A GANTRY TYPE SEMI-PASSIVE ARM TO SUPPORT AUV's OFFSHORE ACTIVITIES

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Abstract. *This article presents a complete analysis of a gantry type Semi-Passive mechanical Arm (SPA), conceived to operate as a support to Autonomous Underwater Vehicles (AUV) during its interventions in sub sea scenarios. Dynamic conditions were included at the structural analysis model. The SPA can be defined as a mechanical arm formed by rigid-body links, with no actuators transmitting mechanical power to the joints. Only brakes are installed at the joints, so that the arm links are free to move in the directions not blocked by brakes. The combination of joints with activated brakes or not activated brakes permit the AUV to move in preferential directions, even if external perturbations like marine currents occur during the execution of a task. The AUV thrusters are still the unique source of power needed to move the AUV-SPA system. An open kinematics chain mathematical model with four degrees-of-freedom of the SPA was considered in the analysis. A finite element method model of an engineered SPA configuration was developed and some results including a docked AUV arm system and external loads such as buoyancy and the fluid drag forces are presented.*

Keywords: *underwater robotics, gantry manipulator, offshore structures, FEM modeling*

1. Introduction

The use of underwater vehicles in the offshore industry activities is rapidly increasing since they can operate in deep water and risk areas where divers are not able to work. Typical applications are: platform, subsea facilities and pipeline inspections, subsea equipments interventions and payload movimentation.

The installation of manipulator arms on these vehicles permits the robotization of many tasks. However, any motion of the manipulator arm located at the vehicle will induce reaction forces and moments that disturb the position and attitude of the supporting base vehicle, raising the control complexity needed to compensate for positioning deviations of the AUV arm system. The same occurs if the system carries a payload, resulting in a change of its center of gravity and consequently its equilibrium configuration. These phenomena happen due to the lack of a fixed base to transmit the force and moments originated by the interaction of the arm with the intervened environment, as occurs in industrial manipulators rigidly fixed at the ground.

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

The use of the second manipulator to prevent the vehicle motion is wasteful as coordinated tasks involving both manipulators can not be performed. With the latter option there are a number of subunits associated with this mechanism including a water pumping unit, water filter, relief valve, and attachment arm hydraulic control manifold, which involves significant mechanical engineering effort.

In addition, in both cases there is a vehicle-manipulator workspace reduction, and all loads are transmitted from the rigidizer to the equipment under intervention which can cause damages in critical situations. Besides, depending on the distance between the part of the equipment to be intervened and where the vehicle is docked, the AUV arm system has to execute an undock operation, go to the position where the task will be done and redo the rigidizer and structure docking process again. Depending on the current marine conditions, this task can demand a long time to converge to the new docking configuration.

Another possible solution to reduce the vehicle position and attitude disturbance is a control system which uses the vehicle thrusters to compensate these effects (Zanoli and Conte, 2003). But, even this control system has not enough precision and repeatability (still considering the current marine variability and the vehicle-manipulator/water hydrodynamic interaction), it will not provide rigidity to the manipulator-vehicle system and it will use the thrusters energy to compensate the position and attitude deviation.

The Semi-Passive mechanical Arm (SPA) proposal increases the capability of manoeuvre and manipulation skills of the AUV arm system nearby the working site, obtained from those control systems, with the rigidity acquired from the rigidizers utilization; also improving the vehicle-manipulator workspace and payload capacity. In addition, all the mechanical loads that appear during the intervention will be transmitted to the SPA structure, regarding the integrity of the equipment, and there will be no need to use the thrusters energy to compensate the position and attitude deviation.

The choice of the SPA structure configuration essentially depends on the manipulated unity operational requirements and dimensions, environmental marine conditions, and the SPA-vehicle performance indices like the manoeuvrability, dynamic behavior and workspace.

2. Semi-Passive mechanical Arm Characteristics

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 the brakes. An open kinematics chain manipulator with 3 planar revolute joints was studied in a previous article (Cabral Junior and Romano, 2003).

The SPA proposed by the authors in this paper has a gantry type configuration with four degrees-of-freedom: 3 prismatic joints (movements in X, Y and Z directions) and one revolute joint (pan motion), Fig. 1.

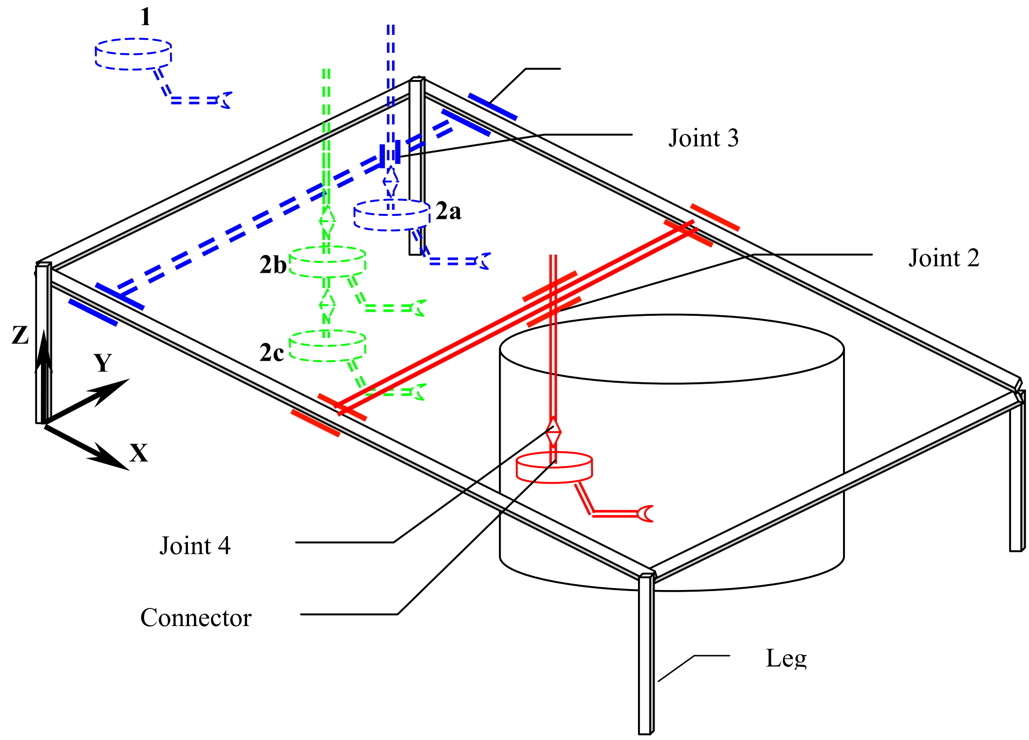


Figure 1 – Description of the SPA-vehicle system movements.

The SPA arm terminal has a special connector to attach the vehicle. The four vertical structural elements, denominated “legs”, form a rigid link between the mechanisms of the SPA-vehicle system and the ground. They can be fixed directly to the underwater facility to be intervened - in this paper represented by a manifold located inside the SPA-vehicle workspace -, by means of special structures, or to the sea bed.

The vehicle thrusters are still the unique source of mechanical power needed to move the SPA-vehicle system. In case the vehicle is a Remote Operated Vehicle (ROV), the energy to activate SPA brakes can be furnished by a dedicated conductor from umbilical cable. For AUV utilization, the energy can be furnished from an external source unit so that no energy is drained from the vehicle.

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. 1: the approach phase (positions 1 to 2a), where the vehicle is moving towards the SPA connector device; the connecting phase (position 2a), related to the vehicle attachment with the SPA; and the intervention phase (position 3), concerning the SPA-vehicle system workspace nearby the working zone.

The trajectory of the SPA-vehicle system from point 2a to point 3, can be described by a sequence of actuated (L – locked) and not actuated (U – unlocked) brakes, according to Table (1). Once the SPA-ROV system achieves the working zone, the brakes will be actuated or not according to the required intervention planning.

Table 1. Brake state conditions for the trajectory from point 2a to point 3.

Motion From	To	Joint 1	Joint 2	Joint 3	Joint 4
2a	2b	L	U	L	L
2b	2c	L	L	U	L
2c	3	U	L	L	L

3. SPA Kinematics Analysis

The kinematics analysis of the SPA is referred in the Joints Space Coordinates. As said before, the SPA is a gantry type manipulator, which has a fixed base (Module X) and 4 links (Module Y, Car Z, Arm Z and Connector) connected as an open kinematics chain with four degrees-of-freedom, Fig.2. The Module X, Module Y and Module Z (composed of the Car Z and Arm Z) have translational movements and the Connector has a rotational one.

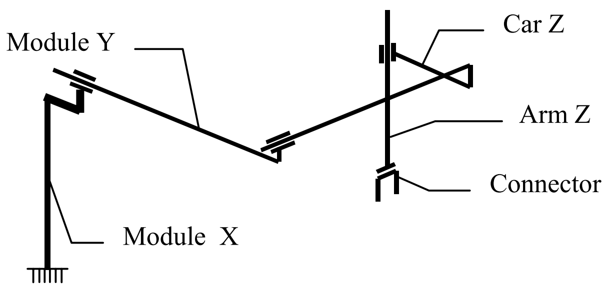


Figure 2 – Simplified model of the manipulator with a fixed base (Module X) and four links (Module Y, Car Z, Arm Z and Connector).

Denavit-Hartenberg (D-H) parameterization method (Sciavicco and Siciliano, 2001) is used in the manipulator kinematics model, Fig. 3. In order to optimize D-H parameters the Car Z was subdivided in two links, Link 2 and Link 3. Local homogeneous transformation matrices ${}^{0}T_{1}$, ${}^{0}T_{2}$, ${}^{2}T_{3}$ and ${}^{3}T_{4}$ are calculated based on D-H parameters. From the Fig. 3 is obtained the homogeneous transformation matrix ${}^{I}T_{0}$, relating the local {0} to the global {I} inertial reference frame.

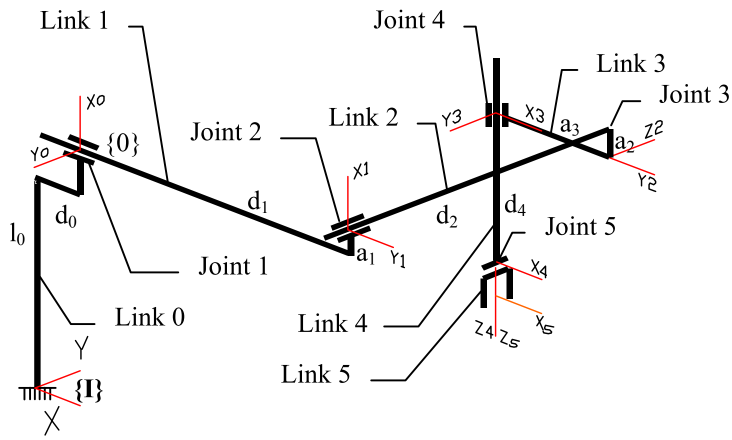


Figure 3 – Simplified model with inertial and local reference frames and D-H parameters.

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:

$$
{}^{\mathbf{I}}\mathbf{T_5} = {}^{\mathbf{I}}\mathbf{T_0} \cdot {}^{\mathbf{0}}\mathbf{T_1} \cdot {}^{\mathbf{1}}\mathbf{T_2} \cdot {}^{\mathbf{2}}\mathbf{T_3} \cdot {}^{\mathbf{3}}\mathbf{T_4} \cdot {}^{\mathbf{4}}\mathbf{T_5} = \begin{bmatrix} \cos\theta_5 & -\operatorname{sen}\theta_5 & 0 & -a_3 + d_1 + d_0 \\ -\operatorname{sen}\theta_5 & -\cos\theta_5 & 0 & d_2 \\ 0 & 0 & -1 & l_0 + a_1 - a_2 - d_4 - d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

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:

$$
{}^{\mathrm{I}}\mathbf{w}_5 = -\dot{\theta}_5\,\mathbf{z} \tag{2}
$$

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):

$$
{}^{\mathbf{I}}\mathbf{V}_C = \left[\left(\mathbf{Q_0} \cdot {}^{\mathbf{I}}\mathbf{T_0} \cdot \dot{\mathbf{d}}_\mathbf{0} \cdot {}^{\mathbf{0}}\mathbf{T_1}\, {}^{\mathbf{1}}\mathbf{T_2} \cdot {}^{\mathbf{2}}\mathbf{T_3} \cdot {}^{\mathbf{3}}\mathbf{T_4}\right) + \ldots + \left({}^{\mathbf{I}}\mathbf{T_0} \cdot {}^{\mathbf{0}}\mathbf{T_1} \cdot {}^{\mathbf{1}}\mathbf{T_2} \cdot {}^{\mathbf{2}}\mathbf{T_3} \cdot \mathbf{Q_4} \cdot {}^{\mathbf{3}}\mathbf{T_4} \cdot \dot{\mathbf{d}}_\mathbf{4}\right)\right] \cdot {}^{\mathbf{5}}\mathbf{P}_C \tag{3}
$$

where:

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

The solution of Eq. (3) yields:

$$
{}^{\mathbf{I}}\mathbf{V}_C = \left(\dot{\mathbf{d}}_\mathbf{1} \quad \dot{\mathbf{d}}_\mathbf{2} \quad -\dot{\mathbf{d}}_\mathbf{4}\right)^{\mathrm{T}} \tag{4}
$$

which can be rewritten as:

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

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.

4. Finite Element Model

To simulate an operational scenario, it is considered here a study of a SPA-AUV system performing an intervention task in a manifold. Some adopted parameters for the structural analysis are:

- manifold dimensions: 15,000 mm x 12,000 mm x 6,000 mm;
- marine current velocity – 1,000 mm/s;
- AUV basic characteristics: dimensions: 3,500 mm x 2,000 mm x 2,000 mm;
  payload: 364 kg;
  maximum speed: 1,750 mm/s.

The finite element model of the SPA structure is presented in Fig. 4. The structure is mainly formed by tubes made in steel and its overall dimensions are 35m x 22m x 10m. These basic dimensions take into consideration a safety space of five meters around the manifold to guarantee the necessary space to dock the AUV at the SPA connector. 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.

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:

- 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, since it can support tension, compression, torsion and flexion. This element also has six degrees-of-freedom in each node (three translations and three rotations referred to X, Y and Z axis).

The external loads of the modeling were: the marine current action on the structure, the force induced on the Arm Z extremity due to the drag force on the AUV, the floating facilities effects on the modules Y and Z and the gravity action. It was also considered that the AUV floating devices support the weight of the moveable parts. The manipulator was modeled for the worst loading condition, with the Arm Z in full extended configuration and located in the middle of the Y module, and the marine current acting perpendicularly at the larger lateral AUV area.

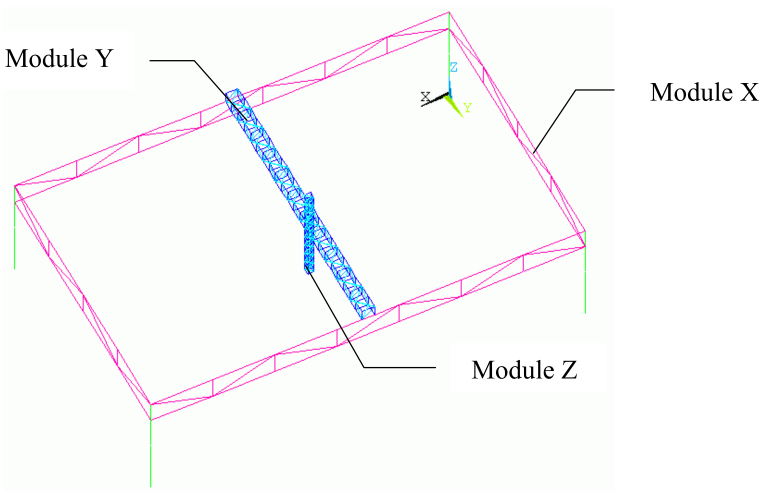


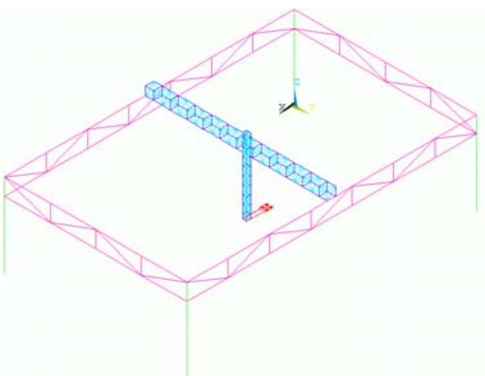
Figure 4 – SPA basic configuration.

4.1 Marine current effects

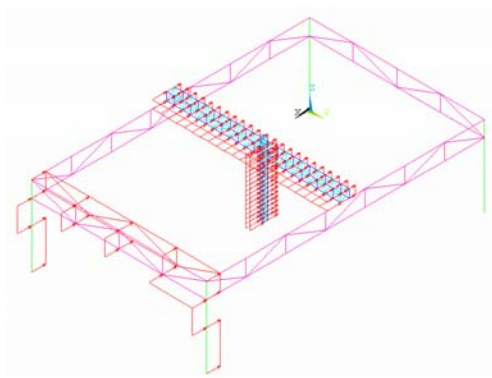
The drag force on the AUV is estimated by Eq. (6) (Bell *et al.*) and acts at the Z module extremity, Fig. 5(a). The AUV is rigidly connected to the Z module, consequently all loads are transmitted from the vehicle to the structure. The marine current effects on the manipulator structure, given by Eq. (6), are indicated in Fig. 5(b).

$$F_A = \rho \,.\, u^2 \,.\, C_{df} \,.\, A \tag{6}$$

where: ρ – sea water density [kg/m^3];
u – marine current velocity [m/s];
C_{df} – drag coefficient (dimensionless);
A – cross sectional area [m^2].



(a)



(b)

Figure 5 – Drag force modeling. (a) AUV contribution. (b) SPA itself.

4.2 Weight compensation

Floating devices are usual solutions to compensate for underwater structures weight. Due to the gantry configuration, they can be installed in Y and Z modules. There effects are considered in the model as shown in Fig. 6.

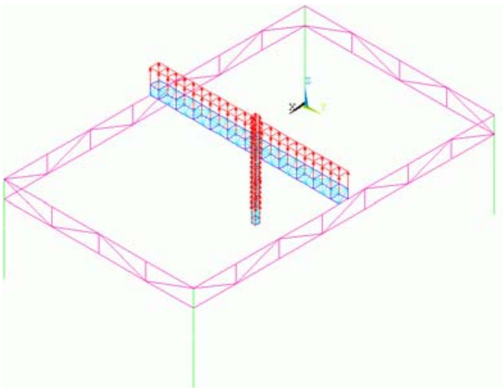


Figure 6 – FEM model with weight compensation.

4.3 SPA complete FEM model

Figure 7 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.

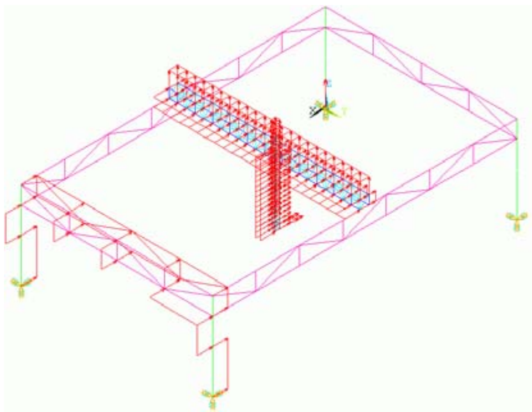


Figure 7 – Complete FEM modeling of the manipulator.

4.4 SPA final configuration

After the study of some different SPA structure configurations based on engineering criteria, it was decided to use the structure showed in Fig. 4, which presented the best deformations and tensions results. The X module has legs with Ø150mm diameter and the other components are formed with Ø127mm commercial tubes. The total mass is estimated in 16,000 Kg.

The Z and Y modules are mainly formed by truss structures, with Ø76 mm frames and Ø25 mm braces, Fig. 8. The Y sub-modules have 1,000 x 1,000 x 1,000 mm and Z sub-module 500 x 500 x 500 mm. The Y and Z modules total masses are respectively 2,952 Kg and 1,214 Kg.

In Figures 9, 10 and 11 are presented the structural deformation results in X, Y and Z directions, with their maximum values corresponding respectively to 105 mm, 3 mm and 25mm. These values are acceptable for operational purposes. In order to minimize these positioning deviation, it could be implemented an automatic correction procedure based on the mapping of the SPA static structural deformations that could occur for any trajectory combination. These deviations could be calculated previously by an off-line program, allowing the SPA motion to be compensated, resulting in higher precision and repeatability (Ferreira, 2000).

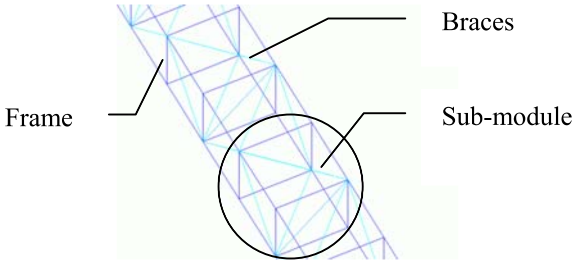


Figure 8 – Construction details of Y and Z Modules.

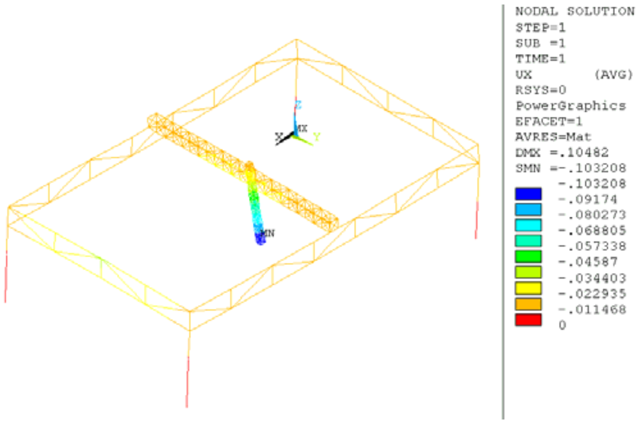


Figure 9 – SPA structural deformations results in X direction. (Dimensions in meters).

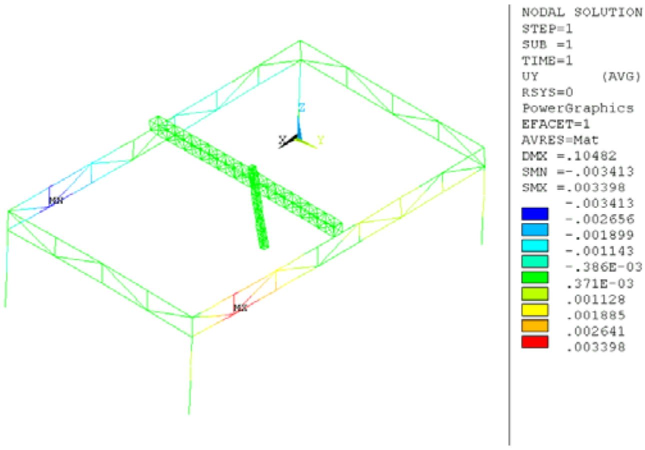


Figure 10 – SPA structural deformations results in Y direction. (Dimensions in meters).

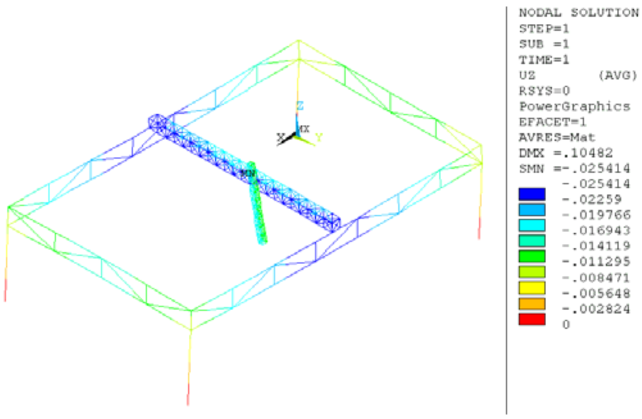


Figure 11 – SPA structural deformations results in Z direction. (Dimensions in meters).

5. Conclusions

This article presented the Semi-Passive mechanical Arm (SPA) in gantry configuration, conceived to improve the underwater vehicle capabilities during its interventions in sub sea scenarios, more specifically an SPA-AUV system performing some activities in a manifold.

Some of the SPA advantages are mentioned 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 the 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 thrust 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 from one point to another nearby the equipment under intervention;

(f) *application of the fixed base industrial manipulators technology:* this is also a very important aspect, since all the advanced industrial and technological development applied on industrial robots can be adapted for the SPA-AUV-arm system. For example, the pre-programmed procedures used in robot cells for car manufacturing tasks.

(g) *design simplification* for *new subsea equipments*: since the SPA-AUV system can reach any part of the equipment under intervention, there is no need to design special override panels for interface purposes in subsea equipments;

In this paper was presented the SPA kinematics analysis to be used on brakes activation/deactivation control system.

The results of the structural deformations and tensions analysis based on finite element method, indicated an optimized gantry manipulator structure to be adopted in a prototype construction.

Some of the future activities planned for this project are the following:

- designing of the breaks to be used in the SPA;
- definition and dimensioning of the linear guides;
- floating devices development;
- design criteria for SPA fabrication, assembly and installation;
- study of a SPA installed directly to the underwater facility to be intervened;
- search for partners and financial support to made a prototype;
- prototype construction to test and make the validation of the modeling analysis.

6. Acknowledgements

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