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TECHNICAL NOTE

FREESUB: NAVIGATION GUIDANCE AND CONTROL OF AN IAUV

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SUMMARY

An intervention Autonomous Underwater Vehicle (AUV) is a significant step forward from a conventional AUV because tasks usually performed using a Remotely Operated Vehicle (ROV) are made possible. In addition, its versatility opens a range of new applications, e.g. black-box recovery. The successful execution of such a mission requires that the Navigation, Guidance and Control of an intervention AUV is capable of simultaneous localisation and mapping, target localisation, obstacle avoidance and robust supervisory operation. In this technical note we will seek to explore the ramifications of these requirements on the technologies, their integration, and mission control. A detailed discussion of all the facets of the mission requirements will be given, and a modular system presented. Furthermore, the concept of an AUV simulator will be introduced as a tool for the testing of navigation, guidance and control systems. Such a simulator environment would allow for complete mission scenarios to be tested.

NOMENCLATURE

AUV	Autonomous Underwater Vehicle
CML	Concurrent Mapping and Localisation
DVL	Doppler Velocity Log
IAUV	Intervention Autonomous Underwater Vehicle
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LBL	Long Baseline
MCU	Mission Control Unit
NGC	Navigation Guidance and Control
ROV	Remote Operated Vehicle
SPZ	Safe Positioning Zone
WP	Waypoint

1. INTRODUCTION

The history of the exploration of the sub-seas started in the late nineteenth century with the first manned submarines. Since then, man steadily increased the depth of deep-sea intervention and research. In the oil-engineering field, exploitation reaches now depths of up to 3000 metres. Owing to the dangers associated with deep-sea diving, sub-sea Remote Operated Vehicles (ROV) linked to the surface by umbilical started to replace human divers in the late 1970's [1] to carry out observation and inspection tasks. Over the following decade, the reliability and sophistication of these sub-sea robots allowed them to become workhorses rather than passive observers.

Further developments in the field of sub-sea robotics led to the Autonomous Underwater Vehicles (AUV). Such AUVs benefit from an on-board autonomous control system and can be linked to the surface via an acoustic modem to allow for the monitoring of the vehicle during a mission.

Autonomous Underwater Vehicles can be divided into three different classes.

- AUVs for survey are already widely used by oceanographic researchers for the exploration of oceans, mapping of the seafloor and probe sampling. These vehicles are characterised by their ability to carry out missions autonomously over great distances [2][3][4].
- Hybrid ROV/AUVs are an intermediate class of sub-sea robots. The concept features an AUV transporting an ROV to the sea-bed. Upon reaching the sea-bed, the AUV docks automatically onto a sub-sea station. The sub-sea station being linked to the surface means that the ROV can be operated in real time. Such a concept was successfully tested on the SWIMMER vehicle of Cybernetix in 2002 [5][6].
- Intervention AUVs (IAUV) could be seen as the successor of the classical ROV. These AUVs differentiate themselves from the others by featuring tools to carry out sub-sea tasks. The control of the AUV becomes rather complex as it must include not only the vehicle itself, but also the control of the robotic tools. As an example, the first European IAUV, the ALIVE vehicle, saw its successful sea trials completed in October 2003 [7].

The development of the technologies for IAUVs is the key of the Research Training Network FREESUB which consists of seven leading European organisations in the research and development of sub-sea robots. Since the objective of FREESUB is not to build a vehicle, its aims are the development of modules that can be implemented on any IAUV. By adopting the modular concept, part or all of the system may be implemented in a future or existing vehicle.

This paper will present an approach to a modular Navigation, Guidance and Control (NGC) System for IAUVs. In a first part, a discussion of the foreseeable missions of an IAUV will be carried out followed by a description of the NGC system base how further enhancement could be implemented. Finally, the possibility to use this NGC system to run simulations of different vehicles in different environments will be discussed. Such a simulator, as a spin-off of the development of the NGC system, can be a valuable tool to test the feasibility of missions and to calculate important mission characteristics such as the energy consumption or the mission duration.

2. MISSIONS

Before defining an NGC system, it is important to assess the context in which the AUV will work, i.e. the missions that the AUV will be designed to fulfil. Once the missions have been clearly defined, their extents and limitations, it will be possible to identify the requirements for the NGC system.

There are several missions an IAUV could be capable of performing. 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***. One could argue that some missions belong to both categories, but there are distinct differences in the manner the navigation and guidance are performed that warrant their separation. A brief overview of other types of missions that FREESUB could perform will also be described.

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 [8][9][10][11]. However, other types of interventions exist, e.g. rescue or salvage operations, cable laying operations.

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 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.

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 damage to the AUV by having suitable protection.
- 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 performed 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. Some examples of Delivery/Recovery missions are presented in Table 2.

A general assumption one can make of these missions is that there is no prior knowledge or incomplete knowledge of the sea landscape, i.e. geophysical data (bathymetric) or visual data (coloured pictures).

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 the Titanic and the recovery of a number of artefacts in or around the wreck). A less general case is the recovery of a known object in a (partially) known location (for example the aeroplane black box equipped with a homing beacon).

In the presence of a homing device, locating the object is simply the case of homing in onto the signal. In the case of an aeroplane black box, difficulties could arise if the

	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

	Delivery / Recovery Mission Examples
Work Activities	Recovery of aeroplane 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

	Assumptions	Mission Navigation and Guidance Phases	Docking / Station Keeping
Intervention	Known structure Known location Available acoustic positioning aids AUV “friendly” structure Well defined map	Descent to SPZ Head to target (with id of target) Approach target for docking Return to SPZ Return to surface	Solid docking carried out by visual means Landing or free-floating
Delivery Recovery	Known structure Unknown Location	Deploy acoustic positioning system Descent to SPZ Mapping & target identification Approach onto candidate for recovery Return to surface	Landing or free-floating
	Known structure Homing acoustic transponder on object / location	Homing onto target Return to surface	

Table 3 - Intervention – Delivery / Recovery Missions Summary

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 IAUV closer to the candidate. If the candidate is confirmed as the object to be recovered, the IAUV 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 MISSION CHARACTERISTICS

The various envisaged mission types possess specific characteristics summarised in
Table 3. Such characteristics define the macro functions the IAUV should perform. Furthermore, some of the various systems that form the NGC 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, and the dynamic stabilisation and station keeping systems.

2.4 OTHER TYPES OF MISSION

Interesting areas of application for underwater vehicle 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 described some general categories [12]: Maritime Reconnaissance, Undersea Search and Survey, Communication/Navigation Aids and Submarine Track and Trail.

The system architecture presented in this technical note 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. NAVIGATION GUIDANCE AND CONTROL SYSTEM BASE

Having detailed the mission scenarios the IAUV 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.

3.1 OVERVIEW OF THE SYSTEM OF THE SYSTEM BASE

The base system is a standard one that matches most of the existing configurations [13][14]. 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 1.

3.2 NAVIGATION SYSTEM

Navigation often refers to the combined processes of estimating one's 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 state. The suite of sensors adopted in the FREESUB case comprises a Doppler Velocity Log (DVL), a compass, a depth sensor and an Inertial Navigation Unit (IMU). This corresponds to a standard set of sensors present on an AUV [15][16]. 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 yield accurate estimates of vehicle’s state. The drawback of this method is the loss of asymptotic stability requirement. FREESUB proposes to investigate non linear data fusion techniques, based on non-linear filtering, with guaranteed stability and performance, adding other types of sensor such as LBL, target acoustic beacon and visual features [17].

3.3 PATH PLANNING

It is the rôle of the path planning module to provide a parameterised path between set way-points. In this basic form, the purpose of 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

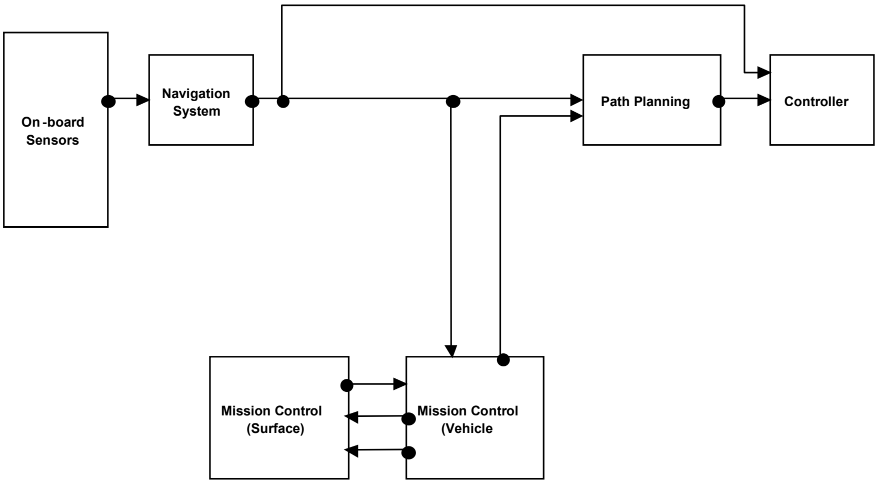

Figure 1 - Basic Navigation, Guidance and Control Architecture

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.

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 error detected between the current AUV location and the parameterised path into forces and moment 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 control surfaces). The third low level controller is in fact a collection of actuator controllers that convert the individual force to be applied by the thrusters and the surfaces into motor inputs.

In the situation of long course mission, the inefficiency of side thrusters leads us to consider the fully-actuated vehicle as an under actuated one. The controller designed for the path following algorithm does not deal with station keeping which is sometimes called point stabilisation.

The first solution consists in designing two controllers and switching between them when a transition between path-following and station keeping occurs. The stability of the transition and of both controllers can be warranted by 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 stabilization 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 manage events and sequence actions throughout 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. To allow for possible human intervention on the control of the vehicle or mission, the human operator is kept in the loop and allowed to monitor and validate the mission control decisions.

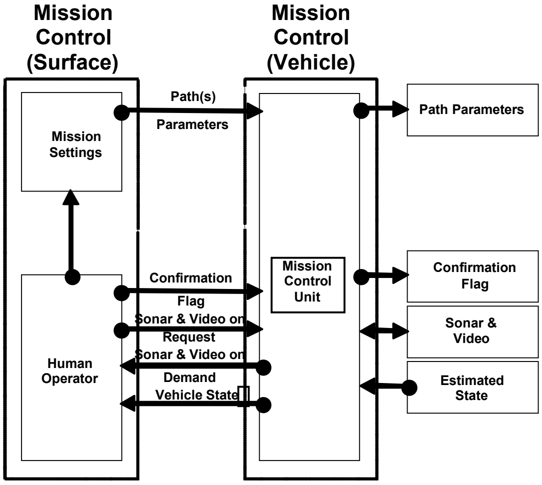

Figure 2 - Simplified Mission Control

At key stages in the mission (e.g. a target is identified, a task is completed), 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 modificatison 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 an acoustic communication system (see Figure 2).
The surface unit includes the mission settings and the human operator. The mission setting defines how a mission is to be carried out. 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 way-point list gives the general direction for the vehicle to travel and specific points it should reach during its mission (see
Figure 3).

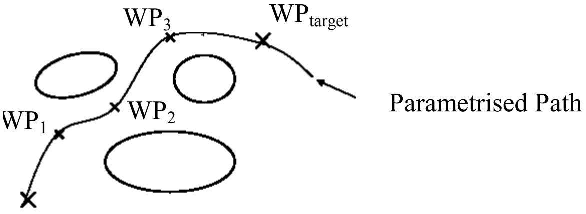

Figure 3 - A priori mission route specified using way-point or parameterised curve

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

$$\text{Way-point list } \mathbf{P} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_t & y_t & z_t \end{bmatrix}.$$

The vehicle's initial (or launch) position is known, i.e. $\mathbf{P}_0 = [x_0 \;\; y_0 \;\; z_0]$ and the safe positioning zone is the first way-point in the list, i.e. $\mathbf{P}_1 = [x_1 \;\; y_1 \;\; z_1]$.

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.

4. COMPLETE FREESUB NAVIGATION GUIDANCE AND CONTROL SYSTEM

4.1 OVERVIEW OF THE COMPLETE SYSTEM

The system described in the previous section forms the base NGC 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 4 shows the complete system including all the additional modules.

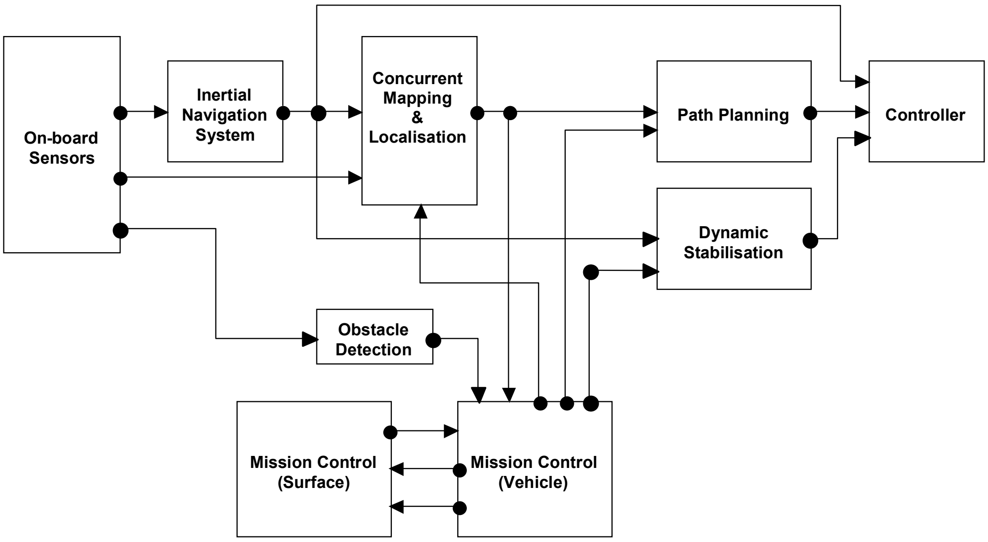

Figure 4 - Complete Navigation, Guidance and Control Architecture

4.2 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 meet a station keeping stability criterion. There exist two cases where the dynamic stabilisation of the vehicle is required:

When a station keep order has been issued by the mission control unit (e.g. when a way-point has been reached)
When the vehicle is in a docked phase.

The difference between the two cases is that the second uses visual means (video) to perform the stabilisation whereas the first one relies solely on the navigation sensors output.

4.3 OBSTACLE DETECTION

The obstacle detection module is an add-on to the guidance system. Its function is simply to detect obstacles primarily from the interrogation of sonar signals. The signals from the dedicated forward-looking sonar is processed using adequate filtering and, on detection of an obstacle, the module alerts the mission control unit. Location and shape of the obstacle are the two main parameters communicated to the mission control unit.

These parameters are 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.

4.4 CONCURRENT MAPPING AND LOCALISATION

The concurrent mapping and localisation (CML) module is an enhancement to the navigation and guidance system. It provides the IAUV 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 part of the module:

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

The aim of mosaic mapping [18][19] is to build a 3D map of the environment using a vertical scanning sonar and at least two camera positions. This map could be used for path planning and localization of the vehicle in future missions. The main purpose 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). Although a black and white map may be sufficient to extract most of the features of the environment, the colours can help in further differentiating and classifying the features. These features are then used to create or update a set of features in the global feature map. The position and attitude of the IAUV 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.

4.5 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 IAUV. Such descriptions may include *a priori* maps of the environment, description of the targets. Figure 5 illustrates the more advanced mission control module.

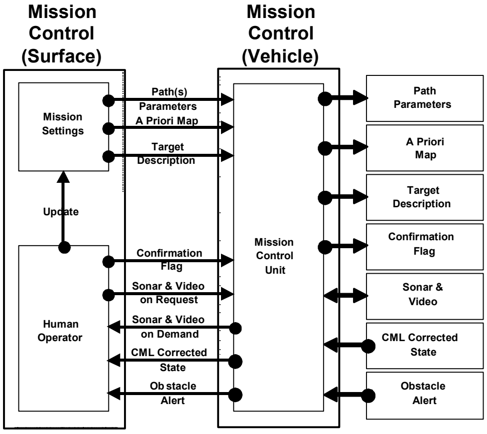

Figure 5 - Mission Control

5. INTEGRATION OF THE NAVIGATION, GUIDANCE AND CONTROL SYSTEM INTO AN AUV SIMULATOR ENVIRONMENT

To test the overall functionality of the system and the various modules, an AUV simulator will be implemented also enabling the testing of complete mission scenarios. Such a simulator is an important tool that would provide a base for the design and test of autonomous underwater vehicle systems.

To allow for a simulation to be developed, a global simulation environment must be set. In the case of FREESUB, this consists of an underwater landscape with its properties, the model and data of the vehicle and the sensor behaviour. This package will be loaded in the simulation at the initiation and can be changed according to the vehicles hardware or the environment where the mission shall be simulated. Figure 6 shows the internal architecture of the Simulated Reality. The integration of the complete navigation, guidance and control system can be seen in Figure 7.

6. CONCLUSION

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

This paper described a modular Navigation, Guidance and Control System 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.

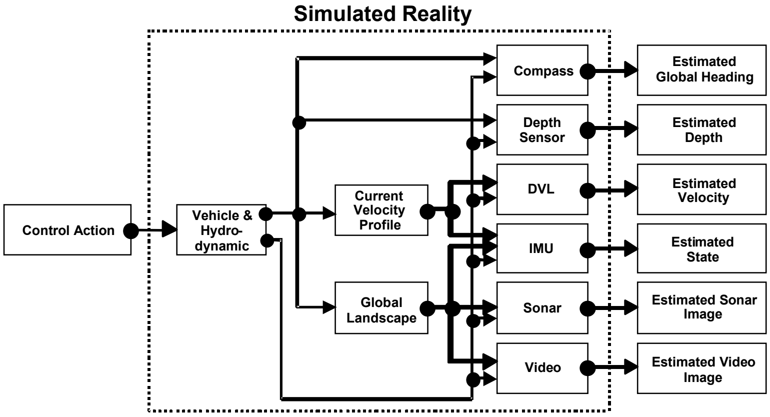

Figure 6 - Simulated Reality Module

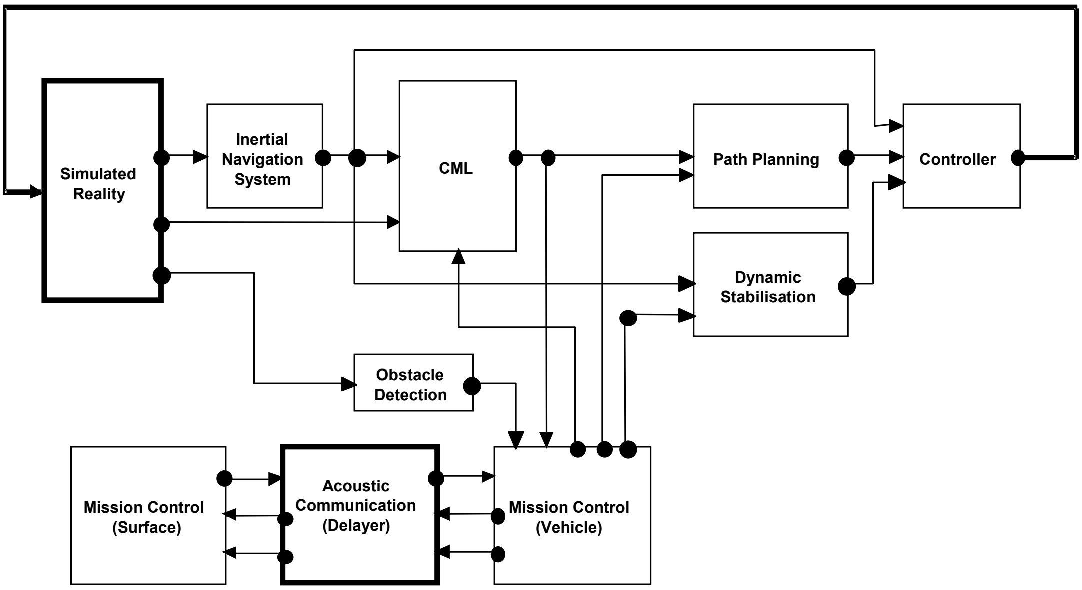

Figure 7 - AUV Simulator Architecture

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8. REFERENCES

1. H. Doyle, Man and Machine: Divers, ROVs, and High-Tech Solutions to Undersea Missions, *Underwater magazine*, article reprint, winter 1994.
2. T. Chance, AUV Surveys: Extending our reach 24,000 kilometers later, UUST'03
3. V. Pennel, B. Veitch, K.Hawboldt, T. Husain, N. Bose, G. Eaton, J. Ferguson, Use of an Autonomous Underwater Vehicles for Environmental Effects Monitoring, UUST'03
4. G. Griffith, N.W. Miller, S.D. McPhail, J. Riggs, Effect of upgrades on the reliability of the Autosub AUV, UUST'03
5. Y. Chardard and T. Copros, Final Sea Demonstration of this Innovative Hybrid AUV/ROV System, AUVSI 2002.
6. Y. Chardard, P. Marty, T. Copros, V. Rigaud, SWIMMER : Final Sea Demonstration of This Innovative Hybrid AUV /ROV System, UDET 2002
7. P. Marty, ALIVE: An Autonomous Light Intervention Vehicle, DOT’03.
8. J.D. Hughes, B.M. Paull, M. Serafin Jr., G. Openshaw and G.I. Smith, Liuhua 11-1 Development – ROV Interventions, *Proc. Offshore Technology Conference*, Houston, Texas, 1996, 337-347.
9. M.M. Becjmann, M.L. Byrd, J. Holt, J.W. Riley, C.K. Snell, C. Tyer and D. Brewster, Pompano Subsea Development: Template/Manifold, Tree and ROV Intervention Systems, *Proc. Offshore Technology Conference*, Houston, Texas, 1996, 509-523.
10. D.A. Hernandez, J.M. McCalla, R.W. McCoy and T.C. Clark, Mensa Project: ROV Interfaces, *Proc. Offshore Technology Conference*, Houston, Texas, 1998, 217-222.
11. C.R. Scates, D.A. Hernandez and D.D. Hickok, Popeye Project: ROV Interface, *Proc. Offshore Technology Conference*, Houston, Texas, 1996, 339-353.
12. The Navy Unmanned Undersea Vehicle (UUV) Master Plan, April 2000.
13. D. Fryxell, P. Oliveira, A. Pascoal, C. Sylvestre and I. Kaminer, Navigation Guidance and Control of AUVs: An Application to the Marius Vehicle, *Control Engineering Practice, 4(3)*, 1996, 401-409.
14. M. Caccia and G. Veruggio, Guidance and Control of a Reconfigurable Unmanned Underwater Vehicle, *Control Engineering Practice, 8*, 2000, 21-37.
15. J.J. Leonard, A.A. Bennett, C.M. Smith and H.J.S. Feder, Autonomous Underwater Vehicle Navigation, *MIT Marine Robotics Laboratory Technical Memorandum 98-1*.
16. L.L. Whitcomb, D.R. Yoerger and H. Singh, Combined Doppler/LBL Based Navigation of Underwater Vehicles, *11th International Symposium on Unmanned Untethered Submersible Technology (UUST99)*, New England Center, Durham, New Hampshire, 1999.
17. S. Majumder, S. Scheding and H.F. Durant-Whyte, Multi-Sensor Data Fusion for Underwater Navigation, *Robotics and Autonomous System, 35*, 2001, 97-108.
18. H. Singh, L. Whitcomb, D.R. Yoerger and O. Pizzaro, Microbathymetric Mapping from Underwater Vehicles in Deep Ocean, *Computer Vision and Image Understanding, 79*, 2000, 143-161.
19. N. Gracias and J. Santos-Victor, Underwater Video Mosaics as Visual Navigation Maps, *Computer Vision and Image Understanding,* 79, 2000, 66-91.