMMER vehicle of Cybernetix [2].

- Intervention AUV (I-AUV): this third class of vehicle can be seen as the successor of the classical ROV. Remote Operated Vehicles have found a vast field of application especially in the offshore oil industry These vehicles pushed “downwards” the frontier of deep sea interventions by replacing the human diver. Typical missions are the activation of valves, the deployment of components or the inspection during the installation and maintenance of sub-sea wellheads. But, linked by an umbilical, these vehicles also meet the limits at more than 3000 meters. Intervention AUVs can be used to replace the ROV in deep sea applications but these vehicles are still in development and some of the technical challenges are not surmounted so far.

Figure 1 shows the different classes of underwater robots.

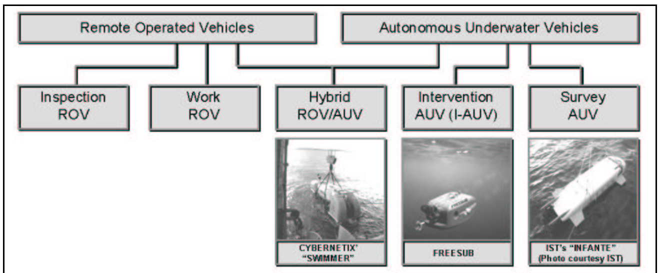

Figure 1. Classes of underwater robots

These categories are generally grouped under a single denomination : AUV. The development of these key technologies for intervention AUVs is subject of the Research Training Network “*FREESUB*” which consist of seven leading European organisations in the research and development of sub-sea robots. Since the objective of FREESUB is not to actually build a vehicle, it deals with the development of modules and key technologies that can be implemented on any AUV. These modules will be mainly on a software basis.

This paper will present an approach to a modular Navigation, Guidance and Control (NGC) System for Intervention AUVs that includes Telemanipulation capabilities. Much importance was given to the modularity of this system. A modular architecture allows either to implement the complete system into one vehicle or only to implement separate parts or modules. The paper is separated into three major parts: The description of a NGC systems base with the implementation of more sophisticated functions and the development of a control structure for telemanipulations with large time delay. The last chapter will describe the possibility to use this NGC system to run simulations of different vehicles in different environments. Such a simulator, as a spin-off of the development of the control system, can be a valuable tool to test the feasibility of missions and to calculate mission data such as for example the energy consumption or the mission duration.
Different missions are foreseeable for Intervention AUVs. As with the AUV for surveying, AUVs for intervention could have possible advantages compared to the ROV. The most important fact to be mentioned here is the increased intervention depth of these autonomous vehicles. But also its fast activation and the cost for the missions can be possible arguments in favour of an AUV.

Before defining a Navigation, Guidance and Control system, it is important to define the context in which the AUV will perform. Such a context can be described by the missions the robot will be designed to fulfil. Once the missions have been clearly defined, their extents and limitations, it is then possible to identify the requirements for the navigation, guidance and control system.

There are several missions an Intervention AUV could be capable to perform [1]. In the frame of the FREESUB project two specific mission types were defined to set up a possible NGC architecture, namely the ***Intervention type*** and the ***Delivery/Recovery type***. Although the vehicle could be capable of performing many more missions, the focus is on its intervention capability initiative. Thus, only these categories will be discussed in the following sections. One could argue that some missions belong to both categories, but there are distinct differences in the way the navigation and guidance are performed that warrant their separation. A brief overview of the other types of missions that FREESUB could perform will however be presented.

2.1 Intervention Type

The missions belonging to the *Intervention type* mainly concern the offshore industry where sub-sea structures require installation and further maintenance or repairs [3,4,5,6]. However, other types of interventions exist, e.g. rescue or salvage operations, cable laying operations, etc.

Sub-sea intervention operations range from simple observation (e.g. status of a valve) to more complicated operations (e.g. complete sub-sea structure installation or removal). At present, it is too ambitious in terms of energy consumption to envisage an I-AUV that can carry out “heavy-duty” operations. Thus, the current capability of FREESUB is to perform “light intervention” operations. Typical interventions are presented in Table 1.

	Intervention Mission Examples
Specific Observations	Location, positioning and orientation survey
	Monitoring of sub sea tree installation process
	Tree, flow line connector and manifold visual inspection for signs of leakage and damage
	Valve & choke status indication
	Valve operation confirmation
	Protective coating integrity
	Marine growth monitoring
	Jumper measurements
Work Activities	Deploy, move or recover acoustic transponders
	Clump weight deployment
	Positioning of navigation/re-entry aids
	Hot stab function operation
	Valve actuator configuration / reconfiguration/ override / operation and function testing
	Cable cutting, debris removal
	Lift line/flying lead attachment/disconnection
	Rigging release

Table 1 - Intervention Missions Examples

The common assumption made for all the intervention missions are:

- The sub-sea structure on which the intervention is to be carried out is in a known location.
- An acoustic positioning system is present on site, providing additional positioning information to the AUV (most underwater installations such as those of the petroleum industry are equipped with Long Base Line (LBL) transponder arrays).
- The structure is "AUV" friendly. In other words, the features are clearly marked and thus make it easily identifiable to AUV sensors. It is designed to prevent possible damages to the AUV by having protective linings. This can be seen as standard since these structures are designed for ROV interventions.
- A map of the sub sea region in which the mission is to be carried out has been previously established and is available as a base map for navigation and guidance.

The main stages of the missions are then:

- descent to the safe positioning zone (SPZ), i.e. a predefined space near the intervention zone where the vehicle can be positioned without the risk of collision. This space takes into account the error in the vehicle measurements and the stabilisation ability of the vehicle. The level of precision may be relaxed where only a safe altitude (large diameter) is necessary, e.g. start of survey mission
- heading to the target (with target identification)
- target approach for docking or free-floating (once in docking range)
- intervention (e.g. mechanical action by using a sub-sea manipulator.)
- return to the surface via the SPZ

2.2 Delivery/Recovery Type

The capability to perform ***Delivery*** or ***Recovery*** missions is another innovative aspect of the FREESUB AUV. Both types of missions require similar functions for the Navigation, Guidance and Control. Table 2 presents some examples of Delivery/Recovery missions.

	Delivery / Recovery Mission Examples
Work Activities	Recovery of airplane "Black Box" (equipped with a homing transponder")
	Recovery of lost objects (e.g. objects from ship wreck / Assistance in ship wreck salvage)
	Recovery of data acquisition pack / battery pack
	Collection of samples from sea bottom (a specific rock, coral…)
	Delivery / recovery of acoustic transponders (e.g. for positioning)
	Delivery / recovery of scientific probing equipment (Temperature, pressure, concentration...)

Table 2 - Delivery / Recovery Mission Examples

A general assumption one can make in these missions is that there is no prior or only incomplete knowledge of the sea landscape.

Recovering objects from the bottom of the sea is a challenging task. The general case involves recovering a known object in an unknown location (an example would be a shipwreck and the recovery of a number of artefacts in or around this site). In a less general case, yet still a very interesting one is recovering a known object in a (partially) known location (for example the airplane "black box" equipped with a homing beacon).

In the presence of a homing device (locator beacon), locating the object is simply the case of homing in onto the signal. In the case of an airplane black box, difficulties could arise if the black box is partly or wholly obscured by parts of the wreck. Further assessments have to be made by the operator before pursuing the operation in supervised mode.

In the case of a search, locate and recover mission the search phase must be carried out at an altitude that will allow target features to be distinguishable from the rest of the sea landscape. This altitude depends on the resolution of the sensors, clutter of the environment and the size and clarity of the target.

When a likely candidate for the recovery object is found, a higher resolution inspection can be performed by moving the AUV closer to the candidate. If the candidate is confirmed by the operator as the object to be recovered, the AUV can proceed onto the recovery phase.

Delivery missions although having a different application purpose, are essential the same as recovery missions in terms of the navigation and guidance process. A delivery location may be known or needs to be identified. The base map (if existing) can be used to determine the local region for the search. Once the exact delivery location has been established, the delivery phase can be performed.

2.3 Summary of Mission Characteristics

The various envisaged mission types possess specific characteristics summarised in Table 3. Such characteristics define the macro functions the AUV should perform. Furthermore, some of the various systems that form the Navigation, Guidance and Control system appear more explicitly, namely the general navigation system offering the capability of positioning the AUV and giving its states, the landscape navigation system with target identification capability, the dynamic stabilisation and station keeping systems.

<table>
<tr><th></th><th>Assumptions</th><th>Mission Navigation and Guidance Phases</th><th>Docking / Station Keeping</th></tr>
<tr><td>Intervention</td><td>• Known structure
• Known location
• Available acoustic positioning aids
• ROV “friendly” structure
• Well defined map</td><td>1. Descent to SPZ
2. Head to target (with id of target)
3. Approach target for docking
(Carry out intervention)
4. Return to SPZ
5. Return to surface</td><td>• “Solid” docking carried out by visual means
• Landing or free-floating</td></tr>
<tr><td rowspan="2">Delivery Recovery</td><td>• Known structure
• Unknown Location</td><td>1. Deploy acoustic positioning system
2. Descent to SPZ
3. Mapping & target identification
4. Approach onto candidate for recovery
(Carry out recovery / delivery)
5. Return to surface</td><td rowspan="2">• Landing or free-floating</td></tr>
<tr><td>• Known structure
• Homing acoustic transponder on object / location</td><td>1. Homing onto target
(Carry out recovery / delivery)
2. Return to surface</td></tr>
</table>

Table 3 - Intervention – Delivery / Recovery Missions Summary

2.4 Other Types of Missions

Interesting areas of application for underwater vehicles are those related to the military or the oceanography fields. To categorise the current and foreseeable missions that could be carried out by an unmanned underwater vehicle, the US navy came up with some general categories [7]: Maritime reconnaissance, Undersea Search and Survey, Communication / Navigation Aids and Submarine Track and Trail. The system architecture presented in this paper will be capable of performing most of these missions. In the frame of the FREESUB project and for simulation purposes the number of missions was limited to the two presented categories. Other missions could be subject of "post" developments in the frame of FREESUB.

3 NGC SYSTEM BASE

Having detailed the mission scenarios the AUV should be capable of fulfilling, it is clear that the Navigation, Guidance and Control system to be designed should be modular to satisfy the various requirements. Also, such a modularity would allow part of the system to be implemented in any existing vehicle, or conversely, an additional module enhancing the system could be easily adapted and implemented in the current system. It is thus important to have a simple yet versatile base system to work on. The delay in the supervision of IAUV requires the development of reliable and robust NGC system. It was chosen to design the NGC system in a non linear setting that allows the extraction of guarantees of performance.

3.1 Overview of the System Base

The base system is a standard one that matches most of the existing configurations [8,9]. It is essentially composed of the navigation module, the path planning module and the control module, all those linked to a mission control module as can be seen in Figure 2.

3.2 Navigation System

Navigation often refers to the combined processes of estimating one's position and state and the course of action to take to reach a new desired state value. Here, these two aspects are separated. "*Navigation*" refers to the estimation of one's state and "*guidance*" refers to the course of action to be taken to reach the desired state value

In this respect, the Navigation module is composed of a suite of sensors integrated to provide the AUV with its position and state. The suite of sensors adopted in the FREESUB case comprises a DVL, a compass, a depth sensor and an IMU. This corresponds to a standard set of sensors present on an AUV [10,11]. Such system could in fact easily be substituted by an “off-the-shelf” system including an Inertial Navigation System (INS).

Generally a Kalman filtering process is used to fuse the data to provide a unique position and state estimation. The drawback of this method is the loss of stability guarantees. FREESUB proposes to investigate non linear data fusion techniques, based on non-linear filtering, which warranties practical stability criterion, adding other types of sensors such that LBL, target acoustic beacon, visual features, etc. [12].

3.3 Path Planning

As mentioned previously, the path planning module is to provide a parameterised path between set way-points. In this basic form, the path planning module is only to propose a safe path between so-called "report way-points" as a function of the expected precision of manoeuvre as a list of way-points or the parameters of a fitted curve such as a spline. These events cause the vehicle to stop and keep station, report to the operator and await further instructions. Input from the operator may simply be a confirmation to proceed or a modification of the proposed path and, in extreme cases, an abort mission order.

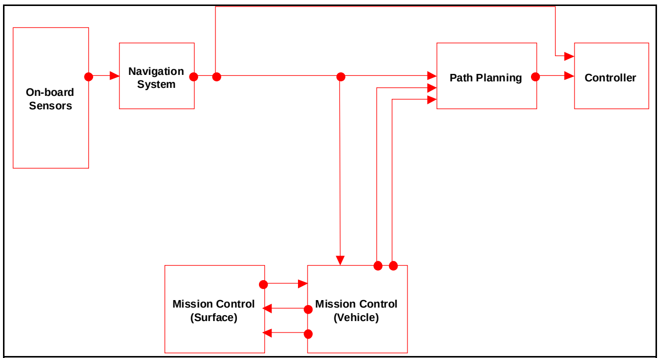

Figure 2. Basic Navigation, Guidance and Control Architecture

Given the desired way-point for the vehicle to reach and its current position and attitude, the low level task of the subsystem is to calculate a realizable path for the vehicle to follow.

3.4 Control

The control module is composed of several sub-systems. A high level controller is in charge of transforming the error calculated between the current AUV state and the parameterised path into forces and moments to be applied to the AUV to reach the path. A second lower level controller distributes these forces and moments onto the various actuators (thrusters and wings). The third low level controller is in fact a collection of actuator controllers that convert the individual force to be applied by the thrusters into motor inputs.

The mission definition shows that two different situations can occur: Path Following (PF)/ Trajectory Tracking (TT) and Station Keeping. Obviously the Station Keeping situation requires for the vehicle to be fully actuated. Nevertheless in the situation of long course mission (PF, TT), the inefficiency of side thrusters leads to consider the fully-actuated vehicle as an under actuated one. In [30] a non singular path following algorithm for an AUV based on Lyapunov and Backstepping design is proposed. But this controller does not deal with station keeping, also called point stabilisation. The first solution consists in designing two controllers and switch between them when a transition between path-following and station keeping occurs. The stability of the transition and of both controllers can be warranted relying on switching system theory. The second solution consists in designing the path-following algorithm in such a way that it will continuously degenerate in a point stabilisation algorithm, smoothly adding the control of the side thrusters as the forward velocity is decreasing, retrieving the holonomic characteristic of the system.

3.5 Mission Control

The task of the mission control modules is to sequence and manage the events that are to be performed during the mission. As part of this process, continuous monitoring of the vehicle is carried out and modifications to the original mission settings are made where necessary. For robust operation, a human operator (at the top of the control loop) monitors and validates the vehicle progress.

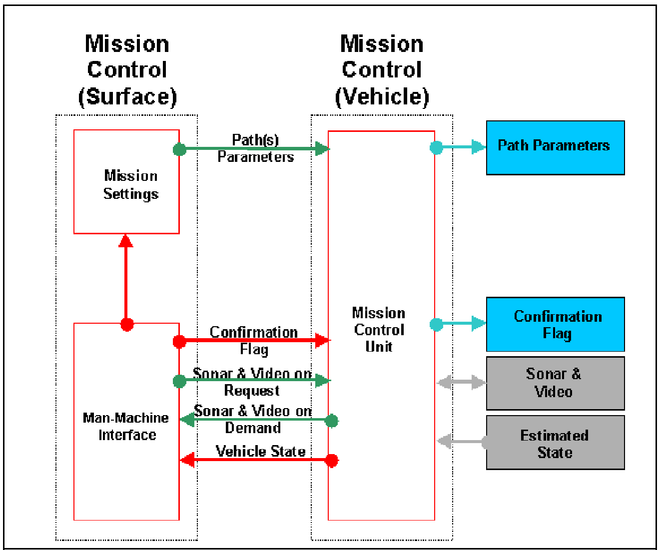

Figure 3. Simplified Mission Control

At key stages in the mission (e.g. a target is identified, a task is completed, etc.), mission control is notified. When this happens, the Mission Control Unit (MCU) evaluates the situation and determines the next task the vehicle should perform. Information is sent to the human operator for validation and confirmation (and if necessary modification and override of what the MCU proposal). On receipt of the operator's response, the MCU orders the next sequence of events.

The Mission Control is separated into two parts: the surface unit and the vehicle unit which are linked by acoustic communication (see Figure 3).

The surface unit includes the mission settings and the Man-Machine Interface. The mission setting defines how a mission is to be carried out. In general this can be seen as a list of Macro Commands defining the different actions the vehicle has to execute and waypoints to be reached. These settings are drawn from what is known of the environment and the particular requirements of the mission.

For intervention missions the navigation route is known and can be pre-determined. However, the exact path may not be fixed in space (because of uncharted obstacles). The state list gives the general direction for the vehicle to travel, specific points it should reach during its mission, and the state it should be in at those points (see Figure 4).

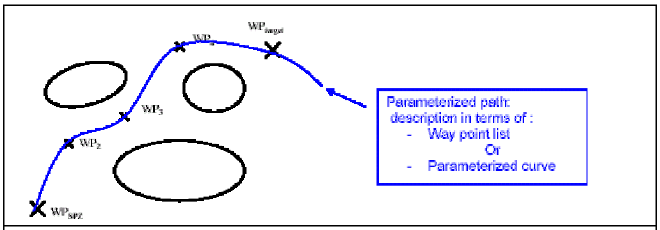

Figure 4. A priori mission route specified using way-point or parameterised curve

In the situation where accuracy is needed, path following gives better results. Otherwise, the way-point tracker is sufficient.

$$\text{State list } State = \begin{bmatrix} x_1 & y_1 & z_1 & \theta_1 & \varphi_1 & \psi_1 \\ x_2 & y_2 & z_2 & \theta_2 & \varphi_2 & \psi_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_3 & y_2 & z_3 & \theta_3 & \varphi_3 & \psi_3 \end{bmatrix}.$$

The vehicle's initial (or launch) state is known, i.e. $\mathbf{State}_0$ and the safe positioning zone is the first state in the list, i.e. $\mathbf{State}_1$.

The manipulation (including docking) sequence, analogous to the way-point list, gives orders to the manipulator to perform a sequence of specific intervention processes.

At this stage, no account for uncharted obstacles is taken. The further addition of modules such as the obstacle detection will provide the mission control with additional information for the decision making process. These modules do not form part of the basic system and as such are not included in the basic mission control module.

3.6 Auxiliary functions

The system described in the previous sections forms the base Navigation, Guidance and Control system. To satisfy the requirements set by the various mission types the AUV is to perform, it is necessary to enhance the system by adding several modules to the basic set. Such modules will add functionality, allowing for example a landscape navigation capability, the ability to identify a target, detect and avoid obstacle and dynamically stabilise the vehicle. Such modules could in fact be added individually and are designed so that they could eventually be added to existing architectures.

Figure 5 shows the complete system including all the additional modules.

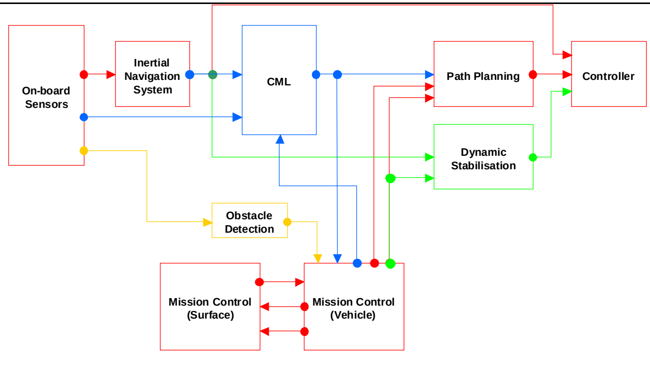

Figure 5. Complete Navigation, Guidance and Control Architecture

3.7 Dynamic Stabilisation System

The function of the dynamic stabilisation system is primarily to compute adequate forces and moments to be applied to the vehicle in order to reach the station keeping stability criteria.
There exist two cases where the dynamic stabilisation of the vehicle is required:

- When the vehicle is reaching in front of the target ready for the docking.
- When a "station keep" order has been issued by the mission control unit (e.g. when a way-point has been reached)

The docking on the structure is done with the help of the hybrid data from the sonar and the video system. The main task at this stage is to dock the vehicle to the target with the use of visual servoing techniques. Visual servoing is the fusion of results from elemental areas including high speed image processing, kinematics, control theory and real time computing. Therefore determining the high speed image processing technique to be used for motion estimation in the vehicle's docking is essential. A parametric motion model estimation algorithm, called Robust MultiResolution (RMR) [13], was evaluated for that purpose. The RMR algorithm has proven to be efficient in numerous applications and presents a low computational cost it could therefore be the solution to the docking task. Figures 6 to 8 show examples of estimated trajectories by the RMR algorithm in the test pool of IFREMER.

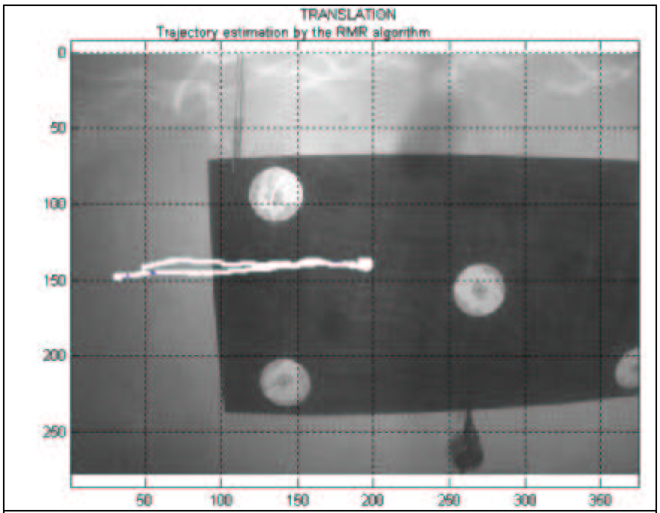

Figure 6. Horizontal movement

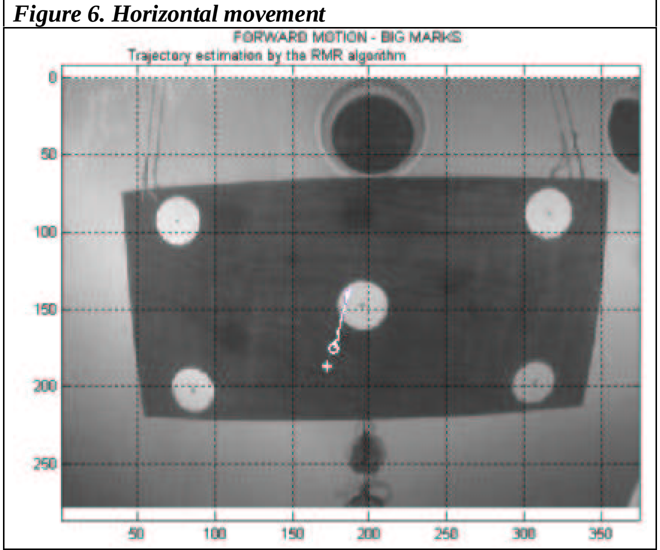

Figure 7. Forward movement with big marks

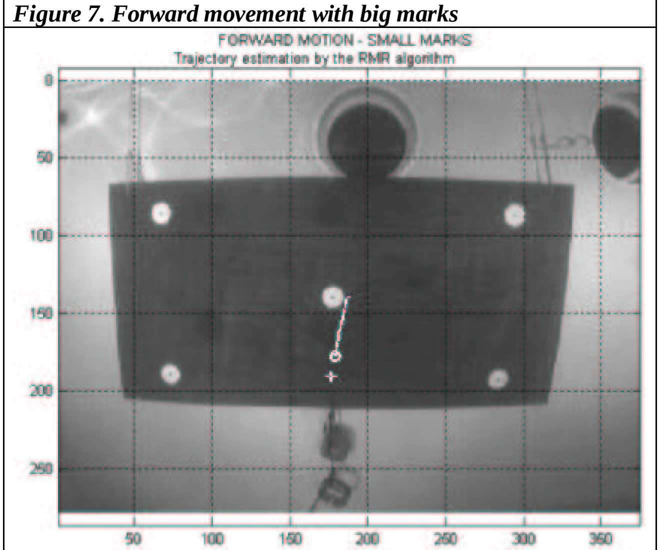

Figure 8. Forward movements small marks.

3.8 Obstacle Detection

The obstacle detection module is an add on to the guidance system. Its function is simply to detect obstacle primarily from the treatment of sonar signals. Adequate filtering is used to process the signal from the dedicated forward looking sonar and alert, on detection of an obstacle the mission control unit. Location and shape of the obstacle are the two main parameters communicated to the mission control unit. These parameters can be further used by the path planning module to devise a safe path around the obstacle. Several paths defined from a rules based algorithm may be suggested to the human operator for confirmation. Further enhancement to the module could include features such as the identification or classification of obstacles and the ability to detect dynamic obstacles.

3.9 Concurrent Mapping And Localisation

The concurrent mapping and localisation module is an enhancement to the navigation and guidance system. It provides the AUV with the ability to perform landscape navigation based on observations made of its surrounding environment. A feature map of the environment can be drawn allowing the vehicle to position itself and devise adequate guidance. The CML module processes information from various sensors. Observations are taken from the treatment of sonar signals and video images and used in conjunction with the inertial navigation system to concurrently map the environment and locate the vehicle in this environment.

Several sub processes are composing the module:

- Mosaic mapping
- Self-localisation on the a features map
- Target Identification

The aim of mosaic mapping [14,15] is to build a 3D map of the environment using vertical scanning sonar and at least two cameras. This map could be used for path planning and localization of the vehicle in future missions. The main process of this module is to mosaic and fuse the sonar and camera images into a single consistent depth and texture terrain map. Errors in vehicle position and attitude and sensor alignment errors need to be considered to produce accurate maps.

The purpose of the CML process is to extract features from the 3D coloured map obtained from the Mosaic mapping module and from the forward looking sensor (sonar and camera). These features are then used to create or update a set of features in the global feature map. The position and attitude of the AUV can then be derived from the observed features.

Furthermore, the CML module will allow for features to be extracted for target identification. The features are compared with a description of the target set in the mission settings and likely candidates are proposed to the human operator through the mission control unit.

3.10 Mission Control

The integration of the various modules into the basic system requires the mission control module to be capable of handling the enhancements. Also, the mission settings can now include more detailed descriptions of the mission phases and navigation, guidance and control tasks to be performed by the AUV. Such descriptions may include *a priori* maps of the environment, description of the targets, etc. Figure 9 illustrates the more advanced mission control module.

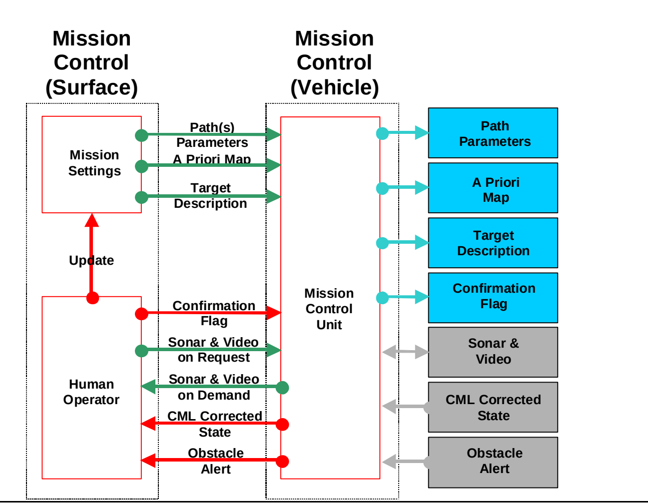

Figure 9. Mission Control

4 AUV TELEMANIPULATION

Several different modes of Telemanipulation are possible with an Intervention AUV, for example:

- *Robotic mode*: This means the vehicle received *an a priori* list of commands and executes those on the seabed.
- *Supervisory control mode*: The operator sends macro commands to the vehicle which executes those in no real-time control due to the time delay of the communication. In this case the control system has to react on changes of the environment.

Figure 10 shows a control procedure of a manipulator in robotic mode.

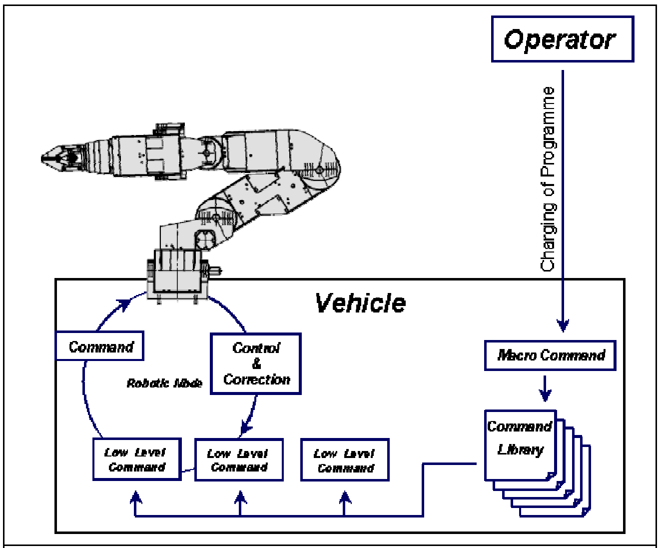

Figure 10. TM in Robotic mode

Thus the manipulator control system receives from the mission control the pre-programmed trajectories and generates the adequate references for the manipulator control module.

The preprogrammed trajectories are a list of references that can be defined in relation to different spaces depending on the necessities of each trajectory segment. Also, the interpolation kind must be defined for each segment in order to have the maximum flexibility.

The supervisor defines the preprogrammed trajectories for ideal conditions, that is, the relative position between the vehicle and the target is known and static. Therefore, these trajectories must be corrected according to the deviations from this nominal position caused by disturbances or a non-determinant docking point (see Figure 11).

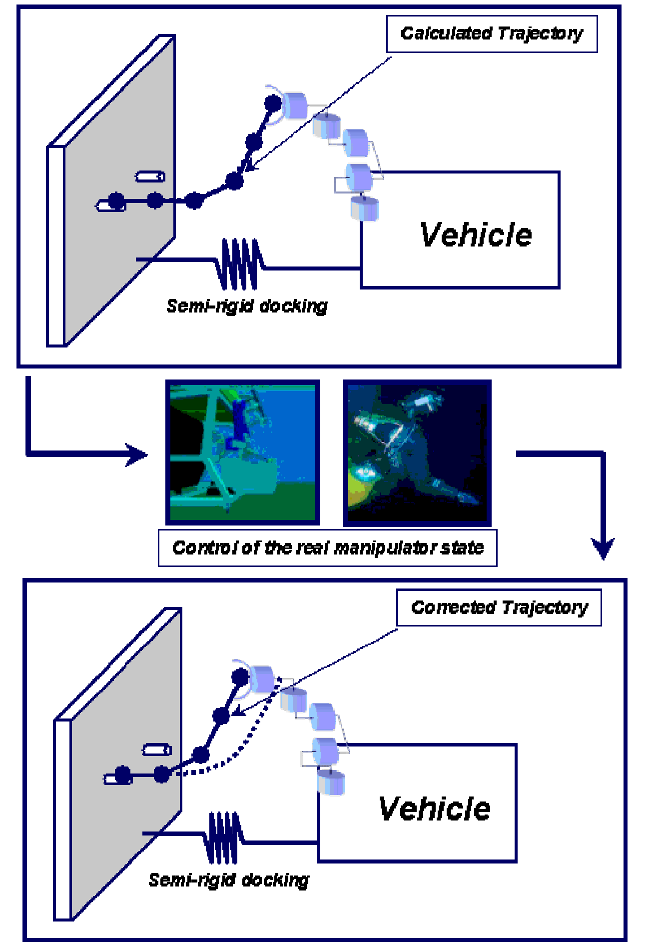

Figure 11. Correction of the trajectory corresponding to the actual manipulator state

To cover all these purposes, Tele-manipulation Control module is divided into five functional components (see Figure 12):

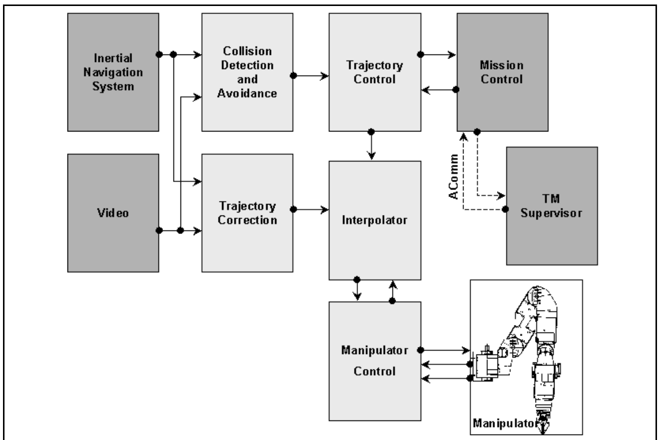

Figure 12.TM Control

Trajectory control

This component offers the interface for connecting the module to the vehicle control mission. There are three kinds of messages that the module can receive:

- *Trajectory*: A list of waypoints, including the interpolation kind and the reference space.
- *Commands*: Autonomous preprogrammed tasks, as "*gotoReadyPosition*" or "*gotoParkingPosition*".
- *High Priority Commands*: Emergency stop, Mission abort sequence, etc.

At the same time, the module can send messages indicating when a task has been completed, when there are problems, or just to inform about the system state.

This component is also in charge of interpreting the received commands, generating the packages of targets, or modifying the trajectory according to the collision detection module.

Interpolator

The interpolator component generates the intermediate points between two references. There are two methods commonly used in robotics for interpolation. First, the monolithic interpolation. It is based on a priori knowledge of the whole trajectory. On it, all the intermediate points are calculated in a computational expensive preprocessing phase. This is the most common interpolation method, but it is inadequate for complex 3D trajectories or trajectories with on-line modifications. The second method is the look-ahead interpolation. On this, the trajectory is divided into packages, reducing the preprocessing time and allowing on-line corrections. The look-ahead is the method required for the purposes of Intervention AUVs.

From the geometric point of view, there are several interpolation kinds [16][17]. Linear, Spline or Bezier are some of them. For our purpose, the Catmull-rom [18][19][20], a Spline subtype, was selected due to its behaviour and its independence respect to the package size.

Trajectory correction

Eventual deviations from the nominal position make the trajectory correction indispensable. It is supposed that the deviations are small, due to the restrictions on the vehicle movement caused by the docking system, but they are not negligible. The accuracy required for manipulation tasks is usually high and these small positioning errors could make an intervention infeasible.

The correction of the manipulator trajectory requires to know, at each period of time, the relative position of the robot tool in respect to the target [21]. In the case of a calibrated manipulator this is the same as knowing the relative position of the vehicle with respect to the target. There are some approaches for solving this problem.

The target configuration defines the accuracy needed for the manipulation and thus the position and velocity errors that are tolerable. The sensors thus used for the trajectory correction must have this accuracy. Video cameras seem to be best adequate in terms of accuracy for this task. But the use of these techniques goes hand in hand with the problems of underwater vision like shadows, hot spots or marine snow[22]. Techniques that can be used for the calculation of the vehicle movements are techniques based on stereoscopic vision or the reconstruction of the movement by using image comparison from different points of view. The first technique needs high computational costs and is thus not adapted. The second method is more commonly used and can give good results, but in the specific case it is very difficult to implement a technique that satisfies all the requirements. The elevated number of features to match for each pair of images, needed for achieving the desired accuracy, added to the disturbances created by the motion of the manipulator between the camera and the target, raise substantially the complexity of the problem. In any case, and due to obvious safety reasons, to work under supervised control mode results indispensable.

Once the vehicle motion has been reconstructed, that means, the relative relation between the vehicle coordinates frame and the target frame is known in each period of time, a simple series of transformations has to be applied to the preprogrammed manipulator trajectory for keeping the relation between the arm's tool and the target as desired [21].

The trajectory correction module should receive directly the images captured by the camera for processing it according the specific necessities of the manipulation. Auxiliary sensor information, from the navigation sensor, can be received already processed from the navigation system. The output of this module is sent to the interpolator.

Collision detection and avoidance

Underwater interventions usually are performed in oil-industry or other dangerous facilities. It is important to have safe systems to prevent accidents. An error in the preprogrammed trajectory or a failure of the docking system must be detected. In this way, the collision detection and avoidance techniques can provide a higher safety level.

If a continuously updated environment map is available, well-known collision detection techniques for manipulators can be used [23][24]. These techniques can provide useful information about the matching between the supposed environment and the current one, generating an alarm if the measured error is outside of a tolerance range. Also, in the improbable case of the presence of an uncontrolled object inside the manipulator working space, it can be detected by these techniques and an evasion trajectory can be generated.

4.1 Manipulator Control

This module generates the torque references for the manipulator actuators. Inputs are the feedback from the sensors integrated in the manipulator and the references sent by the trajectory-planning module.

Usually, control systems for robotic arms are based on PIDs, or derived controls, with the only feedback of the encoders joined to the actuators [16]. Due to the specific characteristics of the underwater autonomous manipulation, where commonly there are uncontrolled contacts between the manipulator end-effector and the target, the force feedback is supposed to be indispensable. A force-torque sensor should be installed in the robot flange and its feedback integrated in the control loop. Controlling the forces applied to the tool gives the possibility to improve the autonomy and accuracy of the interventions [25].

There are several approaches proposed for the force control, but, under the present constraints, the hybrid force/position control is the option that offers more advantages. The objective of the hybrid control is to satisfy simultaneously position and force constraints defined in the task space. This control scheme, proposed initially by Raibert and Craig [26] in 1981 has been improved significantly in flexibility and stability [27][28][29], offering it for several application fields, including underwater robotics[25].

Benefits of using this control are clear. The feedback from the force sensor allows controls of the contact between the manipulator and the target, to find the path to the interior of a device interface as a valve, to keep static a sensor against a hull, or to keep the arm attached to the target during undesired vehicle movements, and many other profits.

4.2 TM Supervisor System

The ultimate objective is to control the TM system extremely easy and natural, so that it can be done intuitively, by the operators which are not specialised in robotics. Using a simulated visual environment, this control could be used even in situations involving difficult conditions like time delay or limited bandwidth. Textual descriptions of such tasks, can, by contrast, be very tedious. The key subsystem to control the TM system is the TM supervisor. It allows the preparation, the simulation and the execution of the TM tasks.

The TM Supervisor is developed based on MAGRITTE application, a graphical supervision software for the robotic and/or tele-operated system developed by the CEA. The TM Supervisor is an independent software application which runs on various operating systems like Windows NT

or Unix. In fact, MAGRITTE is a graphical language of supervision which is based on a 3D virtual representation of the environment of the robot in order to facilitate the man-machine communication. In our case, the 3D virtual representation is a model of the environment represented by the working area of the IAUV. This model is useful, on the one hand, to avoid any collision between any segments of the robot and the closed objects and, on the other hand, to generate the trajectories of the robot (or the grabbers). Additionally, it shows an intuitive representation of abstract robot geometrical concepts, such as reference frames, trajectories, point of views, etc. Figure 13 shows a screenshot of the MAGRITTE supervisor.
The collisions are highlighted in intuitive manner using sound, dialog boxes and change of colour. The detection of any collision is performed using I_COLLIDE library.

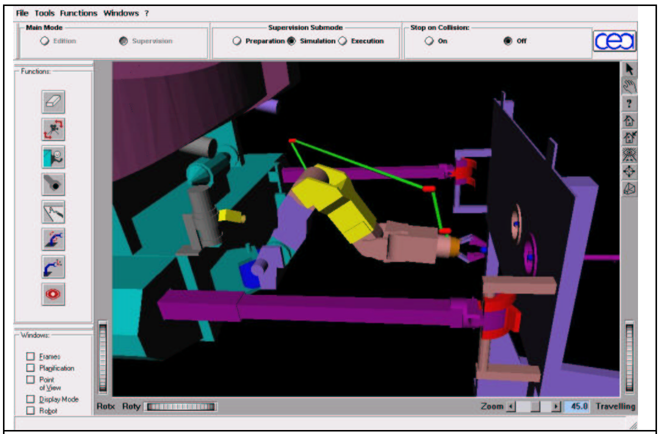

Figure 13. Supervision window containing the 3D environment

The work of the operator mainly consists in specifying the tasks of the robot arm for manipulating various 3D virtual tools which interact with the objects of the environment within the 3D virtual model. In the present case, these tools could be the virtual representations of the grip of the manipulator and the grabbers, objects used to materialise the parameters of the robot functions (i.e. trajectory representation) or simply to assist the creation of these parameters (i.e. handles and levers of the Cartesian frame representation, used for space positioning and orientation). Each one of these virtual tools presents a form and specific behaviour (like moving on the surface of an object of the environment) intended to facilitate their manipulation by the operator.
The setting-up of the parameters of the robot functions intervenes in a mode named "Preparation". The operator passes then in "Simulation" mode in order to test the prepared tasks, without action of the real arm manipulator. The execution mode is finally activated in order to complete the TM tasks.

5 COMPLETE NGC SYSTEM

The last phase in FREESUB's development is the integration of the Telemanipulation System into the Navigation Guidance and Control structure.
Several premises have to been kept for the architecture of the control system like modularity and the possibility to interchange the different modules.
The TCP/IP protocol was identified as one possibility ensuring the distribution of data between the modules while keeping the system open for supplementary functions. Figure 15 shows this structure.
In this architecture the Mission Control unit will act as server for the other modules. Mission parameters and data will be written into a file stocked in the shared memory of the mission control. Every module or function accesses to this file and writes its data onto it. Other modules use these data for its execution.
The Navigation System calculates the vehicles state by using the data of the sensors on board. The Concurrent Mapping and Localisation (CML) corrects this state by using visual or sonar measurements. If the state calculated by the CML corresponds not to the state coming from the Navigation System, the CML corrects this state in the file stocked in the Mission Control Unit. Hierarchical levels have to be established, defining what function or module has the right to change the data of another module. Figure 14 illustrates this procedure.
The distribution of the sensor data will be one critical challenge in this structure due to the fact that several modules need to have access to this data. In the FREESUB structure, the navigation system will be in charge of evaluating this data and to forward it to the Mission Control Unit where every other system can access to it.
This will be the same for the Telemanipulation System. It can reuse the data, e.g. the vehicles states or video, acquired by other modules of the system. No separate sensors are needed for each of these systems.

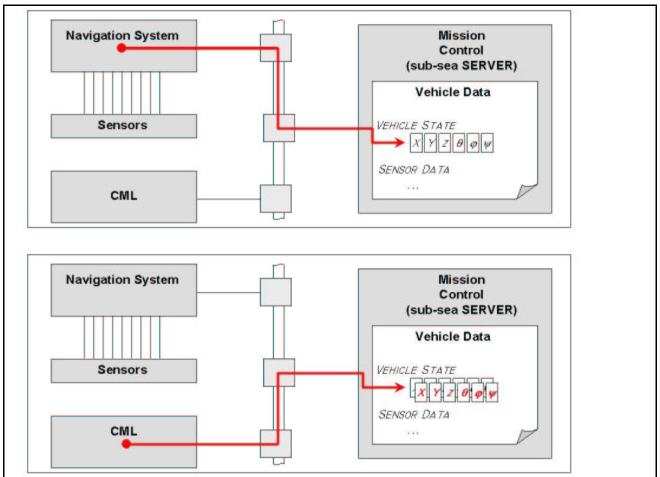

Figure 14. CML is able to correct the data calculated by the Navigation System

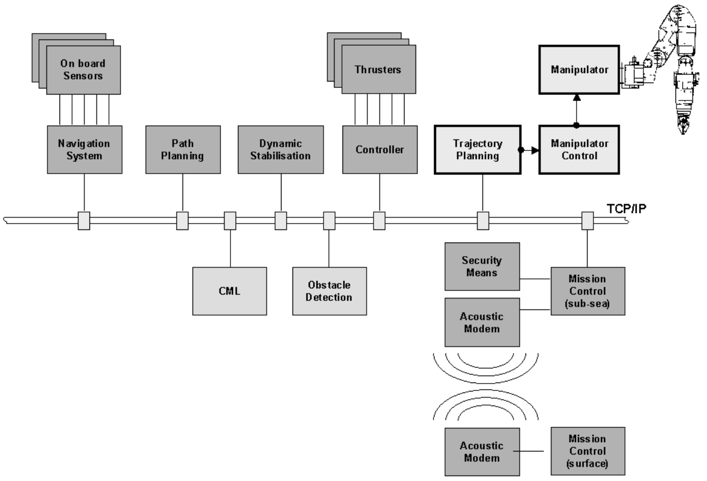

Figure 15. "Marriage" of the NGC with the TM Control

6 SIMULATION ENVIRONMENT

In order to test all the developments of FREESUB in a global system a simulated environment has to be established. This will produce a spin-off development of the project, that could be called an "AUV simulator". This simulator would firstly enable to test the overall functionality of the system and the various modules, also enabling the testing of complete mission scenarios. But such a simulator would be an important tool that could provide a base for the design and test of autonomous underwater vehicle systems. The first part of the development consisted of the design of a global simulation environment, i.e. an underwater landscape with its properties, the model and data of the vehicle and the sensor behaviour. This package is loaded in the simulation at initiation and can be changed according to the vehicles hardware or the environment where the mission shall be simulated. Figure 16 shows the internal architecture of the Simulated Reality. The integration of the complete navigation, guidance and control system can be seen in Figure 17.

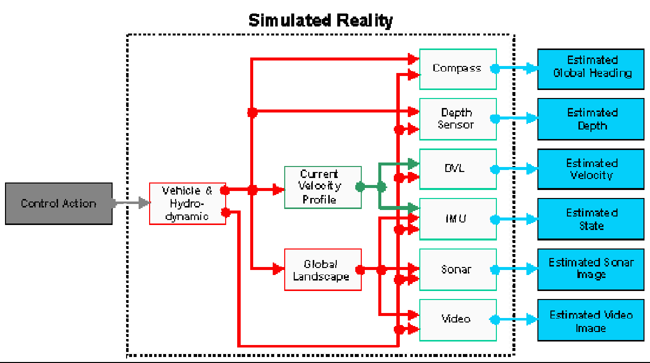

Figure 16. Simulated Reality of the I-AUV Simulator

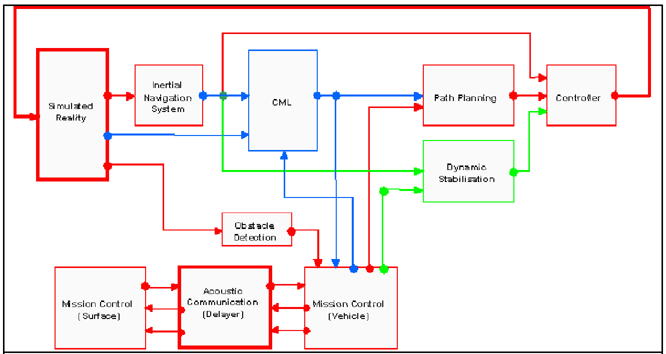

Figure 17. Simulator Architecture

The development of such a simulator is a rather complex task as it involves several difficult problems to be tackled. The first major one is that of the modelling of the sensors. To achieve a first simulation base system, it was decided to employ a simple "geometrical" method. The ray tracing techniques were chosen for that purpose to model the sonar, DVL and echosounder. An unstructured environment is used in which the seabed is represented by a set of points triangulated using Delaunay's triangulation. Further developments of the simulator will allow for several "environmental" objects to be present, static as well as dynamic. The navigation system and associated sensors are simply modelled using the exact data and adding an error based on the error definition of each sensor.

Since versatility and modularity are to be achieved, the simulator is developed allowing for any hydrodynamic model to be used via input files. Also, even though it is not currently implemented, the final version will allow the sensor suite to be user defined, thus allowing any configuration to be tested.

A series of controllers must also be developed to account for any control situation to be handled. The first controller implemented for testing purposes was a bottom following controller. Three echosounders present on the bottom of the AUV at different angles take reading from the bottom (when possible) to derive a local path to be followed. The controller then computes the forces and moments to be applied to the vehicle. Figure 18 shows the path of the AUV following the bottom. The data used to represent the seabed are real bathymetric data taken at the Dom Juan De Castro Bank near the Azores (Courtesy of Paulo Oliveira, IST, Lisbon, Portugal).

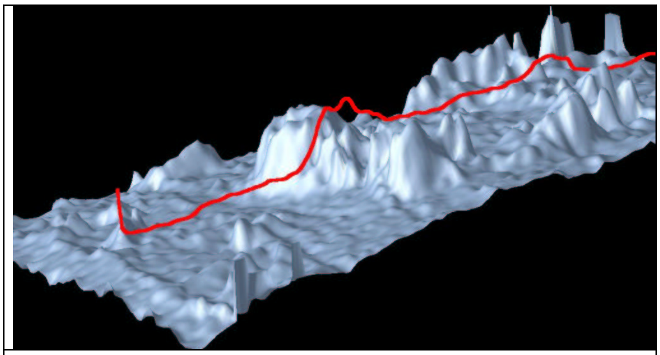

Figure 18. Bottom Following Controller Simulation Output

An example of the output of a sidescan sonar can be seen in Figure 19. The AUV was in that case travelling at a constant depth and in a straight line.

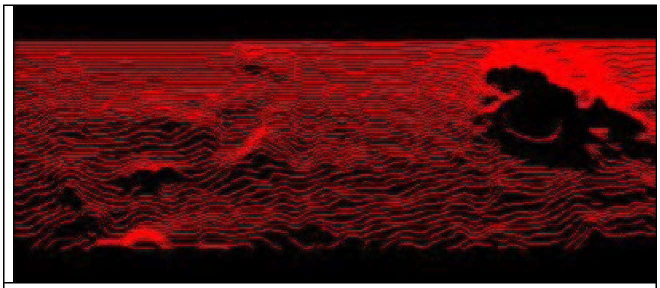

Figure 19. Sidescan Image

Although the simulator is rather simple at present, the first results are promising and enabled the researchers to realise the potential of such a tool. Numerous improvements and extension will be the subject of further work.

7 CONCLUSION

AUVs present the next step in the development of sub-sea robotics. To meet the technical challenges, these vehicles have to work with augmented autonomy and embedded intelligence.

The present paper described a modular Navigation, Guidance and Control System with Telemanipulations capability for a new class of Autonomous Underwater Vehicles – Intervention AUVs. These robots need a high grade of autonomy due to the close interaction with the environment. The presented system includes a basic control structure for Intervention AUVs. Due to the modular architecture, this system is open for the implementation of further technologies or functions. Novelties like an Obstacle Detection and Avoidance, and Navigation with Localisation by CML can be implemented into this architecture. The implementation of the Telemanipulation functions into this structure are transforming the AUV into an Intervention AUV.

The future work of the research will concentrate on the development of the different functional modules for such a vehicle. Some of the modules will be integrated in existing systems for testing purposes. The overall structure will be integrated into a simulation environment allowing the evaluation of the global functionality. This tool will also enable the research team to simulate different missions and situations which could be a valuable "spin-off product" of the development.

Further information on the FREESUB network and its activities can be found under www.cybernetix.fr/freesub/.

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