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A SEMI-PASSIVE ARM CONCEPT TO SUPPORT AUV's ACTIVITIES

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Abstract. *This work presents the complete structural analysis of a gantry type Semi-Passive mechanical Arm (SPA), conceived to increase the capability of manoeuvre, manipulation skills and payload capacity of an Autonomous Underwater Vehicle (AUV) nearby its subsea working site. The SPA has a special connector to attach the AUV and can be fixed directly to the underwater facility to be intervened or to the sea bed. The configuration studied is a four degrees-of-freedom gantry type mechanical arm formed by rigid-body links, with no actuators transmitting mechanical power to the joints. The AUV thrusters are the unique source of power needed to move the AUV-SPA system. An optimized engineered SPA configuration was obtained by finite element method (FEM) modeling, including a complete structural analysis with dynamic conditions. The FEM model operational scenary includes a docked AUV arm system and external loads such as buoyancy and multidirectional fluid drag forces related to marine currents.*

Keywords*: underwater robotics, gantry manipulator, AUV facilities, structural analysis, mechanical design.*

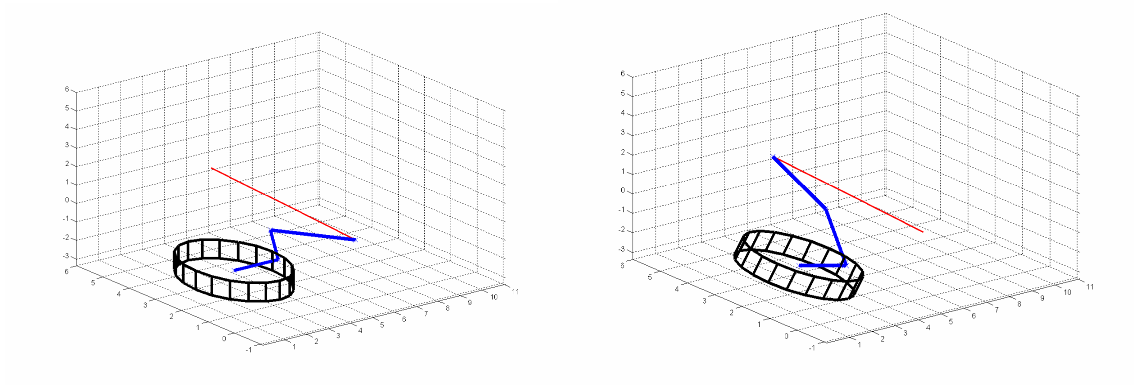
1. INTRODUCTION

Underwater vehicles are widely used to perform activities in deep and ultra-deep waters. Typical applications associated with offshore industry are inspections of platforms, subsea facilities and pipelines, interventions on subsea equipment and payload manipulation. These activities are usually done by Remotely Operated Vehicles (ROVs), characterized by an umbilical cable connecting the control site located at the sea surface to the equipment itself. ROVs can also be used for turbine maintenance in hydro power plants (Queiroz *et al*., 2006).

Autonomous Underwater Vehicles (AUVs) have no umbilical cables, contain its own power supply unit (batteries) and can be programmed to execute some activities in autonomous mode. The installation of manipulator arms on AUVs permits the robotization of many tasks. However, any motion of the manipulator arm located at the vehicle or the manipulation of a payload will induce reaction forces and moments that disturb the position and attitude of the supporting base vehicle due to a change of its center of gravity, raising the control complexity needed to compensate for positioning deviations of the AUV arm system.

To illustrate this problem in Fig.1 is presented a dynamic simulation of a free-flying satellite with a 3 degrees-of-freedom (d.o.f.) arm, which has a similar behavior to AUV-arm system. The arm extremity follows a linear trajectory resulting in position and orientation deviations of the satellite (Ferreira, 2006), (Ferreira and Romano, 2005), (Souza and Maruyama, 2007). Experimental analysis can be performed in free-flying devices (Tinos *et al*., 2006).

Differently from AUV-arm systems, industrial manipulators are rigidly fixed at the ground, so forces and moments originated by its interaction with the intervened environment are transmitted to the basement and no positioning deviations occur.



(a) (b)

Figure 1. Free-flying satellite with a 3 d.o.f. arm in a linear trajectory. (a) initial point. (b) end point.

One solution to compensate these effects is an attachment system, denominated rigidizer, to hold the vehicle on the equipment under intervention. But this involves either using a second manipulator arm or a dedicated hydraulically powered arm mechanism with suction feet that usually fix the vehicle to the equipment (Dunningan and Russel, 1998).

Another possible solution to reduce the vehicle position and attitude disturbance is a control system which uses the vehicle thrusters (Zanoli and Conte, 2003). This strategy has not enough precision and repeatability due to marine current and the vehicle-manipulator/water hydrodynamic interaction. It will not provide rigidity to the manipulator-vehicle system and the use the thrusters means high consumption of energy.

The Semi-Passive mechanical Arm (SPA) proposal increases the capability of maneuver and manipulation skills of the AUV arm system nearby the working site, improving the vehicle-manipulator workspace and payload capacity. In addition, the equipment under intervention will not absorb the mechanical loads - forces and moments - that appear due to the interaction between AUV mechanical arms and the equipment, since they will be transmitted to the SPA structure (Ferreira and Romano, 2005).

The SPA configuration essentially depends on the manipulated unity operational requirements and dimensions, environmental marine conditions, and the SPA-vehicle performance indices like the maneuverability, dynamic behavior and workspace. A power supply unit is installed at the SPA, and then electrical power can be drained to the AUV, once the AUV is connected to the SPA.

2. SEMI-PASSIVE MECHANICAL ARM CONCEPT

2.1. Components description

The Semi-Passive mechanical Arm is conceived as a manipulator formed by rigid-body links, with no actuators transmitting mechanical power to the joints. Only brakes are installed at the joints, so that links are free to move in the directions not blocked by activated brakes. The vehicle thrusters are still the unique source of mechanical power needed to move the SPA-vehicle system.

The SPA arm terminal has a special connector system to attach the vehicle, designed to guarantee the rigidity of the SPA-AUV system, to permit the transmission of command instructions from AUV to the SPA onboard control unit and to supply electrical power to AUV. In case the vehicle is a Remote Operated Vehicle (ROV), the command instructions and the energy to activate SPA brakes can be furnished by dedicated conductors of the umbilical cable connecting the ROV to its control site located at the sea surface.

The gantry type configuration (Fig. 2a) has four degrees-of-freedom: 3 prismatic joints (movements in X, Y and Z directions) and one revolute joint (pan motion).

The four vertical structural elements form a rigid link between the mechanisms of the SPA-vehicle system and the ground. They can be fixed directly to the sea bed (Fig. 2a) or to the underwater facility to be intervened (Fig. 2b).

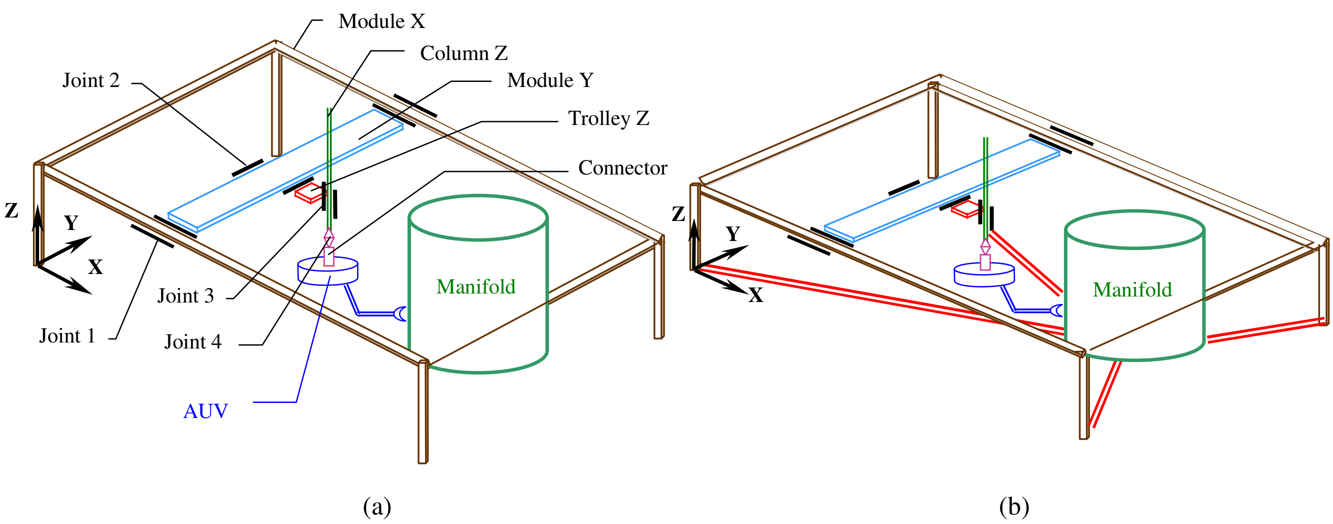


Figure 2. SPA characteristics: (a) main components (b) SPA-manifold fixed configuration.

2.2. Motion strategies

The combination of joints with activated brakes (locked) or not activated brakes (unlocked) permit the vehicle to move in preferential directions, even if external perturbations like marine currents occur during the execution of a task. When all brakes are in active configuration, the SPA-vehicle system will behave as a fixed base manipulator, increasing its structural rigidity, payload capacity, precision and repeatability.

In this example, three operational phases can be defined, as indicated in Fig. 3: the approach phase (positions 1 to 2), where the vehicle is moving towards the SPA connector device; the connecting phase (position 2), related to the vehicle attachment with the SPA; and the intervention phase (position 3), concerning the SPA-vehicle system workspace nearby the working zone.

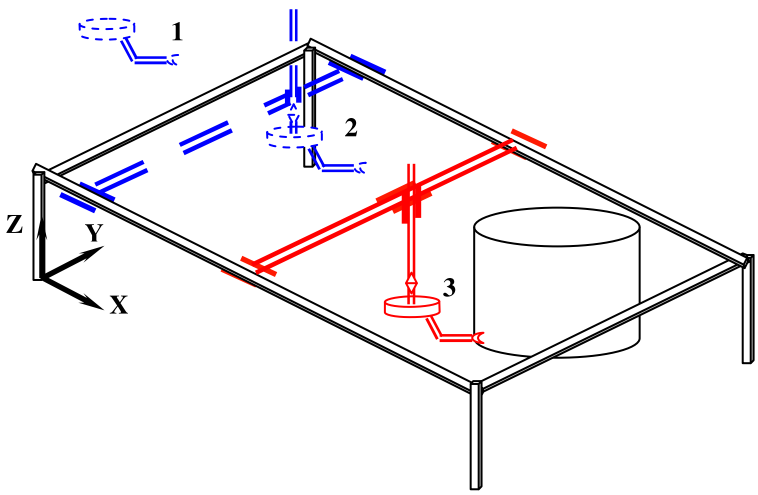


Figure 3. Operational phases of the SPA-vehicle system.

The combination of joints with activated brakes (locked) or not activated brakes (unlocked) permit the vehicle to move in preferential directions, even if external perturbations like marine currents occur during the execution of a task. When all brakes are in active configuration, the SPA-vehicle system will behave as a fixed base manipulator, increasing its structural rigidity, payload capacity, precision and repeatability.

The trajectory of the SPA-vehicle system from point 2 to point 3 can be described by discrete or continuous motions associated to programmed paths defined previously at the AUV onboard microcontroller. Once the SPA-AUV system achieves the working zone, the brakes will be actuated or not according to the required intervention planning.

3. SPA KINEMATICS ANALYSIS

3.1. Direct kinematics

The kinematics analysis of the SPA is referred in the Joints Space Coordinates. In a previous work (Ferreira and Romano, 2005) the authors presented the kinematics model, summarized here.

Denavit-Hartenberg (D-H) parameterization method (Sciavicco and Siciliano, 2001) is used in the manipulator kinematics model, Fig. 4. In order to optimize D-H parameters the component Trolley Z was subdivided in two links, denominated Link 2 and Link 3.

The local homogeneous transformation matrices ${}^{0}T_{1}$, ${}^{0}T_{2}$, ${}^{2}T_{3}$ and ${}^{3}T_{4}$ are calculated based on D-H parameters. The homogeneous transformation matrix ${}^{I}T_{0}$, relating the local {0} to the global {I} inertial reference frame is also obtained.

The global homogeneous transformation matrix ${}^{I}T_{5}$, which describes the Connector position and orientation in the global inertial reference frame {I} is given by:

$$ {}^{I}T_{5} = {}^{I}T_{0} \cdot {}^{0}T_{1} \cdot {}^{1}T_{2} \cdot {}^{2}T_{3} \cdot {}^{3}T_{4} \cdot {}^{4}T_{5} = \begin{bmatrix} \cos\theta_5 & -\mathrm{sen}\theta_5 & 0 & -a_3 + d_1 + d_0 \\ -\mathrm{sen}\theta_5 & -\cos\theta_5 & 0 & d_2 \\ 0 & 0 & -1 & l_0 + a_1 - a_2 - d_4 - d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

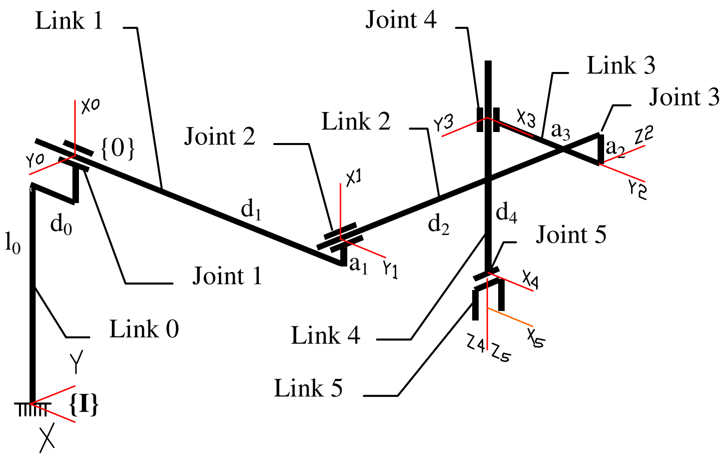


Figure 4. Kinematics model with reference frames and D-H parameters..

The SPA velocity description in Cartesian reference coordinates is given by its linear and angular velocities. Due to the SPA gantry configuration, composed by prismatic joints and one rotational joint, the angular velocity at the SPA extremity or link 5, where is located the connector, is given by:

$$^{I}\mathbf{w}_{5} = -\dot{\theta}_{5}\,\mathbf{z} \tag{2}$$

The linear velocity can be obtained as a function of the homogeneous transformation matrices. The equation of the linear velocity at the connector has the following form (Fu et all, 1987, Sciavicco and Siciliano, 2001):

$$^{I}V_{C} = \left[\left(Q_{0}\cdot{}^{I}T_{0}\cdot\dot{d}_{0}\cdot{}^{0}T_{1}\,{}^{1}T_{2}\cdot{}^{2}T_{3}\cdot{}^{3}T_{4}\right)+\ldots+\left({}^{I}T_{0}\cdot{}^{0}T_{1}\cdot{}^{1}T_{2}\cdot{}^{2}T_{3}\cdot Q_{4}\cdot{}^{3}T_{4}\cdot\dot{d}_{4}\right)\right]\cdot{}^{5}P_{C} \tag{3}$$

where:

Q_i = link matrix for prismatic joints, (dimensionless);
$^{5}P_C$ = connector position in the reference frame {5}, (m).

The solution of Eq. (3) yields:

$$^{I}V_{C} = \left(\dot{d}_{1} \quad \dot{d}_{2} \quad -\dot{d}_{4}\right)^{T} \tag{4}$$

which can be rewritten as:

$$[V] = \mathbf{J}_{L}\cdot[\dot{d}] \text{ or } \begin{Bmatrix} V_X \\ V_Y \\ V_Z \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}\cdot\begin{Bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_4 \end{Bmatrix} \tag{5}$$

The Jacobian matrix J_L is invertible, therefore, it has no geometrical singularities and the manipulator can move without restrictions at any internal point of its workspace.

3.2. Inverse kinematics

The velocity of the prismatic joints due to linear velocity in Cartesian space is calculated by:

$$[\dot{d}] = J_{L}^{-1}\cdot[V]$$

or

$$\begin{Bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}\cdot\begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} \tag{6}$$

given: $\begin{Bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{Bmatrix} = \begin{Bmatrix} v_x \\ v_y \\ -v_z \end{Bmatrix}$

4. STRUCTURAL ANALYSIS

4.1. Operational scenario

The operational scenario here studied considers a SPA-AUV system performing an intervention task in a third generation manifold. AUV selection was based on the thrusters power needed to move the AUV-SPA system.

Some parameters for the structural analysis are presented on table 1 (Bell, C., at all, 2002), (CENPES, Susep, 1990).

Table 1. Operational scenario parameters.

Manifold dimensions	15,000 mm x 12,000 mm x 6,000 mm
Maximum marine current velocity	1,000 mm/s
Vehicle model	HYSUB ATP 150 (large ROV)
Vehicle dimensions	3,500 mm x 2,000 mm x 2,000 mm
Vehicle payload	364 kg
Vehicle maximum speed	1,75 mm/s

4.2. SPA FEM model

The SPA is essentially a truss structure (Fig. 5) formed by commercial tubes made in steel and its overall dimensions are 35m x 22m x 10m. These basic dimensions take into consideration a safety workspace of five meters around the manifold to guarantee the necessary space to SPA-AUV system maneuvering. The truss structure layout gives rigidity and minimizes the phenomena of vortex induced vibrations.

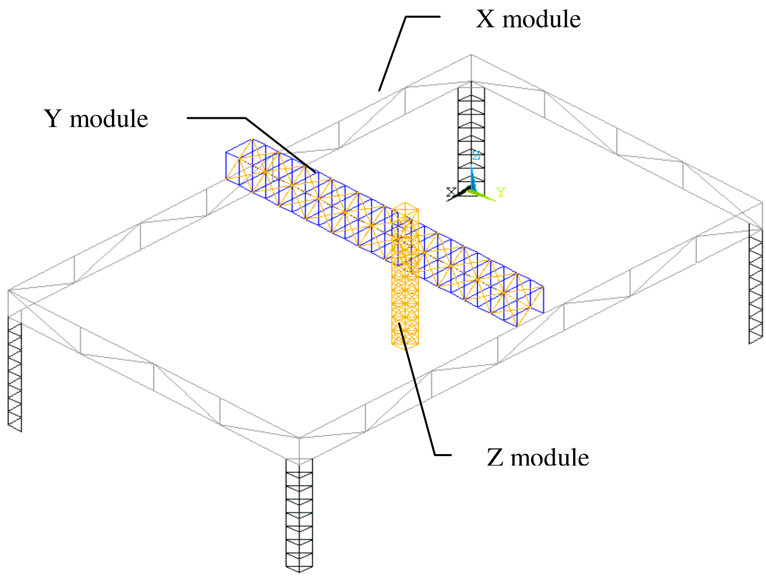


Figure 5. SPA truss structure model.

In this study the X module is considered to be fixed on the sea bed, the Y module moves in the X direction and Z module motion includes Y and Z directions. The displacements of the Y and Z modules are provided by the mechanical power of the vehicle thrusters. These modules also have floating devices to compensate their weight, giving a null vertical resultant force. The estimated masses are 21552 kg for X module, 905 kg for Y module and 715 kg for Z module.

A commercial FEM program, ANSYS® 5.5.1, was used to calculate the structural deformations and tensions, and these results were used to define the final structure configuration. This program has a Static Analysis Package which permits to determine the displacements, stresses, strains and forces in structures caused by external loads.

The most common structural loading conditions are of dynamic nature, that is, they are time-varying loads. But in many cases the loads and the structure responses vary slowly in respect to time. When this occurs the time-varying loads can be approximated as static equivalent loads (Ansys-PC, 1991). This consideration was assumed in the SPA structure analysis.

For the Static Analysis, additional assumptions and restrictions were considered (Ferreira and Romano, 2005):

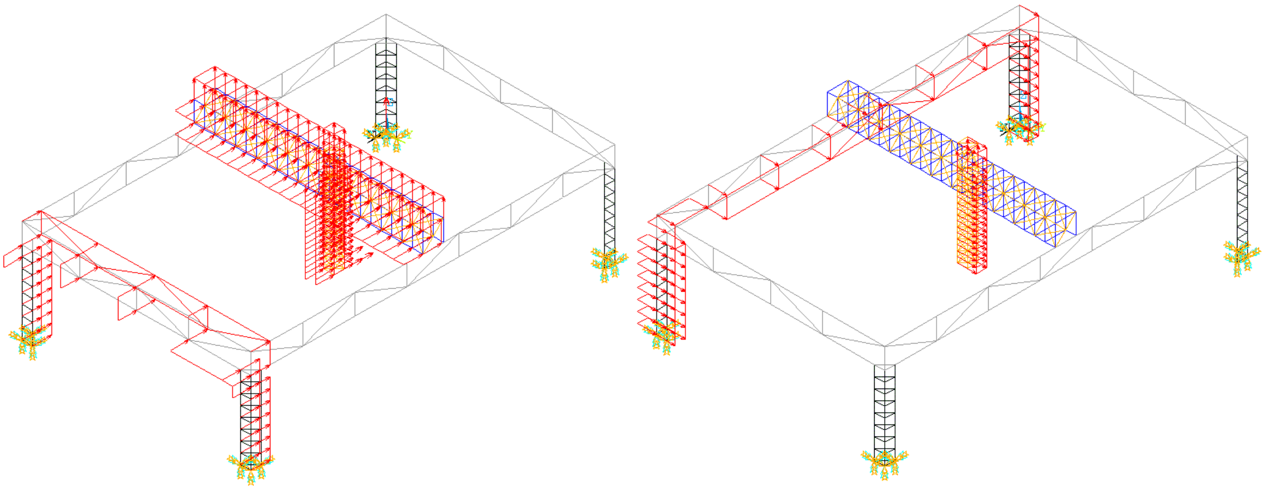
- damping and inertia effects were ignored (except inertia loads such as gravity and rotational velocity);
- only elastic deformations occurred in the SPA FEM modeling;
- the model undergoes small deflections.

The element "3-D Elastic Beam" was used to model the SPA structural components. It can support tension, compression, torsion and flexion. This element has also six degrees-of-freedom in each node (three translations and three rotations referred to X, Y and Z axis).

4.3. Model loading conditions

The external loads included in the SPA model are the marine current action on the structure, the force induced on the Arm Z extremity due to the drag force acting on the AUV lateral surface, and the floating facilities effects on the modules Y and Z. It was also considered that the AUV floating devices support its own weight.

Figure 6 presents the complete gantry manipulator modeling used to evaluate the structural deformations and tensions, with all applied loads, the acceleration gravity vector and the natural constraints such as the zero degree of freedom at each contact point of the manipulator legs and sea bed. SPA modal analysis was also calculated.



(a) (b)

Figure 6. SPA FEM modeling with external loads, constrains and marine currents: (a) X direction. (b) Y direction.

5. RESULTS

5.1. Position deviations and stresses

The manipulator was modeled for the worst loading conditions, with the Arm Z in full extended configuration and marine current forces acting in X and Y directions at SPA structure and perpendicularly at the larger lateral AUV area.

The position deviation mapping of a reference point located in the SPA connector was calculated for 42 combinations of X and Y coordinates, according to Table 2.

The obtained results are given in linear and angular nodal displacements.

In Fig. 7 are presented the simulation results of the SPA connector linear position deviations for different marine current velocities in X direction, variable X coordinates and Y coordinate equal to 7m. In Fig. 8 the linear position deviations are associated to marine current velocities in Y direction, variable X coordinates and Y coordinate equal to 7m. The linear and angular nodal displacements maximum values for marine current in X and Y directions are shown in Table 3.

Table 2. X and Y coordinates of the SPA connector used for position deviation mapping.

Arm Z position (X direction) [m]	2,5	7,5	12,5	17,5	22,5	27,5	32,5
Arm Z position (Y direction) [m]	1	3	5	7	9	11	–

The nodal angular displacements of the model operational loading conditions can be neglected (Table 3).
The maximum stress value obtained for the SPA model computed in ANSYS® 5.5.1 was 155 MPa. This is a low stress for steel elements.

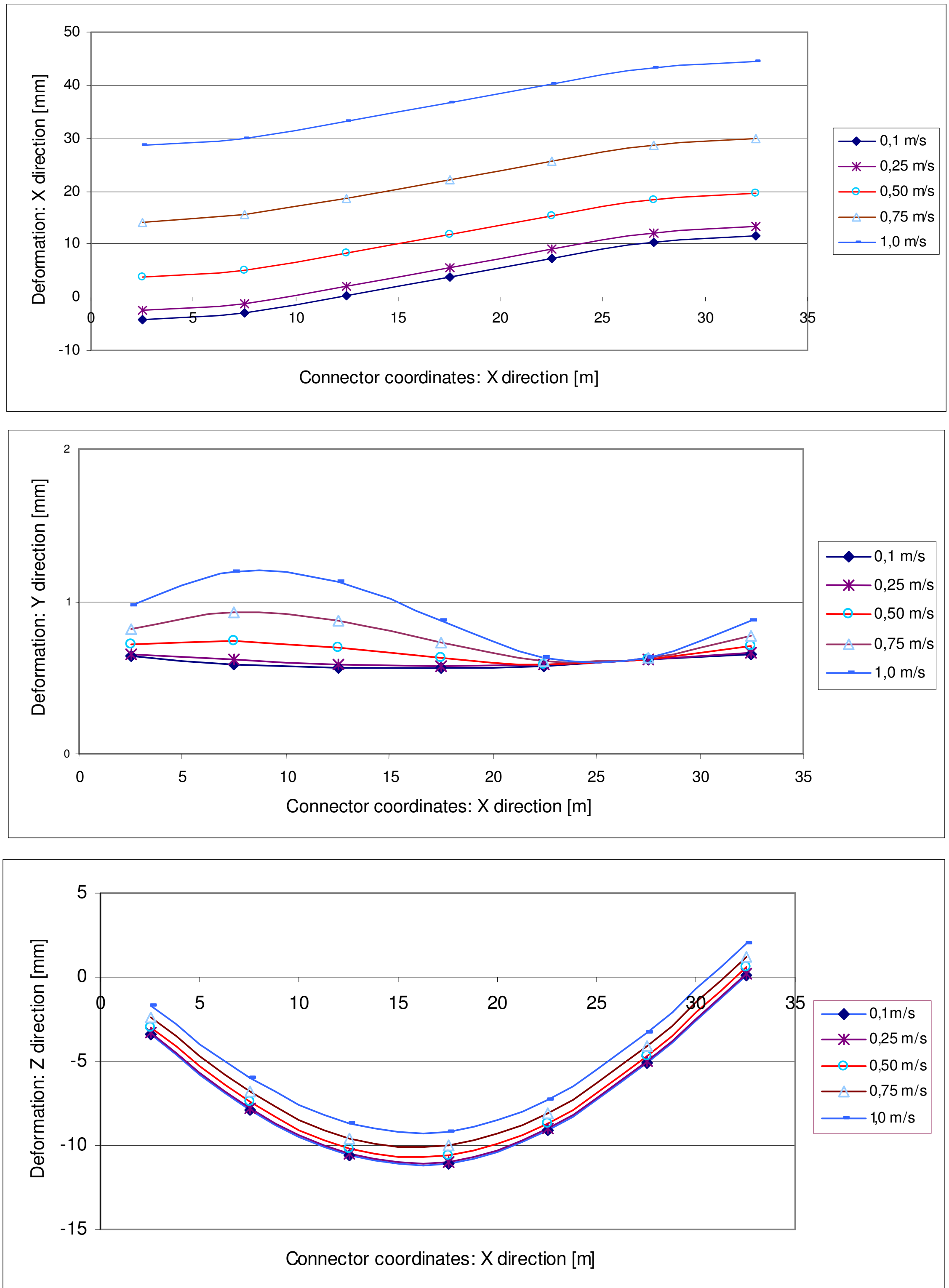


Figure 7. Position deviations for different marine current velocities (X direction). Y coordinate equal to 7 m.

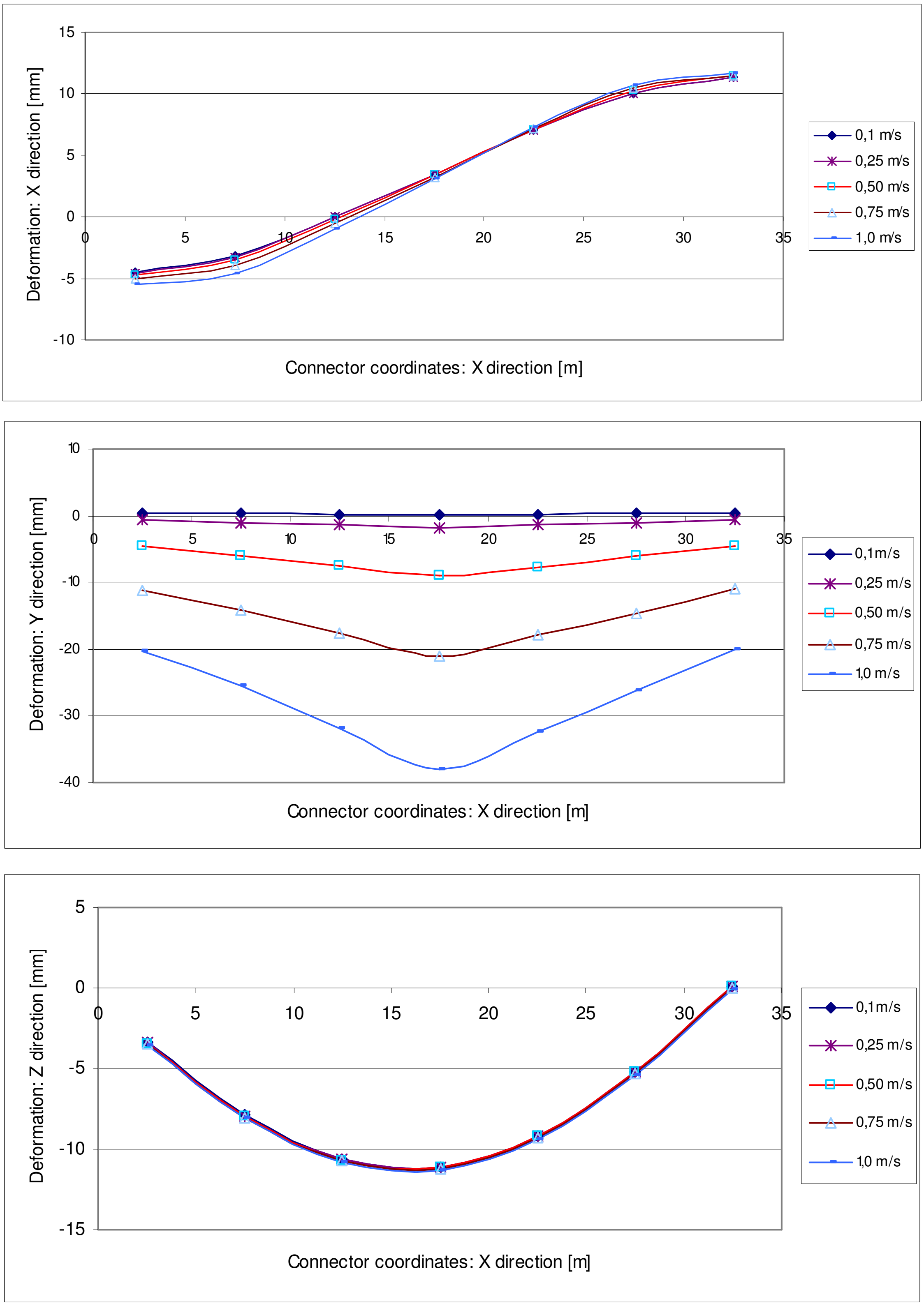
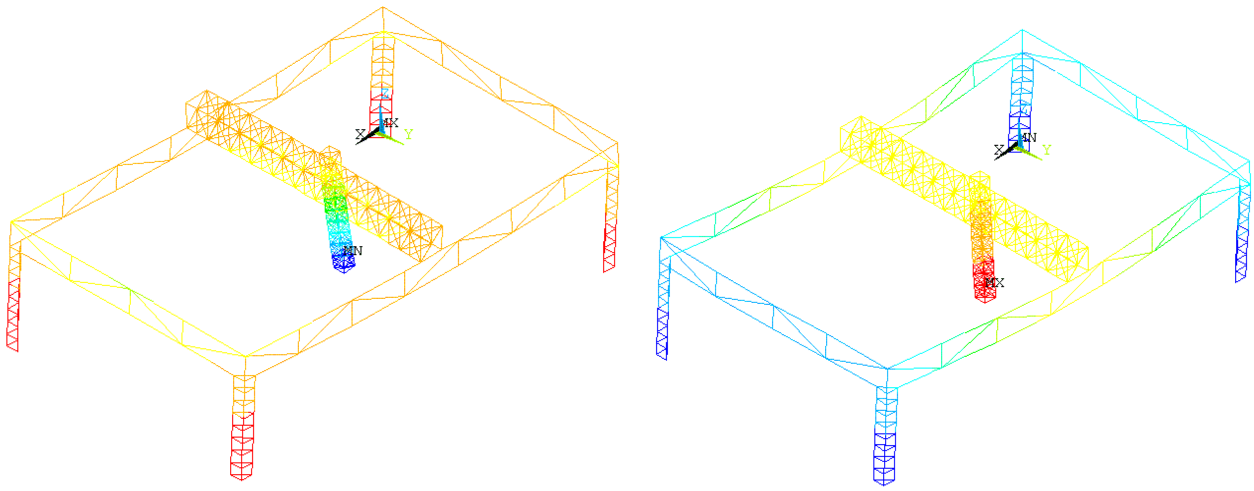


Figure 8. Position deviations for different marine current velocities (Y direction). Y coordinate equal to 7 m.

In Figs. 9(a) and 9(b) are presented the SPA nodal linear displacements for marine currents in X and Y directions. The draws were generated in ANSYS® 5.5.1.

Table 3. Maximum linear and angular nodal displacements.

	Linear nodal displacements [mm]	Angular nodal displacements [rad]	Marine current (X direction)
X direction	38	5×10^{-4}	
Y direction	2	4×10^{-3}	
Z direction	13	2×10^{-3}	
	Linear nodal displacements [mm]	Angular nodal displacements [rad]	Marine current (Y direction)
X direction	4	1×10^{-3}	
Y direction	39	1×10^{-3}	
Z direction	13	2×10^{-3}	

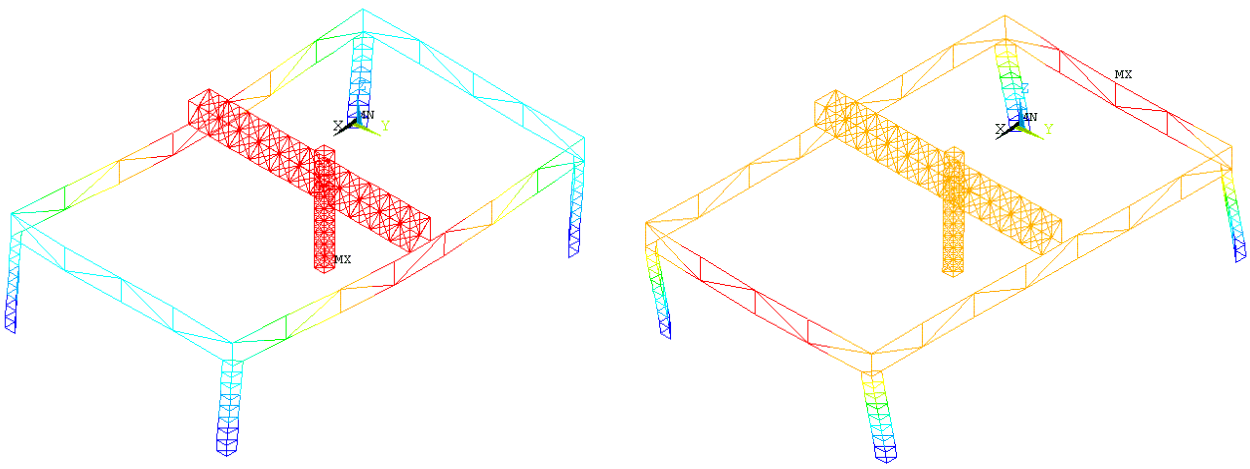


(a) (b)

Figure 9. (a) X direction SPA nodal linear displacements [m]. Marine current in X direction.
(b) Y direction SPA nodal linear displacements [m]. Marine current in Y direction.

5.2. Modal analysis

The determination of the SPA vibration modes and natural frequencies, are useful to evaluate the behavior of the SPA when submitted to excitation forces, mainly due to marine currents. The modal analysis resulted in the following data: 1st mode at 0.54 Hz, 2nd mode at 0.70 Hz, 3rd mode at 0.97 Hz, 4th mode at 1.09 Hz and 5th mode at 1.23 Hz.



(a) (b)

Figura 10. SPA vibration modes. (a) First mode: frequency = 0.54 Hz. (b) Second mode: frequency = 0.70 Hz.

6. CONCLUSIONS

The structural analysis of the Semi-Passive mechanical Arm (SPA) was an important design procedure to obtain the optimized engineered SPA configuration.

The FEM model for the marine currents in X direction (Fig. 7) gives linear position deviations curves with similar profiles in X and Z directions. These curves characteristics can be used as an offline database in future implementation of a control strategy to automatically correct the deviations. The linear position deviations in Y direction are negligible.

The same occurs in the simulations for the marine currents in Y direction (Fig.8). Despite the considerable values of the position deviations in X, Y and Z directions, the curve profiles have a pattern that can be used to provide control information to compensate for these deviations.

A possible solution to reduce the deviations in Z direction is the installation of floating devices in the X module to compensate its weight. The disadvantage of this procedure is the reduction of the normal force at the seabed interface, necessary to keep the anchorage of SPA. The most important SPA advantages are listed below:

(a) *increase the vehicle structural rigidity, precision and repeatability:* when the breaks are activated the SPA-vehicle system behaves as a fixed base manipulator.

(b) *integrity preservation of the equipment under intervention:* during intervention, the vehicle do not have mechanical links with the equipment. Therefore, all the mechanical loads that appear in the interaction between the vehicle and the equipment are transmitted to the SPA structure.

(c) *payload capacity improvement:* although the SPA Y and Z modules have huge masses, the vehicle has the necessary mechanical power to move its inertia and other objects, heavier than its payload capacity.

(d) *decrease in equipment intervention time:* due to the increase of the system structural rigidity, precision and repeatability, resulting in cost reductions of vehicle and support vessel mobilization.

(e) *mobility:* the vehicle acquires mobility to perform the tasks, easy motion nearby the equipment under intervention.

(f) *application of the fixed base industrial manipulators technology:* this is an important aspect, since all the advanced industrial and technological development applied on industrial robots can be adapted for the SPA-AUV-arm system.

(g) *subsea equipments design simplification:* as the SPA-vehicle can reach any part of the equipment under intervention, there is no need to design the override panels in the subsea equipments.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE