Quasi-rigid docking of AUV for underwater manipulations

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Abstract

Autonomous Underwater Vehicles (AUV) are currently been used for exploration missions for sampling and data collection, involving mainly autonomous navigation. Recently, AUV have been proposed for maintenance tasks. These tasks imply either semi-autonomous or robotic manipulation modes. Very stable docking is a pre-requisite, especially for the robotic playback mode; otherwise the motion of the AUV relative to its target must be actively compensated.

Previous works on ROV or AUV docking mainly focused on simplicity and ease as well as on data and power transmission.

The aim of this paper is: a) To investigate on the rigidity of 'standard' docking solutions and their suitability for performing manipulation task in robotic or in semi-autonomous mode and b) to propose an innovative docking solution that, although it remains simple and easy to perform, it offers the necessary rigidity for performing autonomous manipulations with an anthropomorphic 6 DoF robot in simple robotic playback mode.

For that purpose all static and dynamic force components acting on the AUV as well as the reactions on the grabber(s) and manipulator tool have been analyzed and their influence on the dynamics of the AUV has been estimated for different docking methods. Finally, a maximum rigidity docking device has been designed and verified. The primary scope was that of minimizing the motion / vibration of the robot base so as to permit manipulation through simple robotic playback.

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1 Introduction

Although a rigid docking is a perfect condition for an AUV to perform special manipulation tasks, this is not always possible. The rigidity of the docking is always depending on the external forces applied on the AUV and the caused corresponding displacements. Practically the displacements could be ignored if they don't effect significantly the accuracy of the manipulation. In this case the concept of quasi rigid docking could be introduced. By this term one could define a docking as rigid for a purpose and not rigid for an other. In other words each kind of docking, rigid, quasi-rigid or flexible could efficiently be used for different kind of tasks. In our case these tasks imply either semi-autonomous or robotic manipulation modes and our purpose is to investigate the suitability of different ways of docking.

In the literature appear many works simulating the dynamic behaviour of an underwater ROV or AUV. A simplified dynamic model for streamlined underwater vehicles is presented in [1] by Nahon.

Dunnigan and Russell present an approach to the evaluation of the dynamic coupling between a manipulator and an AUV or a ROV in [2]. They formulated the equations for a 6 degrees of freedom (DoF) for the vehicle and 3 DoF for the manipulator. Then the effect of the manipulator motion on the vehicle position/orientation is investigated and a method to reduce this coupling is also presented. Their approach doesn't include any docking and in their conclusions the authors pointed out the need of a stable platform when performing manipulative tasks.

A dynamic simulation algorithm of an Underwater Vehicle (UV) with a 6 DoF manipulator is also presented by McMillan, Orin and McGhee [3]. The algorithm includes the effect of the moving base of the UV and performs forward kinematics, backward dynamics and forward accelerations. The model includes added mass, viscous drag, fluid acceleration and buoyancy forces.

A new motion coordination algorithm for an AUV-Manipulator system is presented in [4] by Sarkar and Podder. The algorithm presented generates both the vehicle and the manipulator trajectories minimizing the hydrodynamic drag on the system. Shapes of vehicles having analytical expressions for the hydrodynamic drag coefficients are selected but the method is general and can be applied to any shape if their coefficients are known or measured.

2 Generalized forces applied

The hydrodynamics loading applied on an AUV is geometrically coupled and content non-linear viscosity. Several resolution methods are available in the literature for resolve this coupling problem. Euler-Lagrange (E-L) and Newton-Euler (N-E) are the commonly used method. Fosen [7] who uses a quasi-Lagrange formulation is becoming the reference. But all those methods are complex and time consuming. As the aim of this paper is to characterize a rigid docking, the hydrodynamic loading will be evaluated for a static submarine. And so the different loading coming from the current will be simply added. Scott McMillan, David E. Orin and Robert B. McGhee [3] have characterized four loading applied on a submerged rigid body: The hydrodynamic forces applied on the docked AUV which are calculated from the sea-water current data and the hydrodynamic coefficients of the AUV. Other forces included are the gravitational, the buoyancy the centrifugal and Coriolis. The added mass is also taken into account.

The general 6 DOF dynamic equation of motion of the AUV

$$-M_{Av} * \dot{E}_v - C_{Av}(E_v) * E_v - D_v(E_v) * E_v \\ - g_v(q_v) + \Gamma_{arm} + \Gamma_{grabber} = 0 \quad (1)$$

Where Ev is the incident speed of the liquid around the vehicle, and is expressed in the submarine coordinate system, M_{Av} is the added mass matrix, Dv (Ev) is the damping matrix, gv (qv) is the gravity and buoyancy matrix, $\Gamma_{grabber}$ is the force vector coming from the docking facilities and Γ_{arm} is the force vector coming from the manipulator arm. In this equation the inertial component are not taking into account. Indeed, the aim is to characterize the loading on a docked AUV.

2.1 Frame representation

The movement and the forces applied on the submarine will be express in a body coordinate system. The origin of this coordinate system is the geometric center of the vehicle {B}. This configuration will facilitate the expression of the hydrodynamic loading.

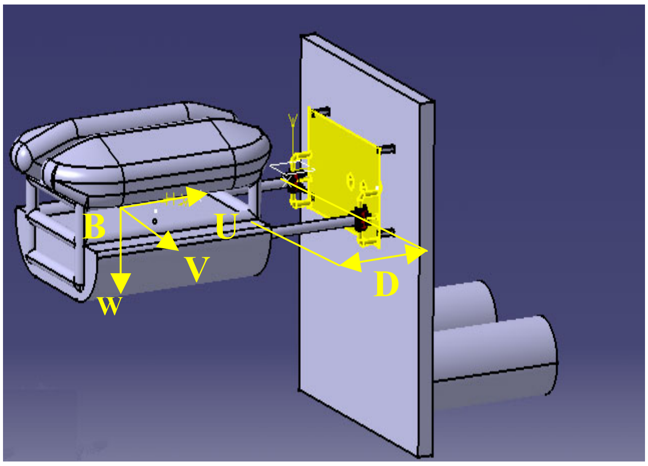

Figure 1: The AUV coordinate system

2.2 Drag forces

Since water density is significant, the main force applied to the submarine is the damping force. When an object moves through a viscous fluid or when the fluid moves around the vehicle, damping forces are exerted on it. Two kind of damping can be observed. The skin friction due to the boundary condition and the drag forces due to vortex shedding created behind the vehicle. The diffraction damping due to wave oscillation will be neglected for the case of deep-sea trial. Theoretically the damping forces can be calculated by integration of the fluid pressure around the vehicle. But this pressure depends of the shape of the submarine. As the shape can be complex, this is difficult to determine and for each axis (i) the damping force is usually given by the relation.

$$-D_{vi}(E_{vi}) * E_{vi} = -\frac{1}{2} \rho\, C_{di} * |E_{vi}| * E_{vi} * A_i \quad (2)$$

C_{di} is the drag coefficient of the vehicle along the (i) axis. It's given by the literature for the common shape [11] or by experiment for more complex shape. A_i is the i-axis normal projected cross-sectional area. This formulation doesn't take into account the tangential damping forces. This is because the skin friction damping is negligible compared to the drag forces. Indeed in water the damping is mainly caused by the drag forces for a speed current higher than 10^{-3} m/s. For each axis (i) the drag force is applied at the center C_i of the projected area. And can be express as if it was applied at the geometric center G_b of the AUV. The (i) drag-force and C_i-G_b being collinear.

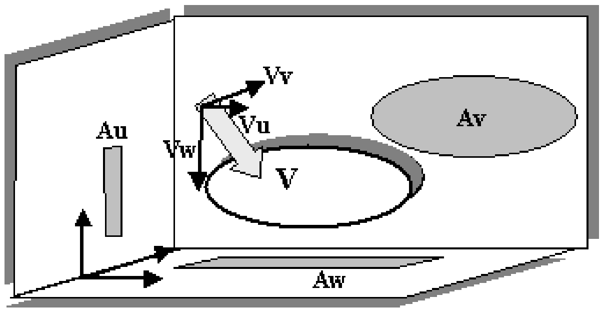

Figure 2: u,v,w orthogonal projection

2.3 Added mass

When a body moves in a fluid (or when the fluid move around the body) the fluid is accelerated. The force needed to accelerate the fluid can be expressed by the added mass. For help the calculation Fosen [7] developed the fluid acceleration feedback by two matrixes using the SNAME (Society of Naval Architects and Marine Engineers) notation. The added mass matrix ' Ma ' which is the relation matrix between the vehicle acceleration and the force feedback received by the vehicle. And the added Coriolis and centripetal matrix 'C_a' which is the relation matrix between the speed of the vehicle (relative to the current) and the Coriolis and centripetal feedback. 'M_a' and 'C_a' are derived from the fluid kinetic Energy using the Kirchhoff equations express in the body frame.

As the acceleration of the fluid is dependent of the shape of the submarine, the added mass matrix depends of the shape of the submarine. For a submerged vehicle the interaction fluid-vehicle doesn't change and the Added coefficients are constant. Under the consideration that the relative velocity vehicle-fluid is small (which is the case for AUV and ROV) and that the vehicle has three planes of symmetry, 'Ma' will be diagonal. For simple vehicle shape, 'M_a' and 'C_a' are find in the literature. As example, Fosen [7] give the added mass coefficient for an ellipsoid. For a diameter of 3x2 m^2,

$$M_{Av} = [I][X_u \; Y_v \; Z_w \; L_p \; M_q \; N_r]^T \tag{3}$$

where X_u = 1776 kg, Y_v = 4150 kg, Z_u = 4150 kg, L_p = 0 kg.m^2, M_q =2100 kg.m^2, N_r = 2100 kg.m^2. The more complex shapes are calculated from a strip theory. The body is divided in strip on which a 2D added mass is assigned. The 3D added mass is the integration of the 2D term on the length of the vehicle.

2.4 Restoring forces and moments

On a submarine the restoring forces are the buoyant and gravitational forces. The buoyant force is applied at the center of buoyancy C_b. The buoyant force is the superficial force due to the Archimedes phenomenon. And is equal to the weight of the fluid displaced by the submarine. And so the buoyant force is applied at the geometric center of the submarine. The gravitational force is applied at the center of gravity. These two forces create a couple of force, which depend of the orientation of the vehicle. For an AUV, the acoustic communication delay imposes a semi autonomous navigation mode. Therefore the stability is primordial and generally the buoyancy center is at the vertical of the gravitational center (C_g). If C_b is the center of the body frame, C_g has for coordinate (x_g,y_g,z_g) with x_g = y_g = 0. If [ϕ, θ, ψ] is the orientation of the body frame, we have:

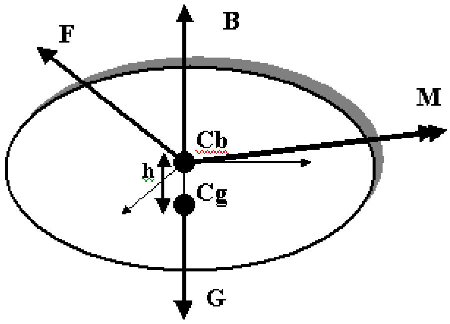

Figure 3: restoring force and hydrodynamic loading

$$\begin{pmatrix}\varphi\\ \theta\\ \psi\end{pmatrix}\begin{vmatrix}roll\\ pitch\\ yaw\end{vmatrix} \quad and \quad g_v(q_v) = \begin{pmatrix}(G-B)\sin\theta\\ -(G-B)\cos\theta\sin\varphi\\ -(G-B)\cos\theta\cos\varphi\\ zg\; G\cos\theta\sin\varphi\\ zg\; G\sin\theta\\ 0\end{pmatrix} \tag{4}$$

2.5 Forces on the AUV due to the manipulation arm

The manipulator generates two kinds of forces: The inertial forces and the forces coming from the manipulation. The inertial forces appear when the arm is moving from its parking position to its operative position and is dependent of the velocity and of the acceleration of this movement. If fast reactions are needed, the inertial force must be including in the calculation procedure. In our case the AUV is docked and quick action are not required. The displacement of the arm will be slow and the inertial forces can be neglect. In more this inertial force appear before the manipulation task and doesn't influence the AUV rigidity and displacement during the manipulation. It's why we will concentrate the study on the forces bringing by the manipulation itself.

In this chapter the forces on the AUV due to the tool end of the manipulator arm are calculated and presented. When manipulating additional arm forces are transmitted to the docked AUV. Those forces can be calculated if the resistance of the manipulation action is known. In general these loads consist of three forces and three moments.

For calculate the forces applied on the submarine, the constraint of the basis of the arm and the constraint of the tool have to be evaluated. In a first approach we will consider the submarine and the arm basis as fixed. The second point is the contact existing between the end effector and the operating point. This contact is depending of the operation and of the interface. For example, the ISO/DIS 1368-8 [13] gives different torque intervention receptacle, where the contact varies with the interface specification. If we consider a flat paddle used as a rotary low torque interface the tool is fixed in displacement and free of rotation during the manipulation. Knowing the constraint specification and the loading needed for operate. The manipulation reaction applied on the AUV is obtained with a finite element solver.

3 Grabbers positioning analysis

The first step needed for design the docking facilities, is to know the forces applied on it. From the loading applied on the AUV the docking facilities reactions are easily obtain with a finite element solver. This method doesn't take into account the elasticity of the system, but allows investigating the docking reaction in function of the grabbers positioning. The main forces damageable to the docking facilities are the moment applied on it. For investigate this moment, we will use the coefficient C

$$C = \sqrt{\sum_{j=1}^{n} \left(M_{xj}^{\;2} + M_{yj}^{\;2} + M_{zj}^{\;2}\right)} \tag{5}$$

The moment M_x, M_y, M_z, are express in the global frame. The index *n* represents the number of docking facilities. This *C* coefficient allows to characterize the global reaction, taking into account the huge component. As the weight and the docking procedure limit the number of docking point, we will limit our positioning analysis from one docking facility to 2 docking facilities

For determinate the influence of the docking position on the reaction, the reaction have been analyzed for different docking(s) facility position. The main forces interesting the rigidity of the docking are coming from the center of buoyancy and from the arm basis. And so the grabber(s) will be place around these emplacements.

3.1 Two docking point

Using a finite element program we have calculated the reaction applied on the grabber for different position of the grabbers.

After looking at the different configuration, it's appearing that the main cause of moment in the grabber is the unsymmetrical positioning ($z_1 \neq z_2$ or $y_1 \neq y_2$). In the second part of the positioning analysis, we will so determinate the influence of the z and y positioning of the grabber.

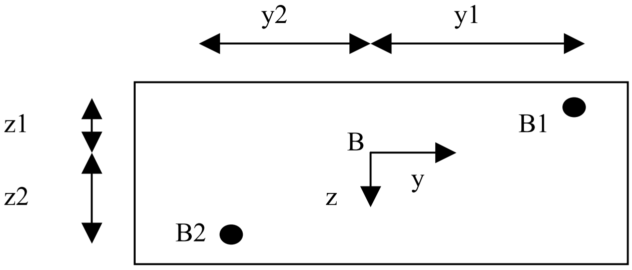

Figure 4: y, z position of the grabber basis

In deep sea the current is mainly horizontal. And so the hydrodynamic loading is also horizontal.

The figures (5,6,7,8) express the C coefficient existing on the two grabbers when a horizontal loading is applies on the AUV. In the figure 7.8 the z position of the two grabber is fixed and opposite(- z1=z2). The y position varies from 0.1m to 1m. In the figure7 the two grabber are on the opposite side (y1=.- y2), and in the figure 8 the two grabber are in the same side (y1=y2).In those configuration The C coefficient is high. The comparison of the two graphs shows that the best configuration is to have the two grabbers on the opposite side.

In the figure 5.6 the y position of the two grabbers is fixed and the z position vary from 0.1m to 1m. In the figure 5 The two grabber are on the same side (y1=y2=1), and have an opposite depth (for each point of the curve, - z1=z2). We can see that in this configuration the C coefficient is important and became small only when the grabber reach the same depth than the center of gravity. In the figure 6 The two grabbers are on the opposite side (y1=.- y2=1), and have the same depth (for each point of the curve, z1=z2). This configuration produces the lowest C coefficient of the four configurations.

And So, for limit the moment coming from this loading, the **best configuration is to have the two grabber on the opposite side (y1=.- y2) and at the same depth (z1=z2), with y maximum and z minimum.**

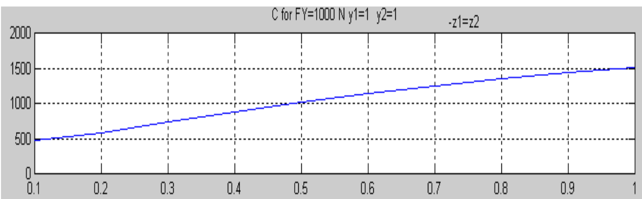

figure5: C(N.m) for y1=y2=1m - z1=z2 from 0.1m to 1m

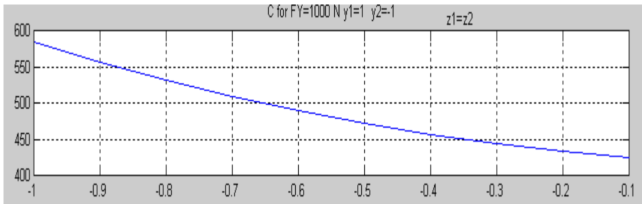

figure6: C(N.m) for y1= - y2=1m z1=z2 from 0.1m to 1m

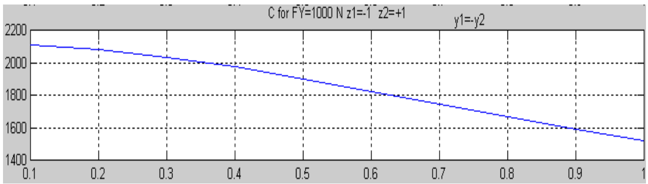

figure7: C(N.m) for z2= -z1=1m y1= -y2 from 0.1m to 1m

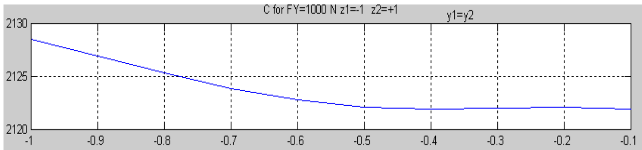

figure8: C(N.m) for z2= -z1=1m y1=y2 from 0.1m to 1m

3.2 One docking point

Using the same notation we have calculate the C coefficient for different position of the grabber around the geometric center of the AUV. As the hydrodynamic loading is horizontal, the influence of the y position is nearly zero. And for reduce the reaction the vertical position of the grabber relative to the geometric center have to be minimum. C.f. figure 9.

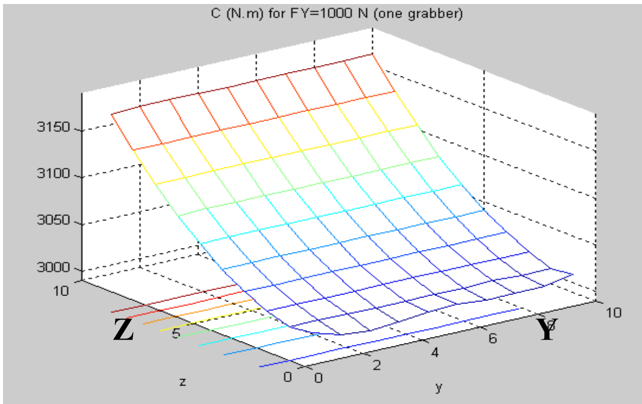

figure 9: C(N.m)for one grabber function of y, z position

4 Claws design

In this chapter, we will present a docking procedure and a claw configuration proposal able to fulfill the requirement of a rigid docking allowing manipulation.

4.1 Docking procedure

For use the AUV as a light intervention vehicle, the AUV has to be able to dock rigidly in front of a standard control panel intervention. So for dock the AUV we will use grabbers. This solution will allow the AUV at operate in front of the control panel. But the grabbers and their position have to be carefully study for insure the stability necessary at an autonomous manipulation.

From the precedent chapter, it appears that the horizontal hydrodynamic loading is the main force applied on the AUV during the docking. For resist at this loading and insure a rigid docking, two grabbers are necessary. The positioning optimization shown that the two grabbers have to be at the same depth for minimizes the reaction.

For take the moment around the line passing by the two grabber, the handlers have to be both perpendiculars at this line (see figure 1, 10)

Different kinds of handlers, used on ROV control panel interface, have being specified by the ISO/DIS 1368-8 [13]. A T shape have been chosen for insure mechanical rigidity and a global positioning.

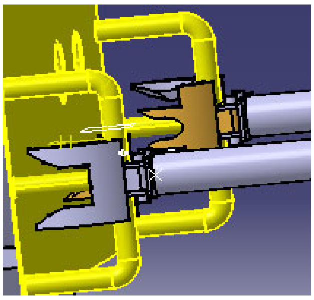

Figure 10 docking procedure

4.2 Claw configuration

4.2.1 Rigidity

The claw design has to be adapted to the operational specification. For realize autonomous manipulation, the claws have to be rigidly grasped to the handler. The T shape of the handler furnishes mechanical contact. The claws, after closing, will totally surrounding the handler. On the figure 11 we can see the contact surface between the claws and the handler. This contact surface is necessary for contact stress calculation. **The claw is totally fixed on the handler**, **in displacement as in rotation**. The fixation is insuring mechanically and not by friction.

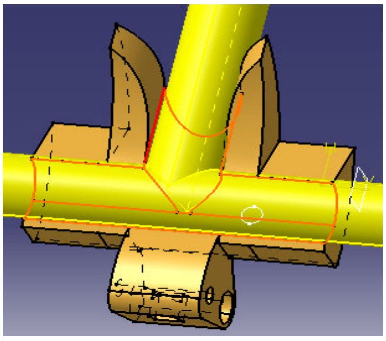

Figure 11: claw-handler contact

4.2.2 Misalignment correction

The second characteristic bring by the operational specification is the misalignment correction. Indeed, during the docking step the AUV will be in semi-autonomous mode and the accuracy will be of several centimeter. For resolve this problem, the claws are curved. During the docking step, if there is misalignment, the contact between the handler and the claw will occurs on the curved surface. Which will bring automatically the claw in the good position.

4.2.3 Positioning adaptation in the horizontal plan

The navigation depth of an AUV is more or less easily controlled. And so the biggest misalignment of the AUV relative to the control panel will occur in the horizontal plan. The claws are design in consequence, and in this

proposal the horizontal length of the claw is 200mm, which furnish a misalignment *tolerance of 500 mm (accuracy required +/- 250mm).*

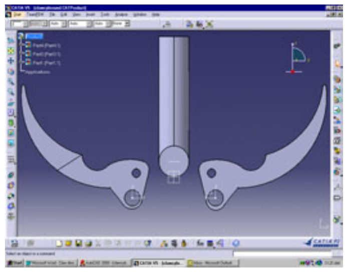

Figure 12: horizontal curve

4.2.4 Positioning adaptation in the vertical plan

The vertical misalignment will be correct during the closing of the claw. The internal surface of the claw (relative to the "feet") is also curved, which will guide the closing until the good position.

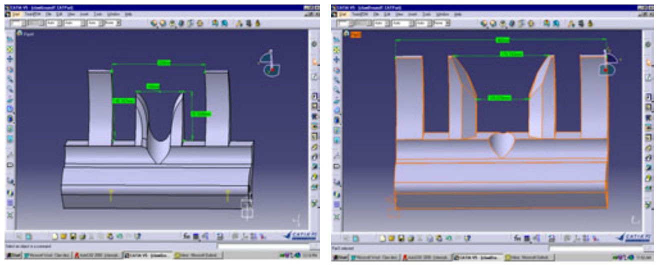

Figure 13: (a) Internal claw (b) External claw

This asymmetric design should perform the correction of the vertical positioning of the grabber relative to the handler. Within this configuration, the tolerance of the external claw is 180 mm (accuracy required +/- 75mm).

The external claw will enter on the vertical plan of the handler for an opening claw of 30-degree (cf. Figure 14 (a)). The middle claw of the internal "hand", which is smaller, will enter on the vertical plan of the handler for an opening claw of 15-degree (cf. Figure 14(b)). From 30-degree to 15-degree, the closing of the claws will be guide by the external claws. When the claw reaches an opening of 15 degree, the feet of the T bar is "bring" by the external claw into the internal claw. And the final closing is guide by the internal claw.

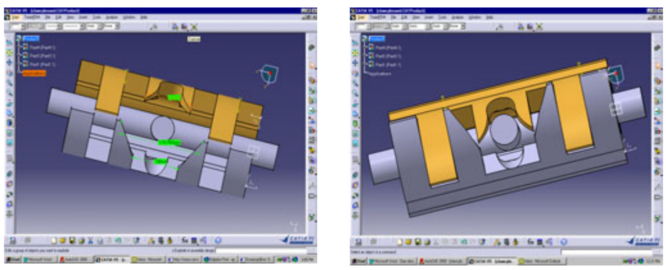

Figure 14: (a) 30 degree opening (b) 15 degree opening

5 Conclusions

The development of deep-water mission interest has recently focus the attention on the Autonomous Underwater Vehicles (AUV). AUV should be the cheapest underwater vehicle for deep subsea interventions. As the acoustic communication delay of the AUV requires a semi autonomous manipulation mode, the last obstacle is to dock rigidly the AUV to the intervention target.

Until now, two kinds of docking have been achieved. Remotely Operated Vehicle (ROV) has been use for underwater telemanipulation. The ROV was grasped to the intervention target for stay in the area of intervention and then the arm was telemanipulated from the surface. This intervention didn't need rigid docking. The second kind of docking is the one of AUV which for a purpose of data transferring and battery recharging has been plugged in subsea structure. In this case, the subsea structure was specially designed to receive the AUV and correct the misalignment due to the semi autonomous navigation mode of the AUV. No manipulation was done.

To use the AUV as a light intervention vehicle, the AUV has to be able to dock rigidly to a standard control panel intervention. The docking has to be robust at AUV misalignment.

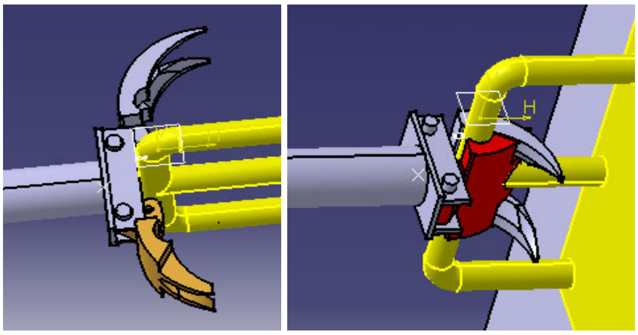

Figure 8: (a) opened claws, (b) closed claws

For that purpose all static and dynamic force components acting on the AUV have been analyzed which has lead to the calculation procedure. The reactions on the grabber(s) and manipulator tool have been characterized and optimized by selecting the grabber positioning. One docking procedure has been chosen (see Figure 1,10). A specific claw has been designed to furnish a maximum rigidity and misalignment correction (see Figs. 8a, 8b).

The residual movement and the influence of the arm displacement have still to be characterized. Different docking procedure will be developed.

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