Modelling and Control of an Autonomous Underwater Vehicle for Mobile Manipulation

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Abstract

In the last few years the development of the Autonomous Underwater Vehicles (AUVs) has had a greater importance because of their fundamental applications in the military field, in underwater explorations (e.g. archaeological field) and in the industrial field (e.g. for Oil&Gas). More specifically, in the evolution of the AUVs the following topics hold an important position, which are still characterized by many open problems: the dynamic performances and the control of the single vehicle, the mobile tele-manipulation of a single vehicle and the cooperation among vehicles (whether including the manipulation operations or not) [1] [2] [3] [5]. In this work the authors describe the multibody modelling and the control architecture of an AUV specifically thought for the mobile underwater manipulation, usually called I-AUV (AUV for Intervention). The performances of such an AUV will have to meet strict planning and control specifications, both as regards the vehicle itself and as for the manipulation phase.

Keywords: *AUV, I-AUV, Underwater, Underwater Manipulation, Grasping*

1 Introduction

In figure 1 a schematic representation of the vehicle is carried, while the logic of the whole model is shown in figure 2. The multibody model of the vehicle and of the robotic arm considers all the DOFs of the I-AUV; in the same way the multibody model of the gripper part accurately describes the dynamics of the object to be grasped and the interaction gripper-environment. The accurate modelling of the gripper-object contact [7] represents one the most important features of the multibody model and affects the behaviour of the whole system. The whole multibody model has been implemented in the Matlab-Simulink environment, through the toolbox SimMechanics, specifically designed to accurately and efficiently reproduce multibody systems.

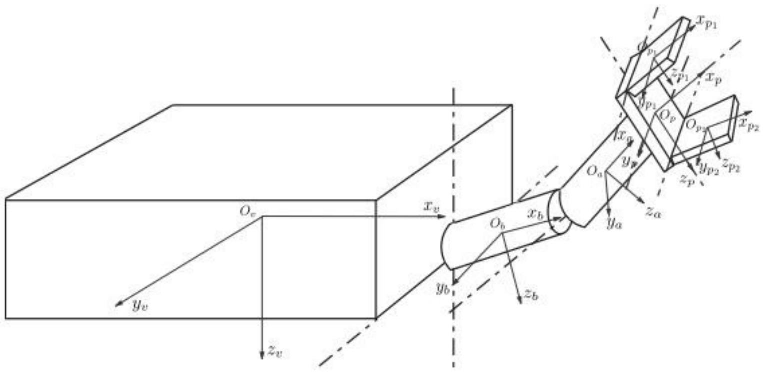

Figure 1. Schematic representation of the I-AUV

The interaction among the different system bodies and the fluid, on the contrary, has been modelled by means of appropriate CFD analyses [4]. In particular the mathematical coupling between the multibody model and the fluid equations has been efficiently performed always through the toolbox SimMechanics. The control architecture is made up of 3 fundamental parts (as visible in figure 2): the trajectory planning [1] [3], the vehicle control [1] [2] and the robotic arm control

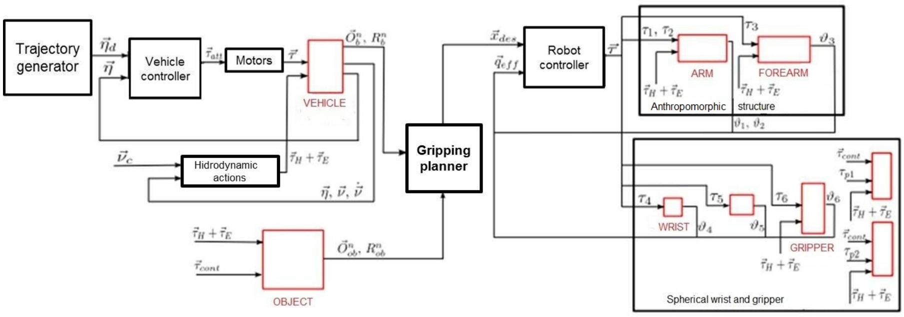

Figure 2. Control logic, with uncoupled controller, of the I-AUV for underwater manipulation

[2] [5]. The trajectory planning is carried out as a function of the mission the vehicle has to complete and of the environment information such as, for instance, the position of the object it has to catch. Many trajectory planning strategies can be currently found in the multibody system literature, concerning different kinds of vehicles. The main approaches are usually based on path following [1] [3] and tracking techniques [6]. In this research activity the authors considered a path following approach because it turned out to be quite suitable for AUV applications [1] [3]. The vehicle control has to keep the AUV along the desired trajectory, modifying it, if necessary, to make the catching and the object manipulation easier. Finally the arm control has to enable the object catching from the gripper which is mounted on the arm itself, considering at the same time the desired trajectory the vehicle has to follow. In this phase a fundamental role will be played by the gripper-object contact [7] that will have to be accurately described from a multibody point of view. The control actions calculated by the previous architecture are in the end provided by the AUV motors which consequently modify the vehicle dynamics. In the development of the control architecture a particular attention has been focused on the interaction between the vehicle control and the control of the robotic arm and of the manipulation [1] [2] [5]. The uncoupled strategy (total or partial) of the control systems is possible when the vehicle dynamics and the robotic arm one are approximately uncoupled during the whole mission of the AUV; in that case the arm dynamics may be considered as a disturbance of the vehicle dynamics to be properly eliminated.
After this first project phase the realization of some prototypes of the proposed AUV is scheduled; the new prototypes will be duly tested providing an appropriate validation of both the multibody model and the control architecture.

2 I-AUV Modelling

2.1 Nomenclature

It is worth to define two reference frames, displayed in figure 3:

- **"Body" frame $< b >$:** reference frame, rigidly connected to the vehicle, with its origin O^b in the center of mass of the vehicle (body) and axes aligned with the inertia principle axes of the body itself. x^b axis is the longitudinal one, positive according to the vehicle advancement, z^b axis vertical and pointing down and y^b axis to compose with the others a dexterous reference frame;
- **"Fixed" frame $< n >$:** inertial reference frame, with its origin O^n on the surface and axes aligned with the ones of a NED (North-East-Down) frame. x^n axis points North, y^n axis points Est and z^n Down.

The authors consider the study of an underwater vehicle (a rigid body) with 6 DOFs. According to SNAME nomenclature the underwater motion of the vehicle can be described using [1]:

$$\begin{aligned} \vec{\eta} &= \left[\vec{\eta}_1^\top \ \vec{\eta}_2^\top\right]^\top \quad \text{with} \quad \vec{\eta}_1 = [x\, y\, z]^\top \qquad \vec{\eta}_2 = [\varphi\, \vartheta\, \psi]^\top \\ \vec{\nu} &= \left[\vec{\nu}_1^\top \ \vec{\nu}_2^\top\right]^\top \quad \text{with} \quad \vec{\nu}_1 = [u\, v\, w]^\top \qquad \vec{\nu}_2 = [p\, q\, r]^\top \\ \vec{\tau} &= \left[\vec{\tau}_1^\top \ \vec{\tau}_2^\top\right]^\top \quad \text{with} \quad \vec{\tau}_1 = [X\, Y\, Z]^\top \qquad \vec{\tau}_2 = [K\, M\, N]^\top , \end{aligned} \tag{1}$$

where $\vec{\eta}$ represents the position ($\vec{\eta}_1$) and orientation ($\vec{\eta}_2$) vector with respect to the fixed frame$< n >$, $\vec{\nu}$ components are the linear ($\vec{\nu}_1$) and angular ($\vec{\nu}_2$) speeds as to the body frame $< b >$, while $\vec{\tau}$ is the vector of the linear forces ($\vec{\tau}_1$) and the

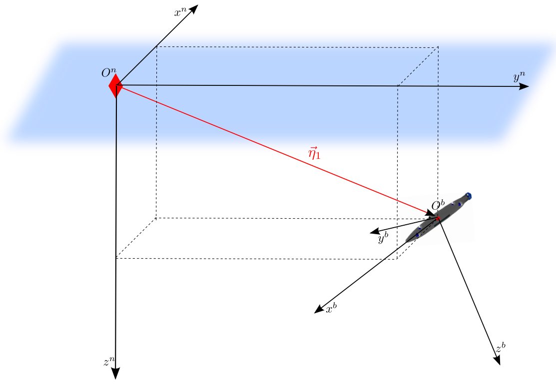

Figure 3. Body frame $< b >$ and fixed frame $< n >$

torques ($\vec{\tau}_2$) applied to the vehicle as to the body frame $< b >$.

2.2 Equation of Motion

The dynamical model of the system (I-AUV) consists in two different parts: an underwater vehicle (AUV) and a robotic arm. The hypotheses to study the models are to assume that both the vehicle and the various links of the manipulator can be considered as rigid bodies and connected by revolute kinematic joints. This whole mechanical system can be studied through classical multibody techniques.
The external forces and torques, i.e. the hydrodynamic effects and the buoyancy, are introduced into the model by means of generalized Lagrangian forces applied to each body constituting the multibody system (the body-vehicle, the links, the robotic manipulator arm and the gripper) in order to increase the reality of the system.
In this paper, the authors propose an effective approach to face the problem of the implementation of the hydrodynamic and the buoyancy effects into the multibody system. The method proposes to separate the dynamical study of the rigid system from the one of hydrodynamic and buoyancy effects; first of all, it is necessary to obtain, from the Newtonian formulation of the system, the external forces and torques acting on the various bodies of the multibody system. These actions, defined by $\vec{\tau}_{RB}$ in the equation of motion [1], are:

- control actions $\vec{\tau}$
- sea current disturbances $\vec{\tau}_E$
- hydrodynamic and buoyancy effects $\vec{\tau}_H$

The absolute velocity of the vehicle $\vec{\nu}$ written in the body reference frame is:

$$\vec{\nu} = \vec{\nu}_r + \vec{\nu}_c \; , \tag{2}$$

where $\vec{\nu}_r$ is the relative velocity and $\vec{\nu}_c$ is the current velocity. The equations of motion to describe the whole system [1] are:

$$\begin{aligned} \vec{\tau}_H + \vec{\tau}_E = \; & M_{RB}\dot{\vec{\nu}}_c - M_A\dot{\vec{\nu}}_r + \\ & + C_{RB}\left(\vec{\nu}_r\right)\vec{\nu}_c + C_{RB}\left(\vec{\nu}_c\right)\vec{\nu}_r + C_{RB}\left(\vec{\nu}_c\right)\vec{\nu}_c - C_A\left(\vec{\nu}_r\right)\vec{\nu}_r + \\ & - D\left(\vec{\nu}_r\right)\vec{\nu}_r - \vec{g}\left(\vec{\eta}\right) \; , \end{aligned} \tag{3}$$

and

$$\dot{\vec{\eta}} = J\left(\vec{\eta}\right)\vec{\nu}_r + J\left(\vec{\eta}\right)\vec{\nu}_c \; , \tag{4}$$

where M_A is the added mass matrix, M_{RB} is the rigid body mass matrix, C_{RB} is the Coriolis rigid body matrix, C_A is the added Coriolis matrix, D is the damping matrix and g is the gravity vector.
Thanks to Eq. 3 and to the knowledge of the control actions τ, it is possible to take into account these effects through:

$$\tau_{RB} = \tau + \tau_H + \tau_E. \tag{5}$$

and to couple this contribute with the whole multibody system dynamics by means of Eq. 9. These actions are reduced and applied to the Center of Gravity (CG) of each rigid bodies. The advantage of the presented method is the possibility to split in two parts the study of the dynamics of rigid bodies immersed in a fluid; in this way it is possible to study the rigid body dynamics through a classical multibody method and considering the effects due to the fluid as external forces and torques.

2.3 Multibody system dynamics

The dynamical analysis of a multibody system can be addressed mainly following two methods: the Newtonian approach and the Lagrangian one. The Newtonian method involves the description of the fundamental equations of dynamic for each rigid body and the introduction, among the external actions, of the reaction forces between the various links and the frame (not known a priori). This approach is quite general, and particularly suitable for the description of the serial mechanisms, due to the recursive nature of the approach.
The second method consists, instead, in the introduction of a pseudo-energetic function and in the use of Lagrange's equations. In this paper, the authors have used the Lagrangian redundant approach to the study of the dynamics of the rigid bodies as it is more systematic and easily automatable (this method is mainly used in softwares able to model and simulate multibody systems).
To uniquely define the state of the system a set of redundant Lagrangian coordinates is introduced:

$$\vec{q} = \left(\vec{q}_1^{\,T}, ..., \vec{q}_N^{\,T}\right) \in \mathbb{R}^{6\text{Nx}1}\ , \ \text{ with } \ \vec{q}_i = \begin{bmatrix} \vec{G}_i \\ \vec{\Phi}_i \end{bmatrix} \in \mathbb{R}^{6\text{x}1} \ \ i = 1, ..., N\ , \tag{6}$$

where $\vec{G}_i$ and $\vec{\Phi}_i$ are respectively the coordinates of the CG and the Euler angles of the i-th rigid bodies.
It is assumed that the constraints are two-sided, sufficiently regular and independent, representable by algebraic equations in which it does not appear explicitly the time variable and holonomic (constraints on the configuration). It is also considered, for this application, the hypothesis that these constraints are smooth (ideal) although it is not strictly necessary for the approach.
With these assumptions the algebraic equation of the constraints can be written in a compact form, such as:

$$\vec{\psi}\left(\vec{q}\right) = \vec{0}\ , \tag{7}$$

with $\vec{\psi} \in \mathbb{R}^p$ (p is the number of Degree of Freedoms DOFs taken out by the constrains).
The Lagrange equations for rigid body systems are obtained as a condition of stationarity (minimization) of the generalized Lagrangian function $\mathcal{L}^*$ estimated as:

$$\mathcal{L}^*\left(\dot{\vec{q}}, \vec{q}, \vec{\lambda}\right) = T\left(\dot{\vec{q}}, \vec{q}\right) - V\left(\vec{q}\right) - \vec{\lambda}^T \vec{\psi}\left(\vec{q}\right)\ , \tag{8}$$

where T is the kinetic energy of the system, V the potential energy and $\vec{\lambda} \in \mathbb{R}^p$ is the Lagrangian vector.
The complete differential-algebraic equation (DAE) system, which is obtained from the previous equation, can be described through a unique matrix equation:

$$\begin{bmatrix} M & \left(\dfrac{\partial\vec{\psi}}{\partial\vec{q}}\dot{\vec{q}}\right)^T \\ \dfrac{\partial\vec{\psi}}{\partial\vec{q}}\dot{\vec{q}} & 0_{p\text{x}p} \end{bmatrix} \begin{Bmatrix} \ddot{\vec{q}} \\ \vec{\lambda} \end{Bmatrix} = \begin{Bmatrix} \vec{Q} - C\dot{\vec{q}} - \left(\dfrac{\partial V}{\partial \vec{q}}\right)^T \\ \vec{\gamma} \end{Bmatrix}\ . \tag{9}$$

The use of the Lagrangian approach allows the study of the complete I-AUV model in terms of rigid dynamic equations. The hydrodynamic effects are taken into account inside the vector $\vec{Q}$.

2.4 Hydrodynamics and buoyancy effects

The modelling of hydrodynamics and buoyancy effects is necessary to reproduce in a proper way the I-AUV during a navigation or a manipulation task. In this paper, the authors have implemented these actions in each bodies belonging to the I-AUV system (vehicle, links of the arm and gripper); the simulated effects are:

- hydrostatic effects due to the added masses;
- hydrodynamic effects due to the added masses;
- drag and lift forces;
- buoyancy effects.

For each body, these terms are described with respect to a reference frame system having its origin in the CG of the body, with axes parallel to the principal axes of inertia, vertical downhill z-axis, x-axis along the direction of the vehicle (when the robotic arm is stretched) and the y-axis accordingly in order to define a dexterous reference frame.
As regards the links of the robotic arm, the authors have supposed three assumptions: cylindrical shape, totally immersed bodies and characterized by three levels of symmetry. Assuming that the arm does not move at high velocities, the added mass matrix M_A and the matrix of the centrifugal and Coriolis effects C_A are respectively described in [1].
For a cylindrical body of mass m, length L and radius R, which moves in a fluid of density ρ_a, the coefficients of the matrices M_A and C_A can be obtained according with the strip theory [1], and according with the hypothesis $R \ll L$, the following equations are obtained:

$$\begin{aligned} &X_{\dot{u}} = -0.1\pi\rho_a R^2 L, \quad Y_{\dot{v}} = -\pi\rho_a R^2 L, \quad Z_{\dot{w}} = -\pi\rho_a R^2 L \\ &K_{\dot{p}} = 0, \qquad M_{\dot{q}} = -\tfrac{1}{12}\pi\rho_a R^2 L^3, \quad N_{\dot{r}} = -\tfrac{1}{12}\pi\rho_a R^2 L^3 \ . \end{aligned} \tag{10}$$

As regards the effects of the hydrodynamic resistance, the elements of the damping matrix D are evaluated, by means of CFD analysis [4], expressing the forces and torques through the following six dimensionless parameters:

- frontal, lateral and vertical drag coefficient:

$$C_{Dx} = \frac{F_x}{\frac{1}{2}\rho_a A_f v^2} \qquad C_{Dy} = \frac{F_y}{\frac{1}{2}\rho_a D L v^2} \qquad C_{Dz} = \frac{F_z}{\frac{1}{2}\rho_a D L v^2} \tag{11}$$

- roll, pitch and yaw resistance coefficient:

$$C_{Mx} = \frac{M_x}{\frac{1}{2}\rho_a A_f D^3 \omega^2} \qquad C_{My} = \frac{M_y}{\frac{1}{2}\rho_a D L^4 \omega^2} \qquad C_{Mz} = \frac{M_z}{\frac{1}{2}\rho_a D L^4 \omega^2} \ . \tag{12}$$

where the used symbols are: speed v, angular velocity ω, frontal area A_f , diameter D, fluid density ρ_a, length L.

3 Planning of the grasping trajectory

In order to estimate the property of robustness of the uncoupled control strategies (for the AUV and Robotic Arm), a complex underwater mission of the I-AUV is planned; the mission consists in grasping an object (generally mobile) simultaneously with the moving forward of the vehicle on a desired trajectory. The achievement of this type of mission requires that the skills of mobile manipulation of the vehicle have to be activated during its navigation, stressing, this way, the dynamic coupling of the system; the controllers will have thus to face non negligible disturbances. The authors point out such operations are typically carried out with the vehicle in course of hovering, i.e. in a phase where the problem of the dynamic coupling is drastically reduced. The problem is shown in a completely general form in figure 4. The vehicle is supposed to move on a desired trajectory, defined in terms of a geometrical path and an associated time law of motion, planned by the trajectory generator on board of the vehicle. The navigation trajectory can be consequently described by the distance vector between the origin of the body system $< b >$ and the origin of the NED system $< n >$, $\vec{O}_b^n$, expressed in the fixed frame, and by the rotation matrix R_b^n:

$$\begin{aligned} \vec{O}_b^n &= \vec{O}_b^n(\pi) \\ R_b^n &= R_b^n(\pi) \qquad \Rightarrow \qquad \vec{O}_b^n = \vec{O}_b^n(t) \ , \ R_b^n = R_b^n(t) \ . \\ \pi &= \pi(t) \end{aligned} \tag{13}$$

The planning of the path and of the time law is carried out in order to make the grasp of the object easier: the vehicle needs to come gradually closer to the object near the grasping point, to make the intervention possible facing the limited arm and forearm length; moreover it is advisable to reduce the speed of the I-AUV compared to the one of the cruise phase, to

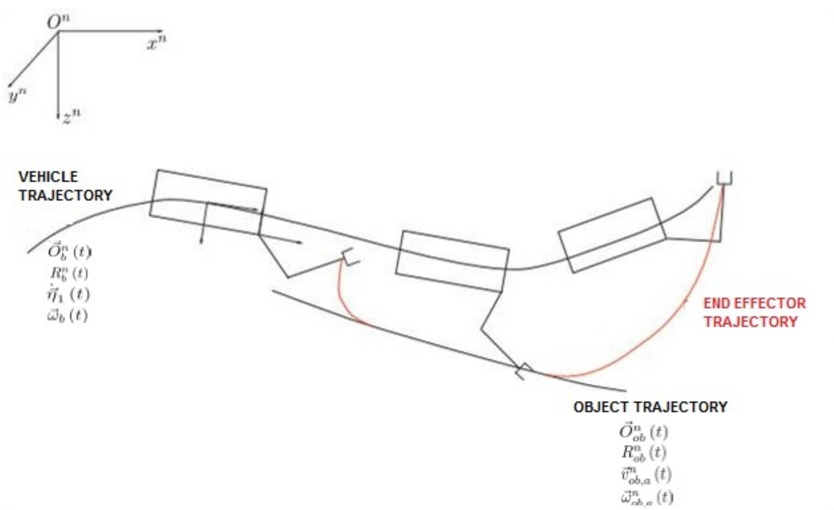

Figure 4. Planning of the trajectory to grasp a mobile object

increase the time for the grasping and thus limit the accelerations required to the joints. $\dot{\vec{\eta}}_1(t)$ is the absolute velocity of the barycenter of the vehicle, while $\vec{\omega}_b(t)$ is its angular velocity, both expressed in the NED frame. As regards the motion of the object, its trajectory is supposed to be known beforehand, as to an inertial reference. Of course, this hypothesis is generally not checked in practice, as neither the exact geometrical shape nor the trajectory of the object itself are initially known. In these cases it will be left to the intelligence on board, thanks to the outputs of the sensors (e.g. optic or acoustic sensors) to reconstruct the shape and the trajectory of the object and consequently to state the best strategies to complete the grasping operation. So right now, the motion of this body is supposed to be described through the following kinematic quantities:

$$\begin{aligned} \vec{O}_{\text{ob}}^n &= \vec{O}_{\text{ob}}^n(t) \\ R_{\text{ob}}^n &= R_{\text{ob}}^n(t) \ , \end{aligned} \tag{14}$$

representing the position and the orientation of the object with respect to an inertial system, expressed in $< n >$ frame. Besides, in the same reference frame the absolute linear and angular velocities $\vec{v}_{\text{ob,a}}^n$ and $\vec{\omega}_{\text{ob,a}}^n$ are known. The case of a still object is a particular sub-case where the position and the orientation in the inertial system are constant (null speeds). To plan the trajectory of the end-effector of the manipulator in the operative space first of all it is necessary to get, on the basis of the knowledge of the kinematic quantities of the centre of mass of the vehicle, the description of the trajectory of the shoulder of the robotic arm, where is fixed the origin of the $< 0 >$ reference frame, according to DH convention. Consequently, it is obtained:

$$\begin{aligned} \vec{O}_0^n &= \vec{O}_b^n + R_b^n \vec{O}_0^b \\ R_0^n &= R_b^n R_0^b \ , \end{aligned} \tag{15}$$

where, with the reference frames shown in figure 4, $\vec{O}_0^b = \left[\frac{B}{2}, 0, -\frac{H}{2}\right]^T$ and $R_0^b = R_x(\pi)$. Moreover, according to the fundamental formula of the rigid motions:

$$\begin{aligned} \vec{v}_{0,\text{a}}^n &= \dot{\vec{\eta}}_1 + \vec{\omega}_b \times \left(\vec{O}_0^n - \vec{O}_b^n\right) \\ \vec{\omega}_{0,\text{a}}^n &= \vec{\omega}_b \ . \end{aligned} \tag{16}$$

Successively, the authors move from the description of the absolute motion of the object to the description of the I-AUV relative motion, thanks to the following kinematic relations:

$$\begin{aligned} \vec{O}_{\text{ob}}^0 &= \left(R_0^n\right)^T \left(\vec{O}_{\text{ob}}^n - \vec{O}_0^n\right) \\ R_{\text{ob}}^0 &= \left(R_0^n\right)^T R_{\text{ob}}^n \ , \end{aligned} \tag{17}$$

where $\vec{O}^0_{\text{ob}} = \vec{O}^0_{\text{ob}}(t)$ and $R^0_{\text{ob}} = R^0_{\text{ob}}(t)$ set out the trajectory of the object with respect to the vehicle. The values of linear and angular velocity of the object as to the DH reference frame $< 0 >$ (the reference frame rigidly connected to the object) are extracted as follows:

$$\begin{aligned} \vec{\text{v}}^0_{\text{ob,r}} &= \left(R^n_0\right)^T \left(\vec{\text{v}}^n_{\text{ob,a}} - \vec{\text{v}}^n_{0,\text{a}}\right) \\ \vec{\omega}^0_{\text{ob,r}} &= \left(R^n_0\right)^T \left(\vec{\omega}^n_{\text{ob,a}} - \vec{\omega}^n_{0,\text{a}}\right) \ . \end{aligned} \tag{18}$$

Relations (17) allow to define the trajectory of the object in the operative space of the manipulator end-effector, expressible as:

$$\vec{x}_{\text{ob}}(t) = \begin{bmatrix} \vec{O}^0_{\text{ob}}(t) \\ \vec{\Phi}^0_{\text{ob}}(t) \end{bmatrix} \ , \tag{19}$$

where vector $\vec{\Phi}^0_{\text{ob}}$ contains RPY Euler's angles extracted by rotation matrix R^0_{ob}. The trajectory of the object, at first, does not match the gripper one, which is in a position of rest; to get the grasping it is necessary the trajectory of the gripper is rapidly brought to match the trajectory of the object, and that the two paths are the same (both as regards the position part and the orientation one) for a period of time ΔT long enough to operate the gripper and allow the grasping of the body. This period ΔT is mandatory to allow a correct grasping; if the manipulator had a robotic arm, or a gripper, more articulated, the operation could also take place with a relative motion between the body and the end-effector, or with a very little time gap of common motion between the two. Since, nevertheless, in the presented case the gripper is formed of just two movable bodies connected to the last link of the wrist, the end-effector is required to position itself and remain, for a sufficient lapse of time, in the position as to the object that makes easier the grasping. When the operation is over, the trajectories of the object and the end-effector break up again and the arm e.g. can go back to a configuration of rest, fixed as to the vehicle. To optimize the performances of the arm controller and the vehicle one it is necessary to guarantee that the trajectory of the end-effector in the operative space is sufficiently smooth, so that the forces required to the actuators of the joints will not excite the system modes (not modelled). A possible process allowing the generation of a trajectory which meets such requirements is the following: the error is set out, in the operative space, between the the object pose and the end-effector one,

$$\vec{e} = \vec{x}_{\text{ob}}(t) - \vec{x}_{\text{des}}(t) \ , \tag{20}$$

for which a time trend is defined beforehand. Particularly, each component of $\vec{e}$ has an evolution shown in figure 5, with a trapezoidal speed profile.

The progress chosen for $e_i(t)$ is made up of a linear section which is joined with two parabolic sections in the neighborhood of the initial and final positions. A constant value of the second derivative is chosen for the initial and final parts, $\ddot{e}_{i_c}$; the second derivative is discontinuous but always limited. When this value has been chosen, with $\text{sign}(\ddot{e}_{i_c}) = -\text{sign}(e_i(0))$, and $e_i(0)$ calculated trough the direct kinematic, it is found:

$$t_c = \frac{t_f}{2} - \frac{1}{2}\sqrt{\frac{t_f^2 |\ddot{e}_{i_c}| - 4|e_i(0)|}{|\ddot{e}_{i_c}|}} \ , \tag{21}$$

with acceleration compliant with:

$$|\ddot{e}_{i_c}| \geq \frac{4|e_i(0)|}{t_f^2} \ . \tag{22}$$

Once the trend of each of the 6 components of $\vec{e}$ is known, from (20) the trajectory of the end-effector, specified in the operative space can be evaluated:

$$\vec{x}_{\text{des}}(t) = \begin{bmatrix} \vec{O}^0_{\text{e,des}}(t) \\ \vec{\Phi}^0_{\text{e,des}}(t) \end{bmatrix} \ , \tag{23}$$

where $\vec{O}^0_{\text{e,des}}$ is the origin of Denavit-Hartenberg frame of the last link of the robotic arm, which, with RPY Euler's angles of the same frame with respect to $< 0 >$ $\vec{\Phi}^0_{\text{e,des}}$, allows getting the homogeneous transformation matrix $T^n_0(\vec{q}_{\text{des}})$; from this matrix, through the inverse kinematics, the vector of the desired joint coordinates $\vec{q}_{\text{des}}$ is calculated. If the I-AUV control is sufficiently ready and robust, tracking this desired trajectory in the joint space and moving the gripper in an appropriate way, the I-AUV mission of the object grasping concludes successfully.

The strategies of uncoupled control have been studied through the simulation architecture of the whole I-AUV system developed in a Matlab-Simulink environment. The rigid dynamics of the vehicle and the robotic arm is reproduced

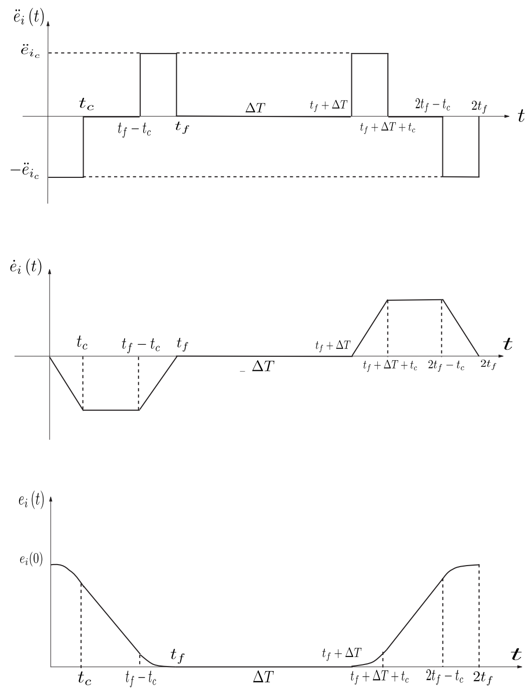

Figure 5. Time evolution of the generic component of the trajectory tracking error $e_i\ (t)$

through the software tool for multibody modelling SimMechanics: this tool allows the I-AUV description through blocks representing rigid bodies, joints, sensors and elements of force and, successively, the formulation and solution of the equations of motion of the whole mechanical system. In the Simulink environment are instead implemented the modelling blocks of the vehicle and manipulator controllers, the trajectory generators and the blocks of the hydrodynamic action characterization. To analyze the performances of the proposed control typologies, and considering the greater complexity of the problem under examination, compared to the one concerning the simulation of a single AUV mission, the knowledge of the state of the dynamic system is presumed, in order to carry out an analysis independent from the quality of the measurement system. Besides, the authors presume to use a controller working with a 100 Hz frequency.

4 Results

In order to evaluate the performances of the proposed uncoupled control strategy, the authors show the results of a simulated rescue mission of an underwater object in motion (e.g. a spherical object).
As previously said, starting from the knowledge of the trajectory of the object, the gripper is controlled to match this trajectory (target), and after a time interval ΔT suitable for the grasping the manipulator moves back in its rest configuration with respect to the vehicle. The mission results have been achieved through a 7 DOFs PID controller for the manipulator (a redundant one to avoid the singularities) and an uncoupled path following strategy for the AUV (suitable also for under-actuated vehicles [3]).
The spherical object moves forward with a speed of $0.04\,\mathrm{m/s}$, keeping a constant depth (as to the frame $< n >$) equal to $-0.18\,\mathrm{m}$ and following the trajectory shown in figure 6. The vehicle navigation is controlled to adapt its trajectory to the object one, approaching the object, to facilitate the grasping (during the grasping phase, the target path has to be included into the workspace of the manipulator): in the proposed example, the I-AUV moves forward, along the x^n axis with a limited speed of $0.05\,\mathrm{m/s}$ and navigating at a constant reference depth. The manipulator, fixed at the beginning in its rest configuration, is activated and controlled to track the planned trajectory for the grasping (figure 6).

The gripper position moves rapidly to the target (object position), in accordance with the planned trend of the error $\vec{e}(t)$. Particularly as concerns $\vec{e}(t)$, the following parameters have been chosen, with reference to figure 5, in order to have an End Effector trajectory smooth enough:

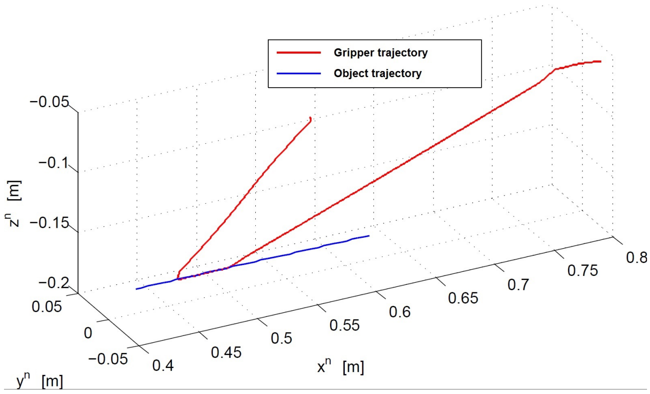

Figure 6. Underwater simulated trajectories of the manipulator End Effector and of the object

$$
\begin{aligned}
t_c &= 2\,\mathrm{s} \\
e_{i_c} &= 0.5\,\mathrm{m/s^2} \\
\Delta T &= 1\,\mathrm{s}\,.
\end{aligned}
$$

The two paths match, with a limited error (a few mm), for 1 s; then the gripper gets back in its rest configuration as to the vehicle (which, during the grasping, has moved of about $0.25\,\mathrm{m}$).
During the grasping intervention, the gripper maintains its orientation with respect to the NED frame: according to the arm motions, the wrist joints rotate in order to comply with the desired orientation of the gripper. The reference roll, pitch and yaw angles are hold with a maximum error of $0.04\,\mathrm{rad}$, caused mainly by the vehicle motion.

The time trend of the position error of the vehicle is shown in figure 7. The error reaches a maximum value of $4\,\mathrm{mm}$ at the time the manipulator starts moving, and remains limited in time (about $10^{-3}\,\mathrm{m}$). The orientation errors are also shown, in terms of roll, pitch and yaw angles of the body frame $< b >$ compared to the desired ones (in this example, the desired ones are equal to zero, as the vehicle has to navigate in the forward direction, along x^n axis, keeping its initial orientation). These errors are important as they are linked to the time trends of the desired joint variables: the trajectory tracking of the AUV has to be accurate, to have, in the operative space, a smooth desired end-effector trajectory (linked to $\vec{q}_{\text{des}}\,(t)$). In the proposed case, the roll and pitch error orders are about $10^{-3}\,\mathrm{rad}$, while the maximum yaw error is $(0.07\,\mathrm{rad})$: the propulsion system is able to compensate the disturbances due to the manipulator motion.

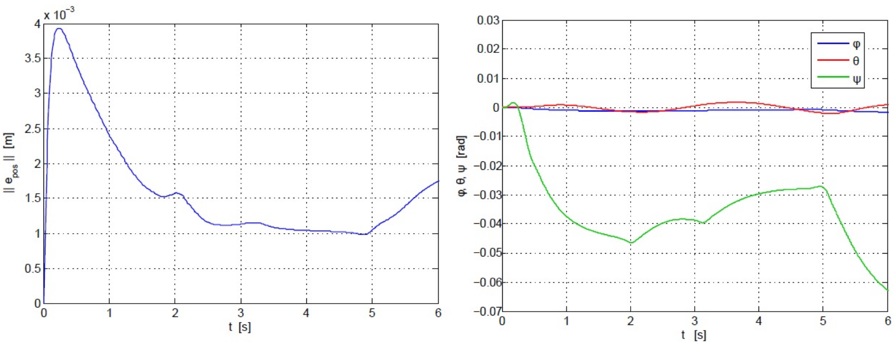

Figure 7. Time evolution of the position error and of the orientation errors of the vehicle

Finally, in figure 8 are shown the joint errors, less than $(0.01\,\mathrm{rad}$ for the shoulder and elbow joints, $10^{-4}\,\mathrm{rad}$ for the wrist joints).

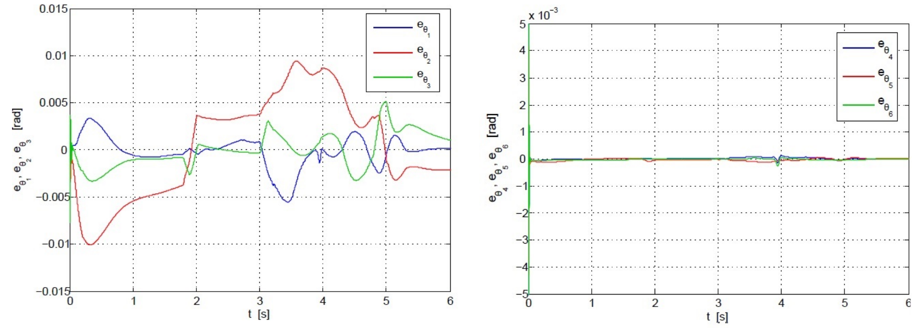

Figure 8. Time evolution of the joint errors of the manipulator: anthropomorphic structure and spherical wrist

5 Conclusions

In this work the authors described the multibody modelling and the control architecture of an AUV specifically thought for the underwater mobile manipulation, usually called I-AUV (AUV for Intervention). The performances of such an AUV have to meet strict planning and control specifications, both as regards the vehicle itself and as for the manipulation phase. The multibody model of the vehicle and of the robotic arm considers all the DOFs of the I-AUV; in the same way the multibody model of the gripper part accurately describes the dynamics of the object to be grasped. In this research activity the authors considered a path following approach suitable for AUV applications. The vehicle control keeps the AUV along the desired trajectory, modifying it, if necessary, to make the catching and the object manipulation easier. The arm control enables the object catching from the gripper which is mounted on the arm itself, considering at the same time the desired trajectory the vehicle has to follow. Finally, a fundamental role is played by the gripper-object.
The preliminary results of the proposed uncoupled control strategy have been satisfactory. Further developments are scheduled in order to reach a more realistic simulation, before the hardware testing phase: particularly, the on board sensors will be accurately modelled, also as regards the acquisition process of the information of the object to be grasped (e.g. acoustic or optical feedbacks).

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