FREESUB: DYNAMIC STABILIZATION AND DOCKING FOR AUTONOMOUS UNDERWATER VEHICLES

Peter WEISS, Cybernetix, France, peter.weiss@cybernetix.fr;
Juan Vicente CATRET MASCARELL, Joint Research Centre, Italy, juanvi.catret@jrc.it ;
Daniel GROSSET, Joint Research Centre, Italy, daniel.grosset@jrc.it;
Lorenzo BRIGNONE, IFREMER, France, Lorenzo.Brignone@ifremer.fr
David LABBE, University of Southampton, United Kingdom, labbe@ship.soton.ac.uk
Philip WILSON, University of Southampton, United Kingdom, p.a.wilson@soton.ac.uk;

1 ABSTRACT

Autonomous Underwater Vehicles (AUV) are more and more used in the field of oceanography. These vehicles present a powerful tool in the hands of scientists due to the augmented autonomy and thus the large mission range. A new class of AUV is arising: the Intervention AUV, able to perform tasks by a manipulator arm on structures in great depths like for example on sub-sea wellheads or benthic stations. The fact that these sub-sea robots have no physical link to the surface holds technical challenges in the development but also advantages for the later application. The large time delay in communication, combined with limited bandwidth and susceptibility to errors do not allow a permanent presence of the operator in the control loop of the robot. Thus, these robotic systems have to be stable enough and have to include a certain degree of intelligence to be able to fulfil the mission autonomously with a minimum of interaction by the operator. One possibility to ensure that the robot can execute manipulations in automatic or semi-robotic mode is to dock the vehicle in a stable manner on the working area. The European Research Training Network "FREESUB" has an objective to develop key technologies for Autonomous Underwater Vehicles for Interventions at 3000 meters depth. This network consists of seven European organizations with an expertise in AUV technology. This paper will describe the hardware requirements and software functions for such robots enabling those to dock on sub-sea structures. This solution presents a consensus allowing the tension between the large positioning errors on one side and the rigidity on the other that has to be reached for the interventions with a manipulator arm. The pre-positioning of the vehicle in front of the docking panel will be further described in this paper since this is the intermediate phase between the free-floating and the docking procedure. During telemanipulations, sensor data of the vehicle can be used to correct errors in the manipulator trajectory due to residual movements. The final part of this paper will give some suggestions on what could be called an "AUV-friendly" docking panel, similar to the standardized ROV panel but with aids for the automatic docking of robots.

2 INTRODUCTION

2.1 Intervention AUVs (I-AUV)

Autonomous Underwater Vehicles can be divided into different types corresponding to the systems architecture and the tasks fulfilled.

- AUVs for survey : AUVs for surveying are already widely used for the exploration of the oceans, cartography of the seafloor and probe sampling. It is not easy to state exactly the first date of development of those vehicles since torpedoes used during the World Wars already could have already been named "Autonomous Underwater Vehicles" even when theses vehicles were not highly sophisticated. But what is called nowadays "AUV" is often a torpedo-like vehicle equipped with different sensors that can execute missions over great distances in an autonomous mode.

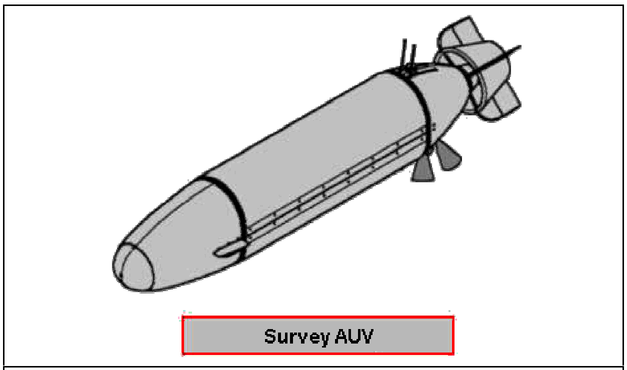

Figure 1. Torpedo-like AUV for survey

- Hybrid ROV/AUV : These vehicles present an intermediate solution for the intervention on deep-sea oil fields. It consists of an autonomous carrier vehicle that carries a Work ROV to a sub-sea docking station. Once arrived there, the vehicle can establish a power and communication link via the docking station to the surface. Thus the ROV can be operated by using the power and the communication delivered by the docking station (the umbilical is preinstalled in the riser structure of the oil field for example). The advantage of this concept is the fact that a classical Work ROV can be operated without any constrains in communication and power supply and without an umbilical from this vehicle to the surface. This concept was tested with the "SWIMMER" vehicle of Cybernetix. which has seen its successful sea trials in autumn 2001 [2].

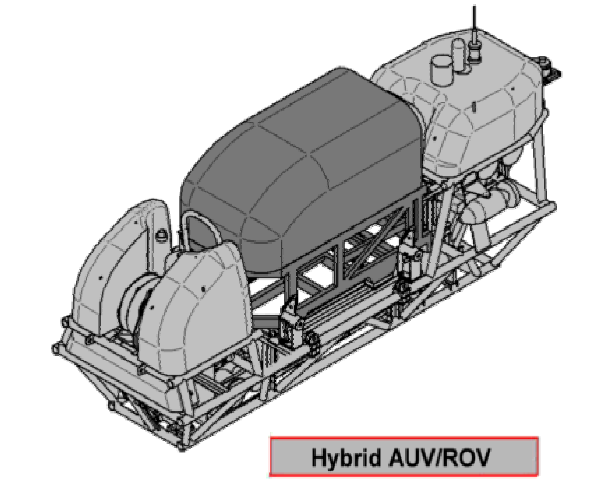

Figure 2. Hybrid AUV/ROV concept "SWIMMER" by Cybernetix. The ROV in dark.

- Intervention AUV: This is the latest class of vehicles under development at this moment. It can be seen as the successor of the classical ROV. Typical missions can be the activation of valves, the deployment of components or the inspection during the installation and maintenance of sub-sea wellheads. But a ROV, linked by an umbilical to the surface encounters large constrains due to the cable (for an intervention in 3000 meters, approximately 5000 meter of cable are necessary). Intervention AUVs can be used to replace the ROV in deep sea applications but these vehicles are is still in development and some of the technical challenges are not surmounted so far.

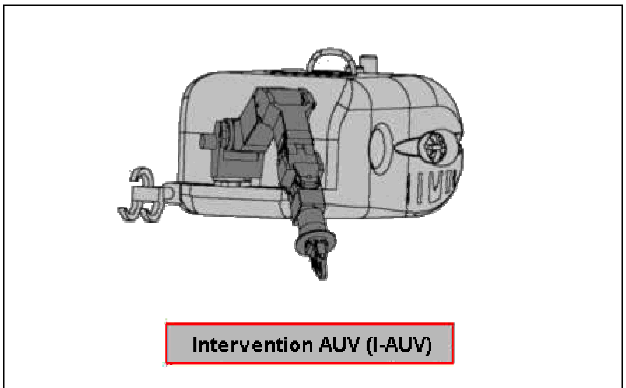

Figure 3. I-AUV with manipulator arm

These three categories are generally grouped under the single denomination "AUV". The development of key technologies for intervention AUVs is the subject of the Research Training Network "*FREESUB*" which consist of seven leading European organizations in the research and development of sub-sea robots.

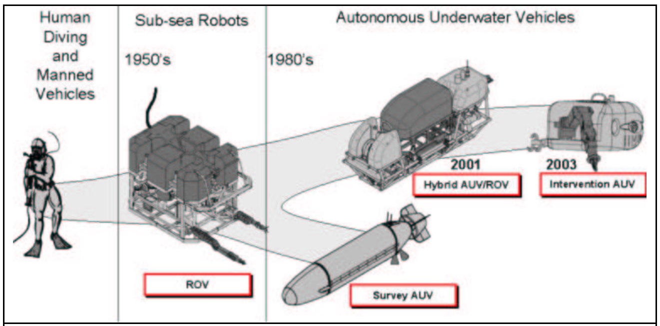

Figure 4. Development of AUVs

In the frame of this network and in interaction with other projects, researchers of FREESUB have been working on the problem of the docking of AUVs since this is one of the main challenges in this field of research. This paper will present some of the results of this work achieved so far.

In the introduction, different missions for the Intervention AUVs will be described. These missions are used to define the needs of I-AUV in terms of technology. A second paragraph will deal with existing standards of the docking of sub-sea vehicles, namely ROVs, and the hardware requirements for the vehicle and on the side of the sub-sea structure enabling an I-AUV to dock onto such a structure. These suggestions for the hardware architecture are then completed by developments for dynamic stabilization and telemanipulation that will be presented in the next two sections. Algorithms and their practical implementation on board an Intervention AUV were developed enabling this vehicle to stabilize in front of a target by visual servoing. The manipulator arm is making the AUV into an I-AUV. But the control of this device is challenging since a real-time control by the human operator is not possible due to the limited communication with the surface. New methods are needed to meet this task. Each section will be underlined by presenting results obtained in the corresponding fields. The last section of this paper will give an outlook in further developments for I-AUVs. Future technologies and designs are proposed to facilitate the docking of AUVs. The assembly of these results onto a standard ROV panel could be what one could call an "AUV-friendly" Docking Panel, which could become a standard for future deep-sea installations.

2.2 Intervention strategy

Different missions are foreseeable for Intervention AUVs. As with the AUV for surveying, I-AUVs 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 lower cost for the missions since no specialized support vessel is needed.
Two main mission categories were identified in the frame of FREESUB: The **intervention mission** on sub-sea structures, e.g. turning a valve on a sub-sea wellhead and the **recovery/delivery type mission**, e.g. the transport of scientific probes from or to the seabed. This paper will deal mainly with the developments related to the first mission type, e.g. the intervention on a sub-sea well head. Some of those developments were implemented and tested on the first European I-AUV named "ALIVE".

Different scenarios for intervention and docking performed by an AUV are imaginable. One first scenario, and probably the most difficult to perform, is an intervention on an unknown structure or on an interface not designed for underwater vehicle intervention. The docking on such a structure is restricted and will probably be limited to a dynamic stabilization in free-floating mode. Hence the intervention in itself has to be smooth and does not have to require high precision. Examples of such a kind would be the cleaning of sub-sea installations or the data acquisition via acoustic modem.
Another possibility is the intervention in a well-known environment. The structure is designed for underwater vehicles, which allows the preparation of an adapted docking procedure. The principle is to adapt the AUV docking device to the existing facilities like handles or conical receptacles. The advantage is that common deep-sea installations are already equipped with standardized ROV panels. These interfaces, designed for manipulations and docking facilities are thus available. But the main purpose of the docking is to stabilize the ROV during telemanipulation. Thus adapted docking interfaces have to be designed to guarantee a good rigidity for automated manipulation.
The last approach is to develop specific interfaces for AUV intervention. The idea is to adapt a ROV control panel to AUVs. The main improvements required are localization and identification systems, the docking facilities, an eventual power supply, and an eventual data link to the surface. Some proposals for future developments will be given in section 6 of this paper.

2.3 Mission Phases

The procedure of docking an AUV can be divided into different mission phases. These phases describe the actions the vehicle has to execute between the arrival on the seabed and the actual telemanipulation.

Figure 5 illustrates the different steps from the approach to the seabed until the telemanipulation on the target:

1. The first position to arrive for the vehicle on the sea ground is the so called Safe Positioning Zone. This is an area approximately 30 meters from the target on an altitude of approximately 3 meters. The objective is to define a safe position, in distance to any possible obstacles, where the vehicle can start the target approach without any risk of collision.
2. Once arrived in the Safe Positioning Zone the vehicle starts going towards the target (after confirmation of the operator) by using sonar and in close proximity also video. At this stage, before the docking, Dynamic Stabilization will ensure that the vehicle is accurately enough in front of the target for the docking.
3. The docking can be achieved with different means corresponding to the target. In the case of standard ROV Docking Panels this can be achieved by grabbers or conical docking receptacles.
4. Once rigidly docked, the vehicle can start the actual telemanipulation on the target by using a manipulator or other tools.

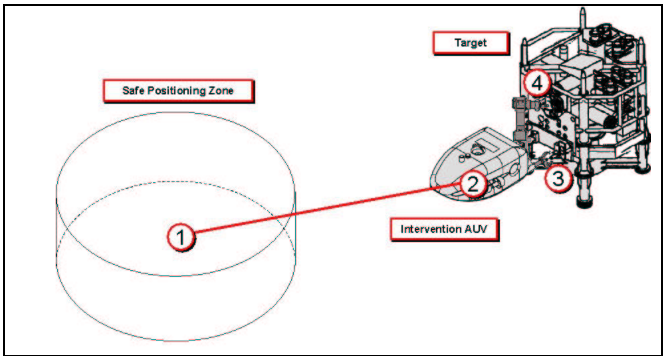

Figure 5. Phases between the descend to the Safe Positioning Zone and the Telemanipulation:
1: Arrival at the Safe Positioning Zone
2: Approach to the target with Dynamic Stabilization
3: Docking
4: Intervention

The following sections will follow this logical order of steps by illustrating the developments and results achieved in the frame of the FREESUB network.

3 DYNAMIC STABILISATION

The predocking stabilization stage is of key importance for the success of the mission of an I-AUV. The complexity of the task lies mainly with the high position accuracy required for docking, as the positional errors between the vehicle and the receiving structures have to be restricted to a minimum. As discussed above, the allowed error is a parameter easily identified by the geometry of the mating components (pin-hole clearance, grabber compliance, etc.) and it is typically one order of magnitude smaller than the resolution of the measures provided by the onboard navigation sensors. Exceeding the allowed positional error may not only lead to the failure of the mission, but it may also cause serious damage to the vehicle and the receiving structure or even the loss of the vehicle itself.

It becomes therefore a necessity to develop a specific control architecture to cater the needs of this delicate stage of the mission. Stemming from the considerations highlighted above, the following main requirements can be identified:

1) the stabilization algorithm position system has to ensure a positional accuracy smaller than the allowed maximal error
2) the closed loop frequency of the controller has to be the highest possible to ensure the robustness of the stabilization.

The latter point also leads to a further consideration. The dynamic stabilization algorithm has to rely on sensors that ensure a refresh rate typically higher than the standard acoustic positioning devices used by the AUV to navigate in open water. Also the accuracy has to be higher than a dead reckoning estimation. Camera and sonar image processing becomes therefore the ideal candidate for the task, as the information gathered can be processed directly onboard the vehicle and the computation time (hence the refresh rate) depend only on the accuracy sought.

3.1 Dynamic Stabilisation: station keeping and positioning

The predocking stabilization task is twofold. Firstly the vehicle has to be capable keeping a fixed position in front of the receiving structure within the maximal positional error. This is to ensure that no drift will occur while performing other tasks than the docking itself, for example communicating with the surface (through a delayed acoustic link) or surveying the intervention area to gather relevant information for the continuation of the operation. Taking into account the effect of currents and the possibility of the presence of other structures close to the docking area, it becomes evident that efficient station keeping is a key to the success of the intervention stage.
Secondly the vehicle requires the ability to probe the receiving structure to extract accurate information and generate a set of waypoints leading to the final docking position. Regarding this latter point, it is important to observe that computational time is not a crucial issue, as much as it is for the station keeping. Provided that effective station keeping is in place, the computation of waypoints from sonar/video data can be performed at a much lower frequency.

The experimental I-AUV "ALIVE" features a Dynamic Stabilization architecture which includes the main characteristics discussed above (see Figure 6). The computational load is distributed onto several agents, each designed to perform a specific task at a given frequency. The positioning subsystem computes range information from sonar scanning, as well as position offsets from image processing. The position offsets are computed by a feature matching algorithm which uses the image of known features on the receiving structure (i.e. valves, docking pins, handles, etc.) and the known configuration of the camera in the vehicle's frame. The main constraint of the feature matching algorithm lies in the requirements for explicit knowledge of task-dependent information such as the position/orientation and geometry of recognizable features on the receiving panel. According to the geometry and the overall conditions considered, the computation of offsets may in general be very costly.

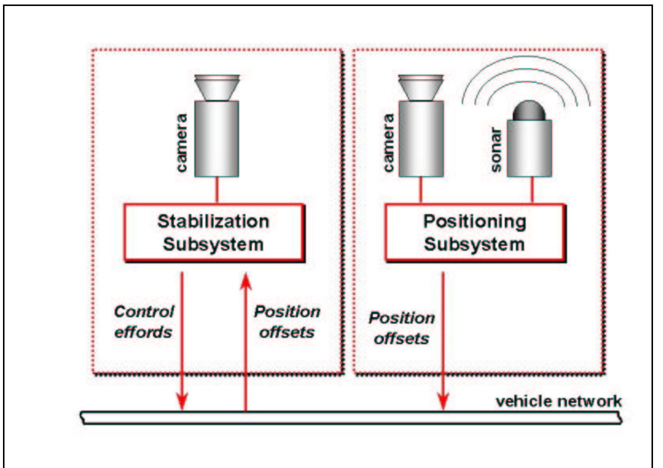

Figure 6. The structure of the stabilization system

The stabilization subsystem (Figure 6) is as well based upon image processing but uses an optical flow estimator to measure the dominant motion between two subsequent images from the docking scene.

3.2 Optical flow based dynamic stabilization

The use of optical flow estimation offers the distinct advantage that any feature on the receiving panel which appears in the camera's field of view contributes to the identification of the dominant motion. In other words, the estimation of the optical flow rids of the need for including specific marks or special recognizable features on the receiving panel. In addition to that, despite varying largely according to that algorithm chosen, the computation time depends mainly on image size and accuracy sought, therefore the desired closed loop control frequency can be achieved by tuning a restricted number of parameters.

The experimental I-AUV prototype ALIVE features an optical flow based dynamic stabilization controller based on the RMR (Robust Multi Resolution) optical flow estimator developed by INRIA [3]. The algorithm was chosen for its well proven robustness and versatility in previous underwater image processing (i.e. video mosaicking [14][15]).

Due to the nature of the task (i.e. small vehicle motions parallel to the intervention panel) the choice of a 2D motion model instead of a full 3D one is not particularly restrictive and offers large advantages in terms of process time.

Therefore, being $X_i = (x_i, y_i)$ the spatial image position of a point, the flow vector at point X_i, $V(X_i)$, is computed using a simple model linear with 6 motion parameters, as in:

$$V(X_i) = \begin{cases} u(X_i) = a_1 + a_2 x_i + a_3 y_i \\ v(X_i) = a_4 + a_5 x_i + a_6 y_i \end{cases}$$

where the vector $A = (a_1, ..., a_6)$ of motion parameters is computed by the RMR algorithm. The model offers a good tradeoff between complexity and representativeness as it enables to take into account many kinds of motion: translation, rotation, scaling, etc. ([3]).

The optical flow stabilization algorithm is currently undergoing wet trials at Ifremer's test pool using a mock up of the docking panel. The particularly favorable roll stability of the vehicle, has also enabled to discard computing the linear motion parameters $(a_3, ..., a_6)$ therefore contributing to a further reduction in computation time. In this configuration, the optical flow estimator has been tested in a number of wet trials aiming to establish the efficiency of the approach . The closed loop frequency achieved oscillates between 10 Hz and 5 Hz and the accuracy of the motion estimation is below 10 mm. At present, the positioning accuracy of the I-AUV "ALIVE " under visual servoing is estimated at around 100 mm, as further work is necessary to tune appropriately the PID controller. In addition to that a strategy is currently under development to filter the apparent optical flow due to changes in heading and pitch attitude of the vehicle in front of the receiving structure. These undesired effects are especially marked along the horizontal axis, where because of the vehicle oscillating around a fixed heading (typically ± 2°), an apparent displacement proportional to the distance from the target and the tangent of the oscillation is measured.

4 AUV DOCKING SOLUTIONS.

The docking of an AUV is a complex task. Even if this problem has some general requirements, the solutions are highly dependent on the available underwater structure. This is why, after having developed the characteristic of the procedure of AUV docking, this paper will propose different solutions depending on the environment.

The delay caused by the acoustic communication of the AUV calls for an autonomous dynamic stabilization, but this cannot offer a perfect accuracy in the position prior to the docking. This is another requirement for making an AUV able to dock is to design a docking device able to tolerate the misalignment during this docking procedure. Once the docking is effective, it has to sustain the rigidity needed for the autonomous or semi-autonomous manipulation.

4.1.1 Misalignment tolerance

There are two approaches to resolve the positioning misalignment. The first is to perform a docking allowing an approximate position. Which means a docking system with no specific docking point, but with a docking surface. For example an AUV equipped with an electro permanent magnet can be docked, or more exactly, stabilized on a flat steel plate. In this case, the contact point is not fixed. The width of the contact point area is dependent on the positioning accuracy of the AUV. The main problem of this solution is its restricted rigidity .

The second strategy is a docking that at the same time performs an auto-correction of the position. The correction is done thanks to the contact between the two interfaces. A straight forward example is conical docking. The AUV is equipped with a conical plug. When the cone enters into the hole interface, the cone, and so the AUV, is automatically centralized. This solution has the advantage to provide a good rigidity, but it calls for a specific interface.

These cases illustrate the interaction with the environment and the variety of possible answers. One solution for each case, the structured and unstructured environment, will be retained in the following sections.

4.1.2 Grasping on structured environment

To dock rigidly an underwater vehicle, conical plugs or grasping claws can be used. The conical plug offers only a small misalignment tolerance of a few centimeters [4]. Furthermore this option can only be used on specific ROV panels (other underwater installations do not dispose of such device). The claw offers a good misalignment correction, and specific claws can be designed for each kind of handling bar or tube on the intervention target.

The different kinds of handles, used on ROV control panels, are specified by the ISO/DIS 1368-8 [4]. The T shape offers a good possibility for the correction of the position and to ensure rigidity. This is why, in the case of the ALIVE project, specific claws for T handling were developed [5]. The following description is an example of a specific handling bar configuration adapted claw .

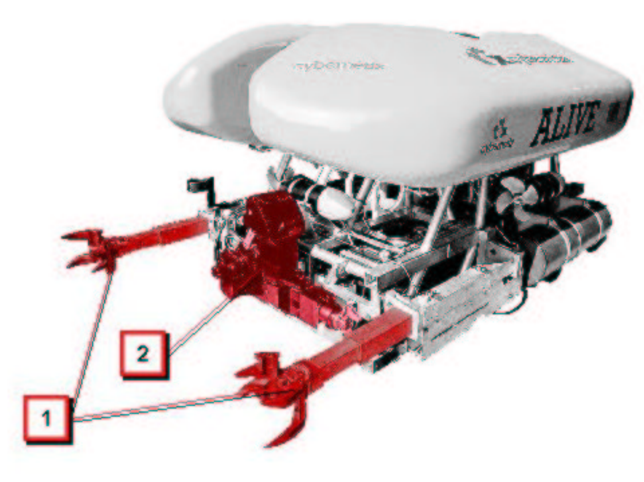

Figure 7. The "ALIVE" I-AUV:
(1) Docking claws; (2) the hydraulic SAMM Manipulator

4.1.3 Misalignment correction

To achieve a correction of the misalignment of the AUV, its claws are designed in a curved shape.

During the docking step the AUV approaches with the open claws. In the case of a misalignment, the handle will touch the claw on this curved surface which will guide the vehicle automatically into the right position. The altitude of the AUV is more or less precisely controlled: and so the biggest misalignment of the AUV relative to the control panel will occur in the horizontal plan. This claw design allows a misalignment correction of *+/- 135mm*. Thus, this is the minimum accuracy to be achieved by the dynamic stabilization system.

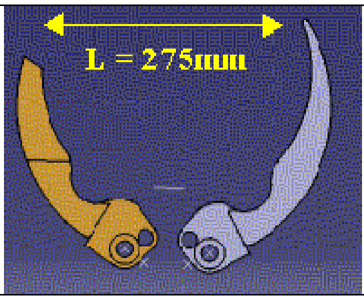

Figure 8. Horizontal curve

The vertical misalignment will be corrected during the closing of the claw. The internal surface of the claw is also curved, which will guide the vehicle during the closing into the right position. Within this configuration, the tolerance of the external claw is 150 mm (accuracy required +/- 75mm).

The following figure shows the transitions between the different mission phases and the accuracy needed to pass from one to another.

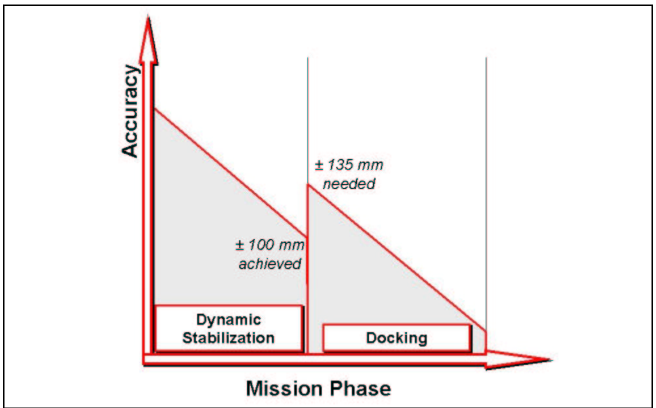

Figure 9. Accuracy needed to pass to the next mission phase

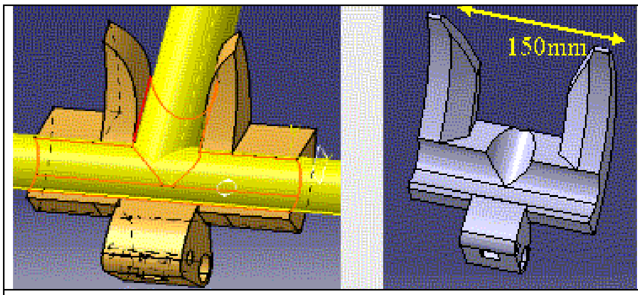

Figure 10.(a) Internal claw part (b) External claw part

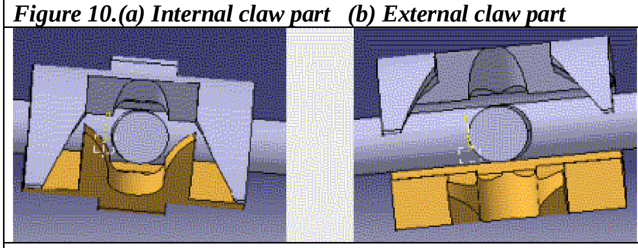

Figure 11. (a) 15 degree opening (b) 30 degree opening

The external claw will enter on the vertical plan of the handle with an opening of 30-degree (cf. Figure 11 (b)). The internal, smaller claw part will enter on the vertical plan of the handle with an opening of 15-degree (cf. Figure 11 (a)). Between 30-degree and 15-degree, the closing of the claw will be guided by the external claws part. When the claws reach an opening of 15 degree, the feet of the T bar is lead by the external claw part into the internal claw part. At this stage the grabber is guided by the internal claw part.

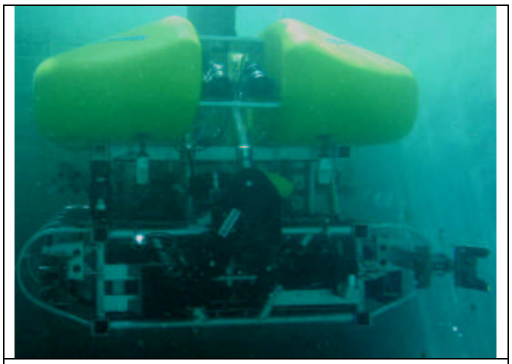

Figure 12. Pool trials of "ALIVE". Grabbers extended

4.1.4 Rigidity

The T shape of the handle is used for the mechanical contact. The claws will completely surround the handle. In figure 10 (a) one can see the contact surface between the claws and the handler. **The claw thus completely encloses the T part of the handle which blocks every displacement and rotation.** The fixture is thus insured mechanically and not by friction.

This claw design compiles rigidity, misalignment tolerance and correction. Furthermore due to the T shape of the handling bar, the docking position is fixed, which should facilitate the autonomous manipulation. This design is configured for T shaped handles. If the docking is performed on different handles, specific claws have to been installed.

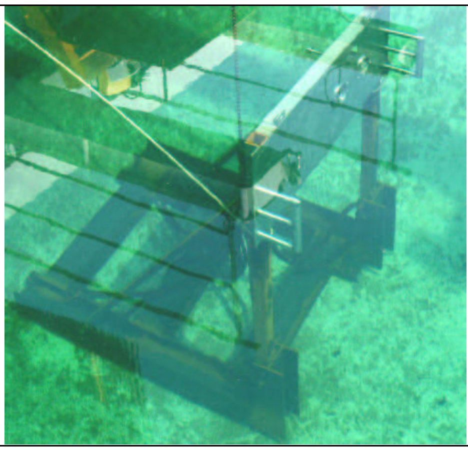

Figure 13. The docking Panel for the "ALIVE" robot (in the test pool)

4.1.5 Stabilization on common environment

In this case, the environment is unknown or not adapted to docking. And so, the solution has to be adapted to the existing hardware but will never be perfect. The following description will try to categorize the different technological aspects and the possible answers.

Stabilization on plane surface

The only possibilities to dock on a quasi-plane surface are the use of magnets or suction. The suction is power consuming and necessitates a smooth and clean surface. Its high rate power/suction forces imply a limited use of this possibility. On the other hand, the magnet has the advantage of not consuming power during the docking. The electro-permanent magnet is a permanent magnet disabled by an electrical current. If an electro-permanent magnet is used it will only consume power during the undocking phase. A restriction for the magnet must be the ability of sticking on a steel plate free from marine growth. The magnet, as the suction, are helpful during the docking approach thanks to their action force characteristics. The problem of these systems is their incapacity to restrain the translation displacement on the surface.

Grasping stabilization

Using claws for grasping asperity has the advantage to fix the AUV in displacement on the grasping point. But if the asperity is not characterized before the operation or is not offering fine grasping contact, the claws will not perfectly fit on the asperity. In this case, the claw risks to move around the asperity and does not block the rotational movement.

Combination

Thus a potential solution to dock on unstructured environment is to combine magnets and a grasping system. The combination will allow to fix the system in rotation and translation. Furthermore, if the configuration of the sea-bed infrastructure does not permit the use of the both systems, their complementary of application should allow one of the systems to work and to execute a stabilization.

5 AUTONOMOUS TELEMANIPULATION

4.1 Introduction

Nowadays, underwater interventions are carried out by ROVs. These vehicles are characterized by having an umbilical cable that links them to the surface. The cable is used for supplying power to the vehicle as well as communication link to the vehicle from the surface control unit. Owing to this communication type, the control of the vehicle mounted manipulator arm from the surface does not present a problem. Sometimes, under some particular conditions where delays occurs, it is possible to resort to assisting techniques, such as predictive displays, force feed-back, or shared compliance control [6], to achieve the manipulation task. In the case of I-AUVs, the communication used is acoustic. The significant delay appearing in this type of communication, combined with a very narrow bandwidth, result in the impossibility of using a direct or real-time tele-operation, even using assisting techniques [7]. The intervention must be carried out autonomously.

There are two main critical points in the autonomous manipulation: the environment knowledge and the vehicle motion.

Environment Knowledge

Before starting the manipulation task, an accurate 3D map of the target and its surrounding elements must be available. If information is not available before the mission start, it can be acquired using onboard sensors. The main problem is the calibration process. Both cases require the intervention of a human supervisor to match the reference points. Entrusting this task to auto-calibration techniques or other autonomous methods would exceed the safety parameters [8][9].

From the feasibility point of view, a small lack of precision in the environment map or an inaccurate calibration, even inside the safety margin, could generate problems once the manipulator's tool contacts the target. Adjusting autonomously the tool position and orientation to the target requires the use of hybrid position/force control [10] or other similar techniques.

Residual Movement

After the docking maneuver, the vehicle movement can be reduced significantly, even up to a theoretically static state [9]. But to assume that the vehicle will remain static during the whole intervention could be too self-assure. It is important to remark that when interventions are performed on oil wells or other sensitive facilities, an accident can be catastrophic. Thus any risks that could lead to an accident cannot be accepted. The residual motion problem can be divided in three phases, and each phase requires a specific solution.

Approaching trajectory: This phase starts with the manipulator in the parked position, a safe position far from the target, and ends when the manipulator's tool has physical contact with the target. During this phase, the vehicle movement can cause divergences between the desired trajectory and the current one. These divergences must be corrected in real-time closing the control loop with the information from the on-board sensors.

Target grasping: Due to lacks of precision in the target map, calibration errors, manipulator inaccuracies, and vehicle movement, the contact between the panel and the tool can be produced in a wrong point. Using a trajectory correction technique these positioning errors can be reduced significantly, but eventually not enough for a correct target grasping. Correcting these small errors can be done using a force control in the manipulator and specific designs of the target. If the target does not offer this friendly interface, the force control can be complemented with video camera feedback.

Motion following: Once the target has been grasped, the manipulator has to operate on it and, sometimes, wait for instructions from the surface. During this period of time, the vehicle can be in motion. The arm control has to be designed to resist these strong disturbances and to accommodate the arm configuration to the new position relation between the arm basis and the tool. This phase will also require force control.

5.2 Trajectory Correction

To correct the manipulators trajectory during the approaching phase it is necessary to know, for each period of time, the variable relative position of the robot tool with respect to the target[11]. If the arm is calibrated, as it is supposed to be, this is the same as knowing the relative position of the vehicle with respect to the target. There are some approaches to solving this problem, but all of them have to be based on the sensors feedback.

The accuracy required for this task depends, mainly, on the target configuration. This will determine the maximum position and velocity errors tolerable at the moment of a contact between the robot's end-effector and the target. In a common intervention, it can be supposed that position errors over just a few centimeters are not acceptable. Therefore, sensors to be used in the trajectory correction must have, at least, this accuracy level. Inertial navigation sensors, though they could be used to obtain auxiliary information in order to improve the robustness of the correction technique, barely can reach this accuracy level. The ideal candidate sensor is the video camera.

Underwater computer imaging has inherently associated problems such as shadows, hot spots or marine snow. Under these conditions, developing a safe, robust, and accurate technique for detecting and quantifying the translations and rotations of the docked vehicle represent a complex problem. Diverse techniques have been proposed and experimented, but this field still remains open to research [12].

There are two main approaches for the reconstruction of the vehicle movements. First, the techniques based on stereoscopic vision. These methods are not a good option due to their high computational cost, bad accuracy, and calibration problems. The other group of techniques, based on monoscopic vision, uses the vehicle movement to take images from diverse points of view and reconstructs with them the vehicle movement. This group is more commonly used and can give good results, but in this specific case it is very difficult to implement a technique that satisfies all the requirements. The large number of features to match for each pair of images, needed to achieve 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, working under supervised control mode is indispensable.

Once the vehicle motion has been reconstructed, that is, 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 to keep the relation between the arm's tool and the target as desired [11]. Small accuracy lacks will be corrected, after the contact with the target, by a force control.

5.3 Active Compliance

During the final phase, the manipulator motion is constrained due to its contact with the rigid surface of the target. This circumstance is worsened by other factors as inaccuracies in the manipulator tool positioning, incomplete target knowledge or residual vehicle motion. Operating autonomously the arm under these conditions is not possible without a mechanism for adapting the tool position and arm configuration to the current constraints.

There are mainly two types of compliance [13]:

- Passive compliance, e.g. a non tuneable, mechanic compliance, such as dampers or springs.
- Active compliance, e.g. a tuneable controlled compliance mechanism.

Passive compliance can be present in the device to be operated or in the manipulator (tool, joints, or base).

The passive compliance applied in the device requires that all the devices to be operated have to be adapted to these requirements, which is unacceptable in underwater industries. Applying this compliance to the manipulator will deteriorate the arm dexterity. In both cases, passive compliance is limited and, by definition, uncontrolled.

The active compliance requires a feedback of the forces applied on the tool during its contact with the target. This force feedback combined with the desired trajectory, can be used to find the target interface or to modify the arm configuration in order to minimize the forces acting on the tool when it reaches the target.

Due to the obvious necessity of a compliance in underwater autonomous manipulation and the superiority in yield of the active compliance compared to the passive one, the using of force sensors, and the integration of the feedback received from it in the control loop, seems to be essential.

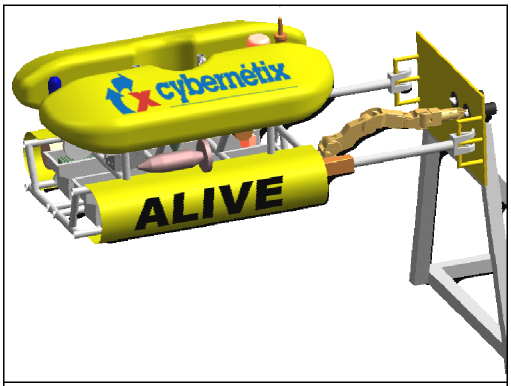

Figure 14. The "ALIVE" I-AUV

Autonomous underwater intervention represents a big challenge. Factors such as the ocean currents, tolerances in the docking system, lack of knowledge of the environment, and calibration inaccuracies, raise substantially the complexity of this kind of manipulation.

Owing to this complexity and the elevated risk of interventions in underwater oil-industry facilities, the working under supervisor control mode is necessary.

Trajectory correction techniques, when the residual movements of the vehicle are not worthless, must be applied. The proposed way to solve the problem is based on the use of image processing methods, reinforced by available data from the inertial navigation sensors.

Due to the required contact between the manipulator and an unstructured environment, the use of force control, in any of their different configurations, seems to be indispensable.

6 SUGGESTIONS FOR A "AUV-FRIENDLY" DOCKING

A further direction of research in the frame of the FREESUB network is dealing with the equipment to be used for I-AUV docking. In the specific case of interventions on a sub-sea wellhead it is the docking panel for AUVs that could be reviewed.

To introduce these robots in offshore industry, I-AUVs have nowadays to be adapted on what can be found on sub-sea installations. In fact the robot must be capable of docking onto the standardized ROV panel [4]. But, for future applications it would be worth investigating what kind of technologies could be integrated into these installation to facilitate the docking of autonomous underwater robots.

Special target forms or visual patterns could be used allowing a robust automatic identification of the target. Visual markings, that can be easily processed by a computer, could help to dock the vehicle onto such a station. But also the mechanical design (which was developed for human controlled ROV manipulation) can be reviewed, introducing for example increased tolerances enabling the vehicle to dock and manipulate even in the presence of currents or residual movements of the vehicle.

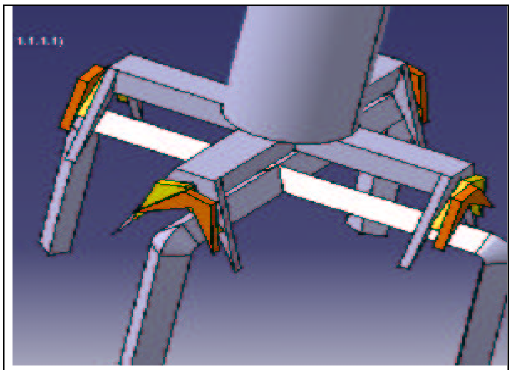

Figure 15. The X handler and the adapter claw

A new handle concept could be the X handles. This concept allows an automatic closing of the claw. Figure 15 shows a claw adapted to a X handles. The contact between the claw and the handle closes automatically the claw onto the handle. Such a system would facilitate the docking and reduces it to a minimum intervention of the operator. The triangular shape of the base assumes the misalignment correction. The rigidity is assured by four contact points. The squared basis of the handler assures a good rigidity in rotation at each of the four contact points where the claw surrounds totally the handle.

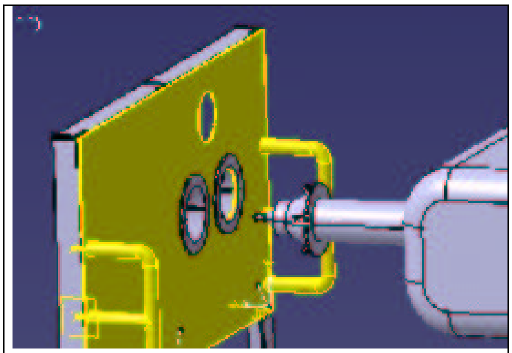

Figure 16. The X handler and the adapter claw

A new philosophy of intervention can also be taken into account. As an AUV for intervention can only do basic tasks nowadays and requires adaptation of the underwater infrastructure, the AUV has to be adapted to one single, specified task. The idea is to launch an AUV equipped with the minimum of tooling to execute a task. For example, in order to turn a valve, an AUV would only need a torque tool and a docking system to stabilise itself during the intervention. A possible concept is to integrate the torque tool in the docking device. This will allow a reduction of the tool and size of the AUV and on the same time offer a good stability. This solution implies a simultaneous development of the I-AUV and of the underwater infrastructure. Collaboration of the intervention industry and the offshore production installation is pre-required. In the solution proposed in figure 16 the torque tool is integrated inside a conical docking device. The device, with a diameter of 200 mm, furnishes a misalignment correction of (+/-100mm) and a perfect stability of the tool during the operation.

A further approach, which corresponds in some terms to the concept of the SWIMMER AUV, is to foresee power supply and communication links in the docking facility. In this scenario, the AUV would have to dock onto the station and connect itself to these links in autonomous mode. Any further operation can than be done by using the power supply from the surface and the real-time assistance of the human operator.

7 CONCLUSION

In this paper several developments dealing with the problems of docking an Intervention AUV were presented. Some of these developments as the Dynamic Stabilization system by visual servoing or the docking grabbers were already tested on an Intervention AUV.
But those developments will be lead further like e.g. the "AUV-Friendly" Docking Panel which calls for a new philosophy in sub-sea installation design. Since those installations are reaching progressively deeper depths, AUVs and especially I-AUVs will be unavoidable. But its design has to be reviewed, like it was done for the intervention of ROVs, to a AUV friendly design.

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

8 ACKNOWLEDGEMENT

The authors want to thank all members of the FREESUB network who helped to write this paper with their suggestions, comments and ideas.

Some of the developments of the Young Researchers of the FREESUB network were tested on the "ALIVE" AUV which was financed by the European Commission under the GROWTH programme. The authors are much indebted to the participants of this project, opening them an opportunity for doing real tests on such a vehicle.

FREESUB is a Research Training Network financed by the European Commission dedicated to the research in sub-sea robotics and the training of young researchers in this field. The authors want to express their thankfulness to the European Commission making this research possible.

9 REFERENCES

[1] D. Labbé, P.Wilson, P.Weiss, L. Lapierre "FREESUB: Navigation Guidance and Control System for Intervention an AUV" SCSS 2003

[2] Y.Chardard, T.Copros " Final Sea Demonstration of This Innovative Hybrid AUV /ROV System" AUVSI 2002

[3] J.-M. Odobez, P. Bouthemy. Robust multiresolution estimation of parametric motion models. Journal of Visual Communication and Image Representation, 6(4):348-365, December 1995

[4] Petroleum and Natural Gas Industries – Design and Operation of Subsea Production Systems – Part 8: ROV Interfaces ISO/DIS 13628-8

[5] D. Grosset, J.V. Catret, F. Andritsos.,C. Papadopoulos, "Quasi-rigid Docking of AUV for Underwater Manipulations", CSIT 2002.

[6] A. Bejczy and W. Kim. "Predictive Displays and Shared Compliance Control for Time-Delayed Telemanipulation". IEEE IROS'90. pp. 407-412.

[7] T. Sheridan. "Telerobotics, Automation, and Human Supervisory Control". MIT Press, 1992. ISBN 0-262-19316-7.

[8] K. Plakas, E. Trucco, y A. Fusiello. "Uncalibrated Vision for 3-D Underwater Applications". Proceedings of the OCEANS 98 Conference, Nice, France, September 1998.

[9] B. Triggs. "Autocalibration from Planar Scenes". European Conference on Computer Vision, Freiburg. 1998.

[10] M. Dunnigan, D. Lane, A. Clegg, and I. Edwards. "Hybrid position/force control of a hydraulic underwater manipulator". IEE Proc.-Control Theory Appl., 1996.

[11] J.V. Catret, D. Grosset, C. Papadopoulos, and F. Andritsos, "Trajectory Correction of an AUV-mounted Underwater Robotic Manipulator", CSIT 2002.

[12] G. Foresti and S. Gentili. "A Vision Based System for Object Detection in Underwater Images". International Journal of Pattern Recognition and Artificial Intelligence. 2000.

[13] A. Lanzon. "Compliant Motion Control for Robotic Manipulators". University of Cambridge.1997.

[14] Real-Time Georeferenced Video Mosaicking with the MATISSE System, Anne-Gaëlle Vincent, Nathalie Pessel, Manon Borgetto, Jérôùe Jouffroy, Jan Opderbecke, Vincent Rigaud, Oceans'2003 Marine Technology and Ocean Science Conference, San-Diego,USA, September 2003 (to appear)

[15] F. Spindler, P. Bouthemy, Real-time estimation of dominant motion in underwater video images for dynamic positionning, in IEEE Int. Conf. on Robotics and Automation, ICRA'98, Volume 2, Pages 1063-1068, Leuven, Belgium, May 1998.