

## A Real Time ROV Simulator For Underwater Mission Training

**Marcelo Prado, marcelo@multicorpos.com.br**  
Multicorpos Engenharia

**Alvaro Costa Neto, costa@sc.usp.br**  
Escola de Engenharia de São Carlos - USP

**Gerson Brand, gerson.brand@uk.cd-adapco.com**  
CD-adapco – London Office

**Eduardo Aoun Tannuri, eduat@usp.br**  
Escola Politécnica da Universidade de São Paulo – Departamento de Engenharia Mecatrônica e Sistemas Mecânicos.

***Abstract.** The use of Remotely Operated Vehicle (ROV) for inspection, maintenance, building structures and surveillance in deep water offshore platforms is very intensive. These missions are performed in risky environment were human beings could not reach. The ROV's pilot needs to have a great skill and experience in order to control the thrusters and the manipulator of the ROV. The cost of these missions is very expensive and sometimes the pilot could not finish the mission in only one day. One alternative to reduce time and cost of these missions is to simulate the tasks of the mission using a real-time ROV simulator. In this work a MSC.Adams/View real time ROV simulator was built with inputs via joysticks and the geometry of undersea environment and offshore structures. The MSC.Adams/View is a multibody software for general use and it is possible to model any type of ROV and manipulator specific to each task. This human in the loop environment system using MSC.Adams/View and Matlab/Simulink softwares will open many possibilities in the future when the real-time simulation ROV will include a very complex undersea environment system and all the tasks necessary to complete the mission).*

**Keywords:** ROV simulator, ROV, multibody model, human-in-the-loop

### 1. INTRODUCTION

Simulation as a tool for training ROV's pilots plays an important role nowadays. The missions are very complex and the time needed to prepare the ROV's pilot for a specific mission can be very expensive and time-consuming. There are several toolboxes available on the market to be used for ROVs. Although these toolboxes are very useful for the simulation of ROVs models, they are not flexible enough in order to simulate all types of ROVs available on the market. They are black boxes and the user must choose one of the mathematical model of the ROV available in the software. All these ROV's mathematical models are determined a priori and their equations are built by hand. Usually, these models have a very simplified mathematical model and the user have a few options to choose.

In this work we made a different approach, using a multibody software to build a ROV's model and the manipulator. With this approach the user can use the standard ROV's model or s/he can build a different model. Also, it is possible to include a very complex model of the manipulator and thrusters. With an open environment to build complex mechanical systems the user is not anymore dependent on the company that developed the software. They can build your own model and test many possibilities and task missions.

One the great issue in the past is that multibody software packages are not well suited for human-in-the-loop applications because numerical approach was slow for this type of simulation. But the power computing is increasing every day and today there are small computers that are hundred times faster than the old main frame computers.

In this work we used the MSC.Adams/View multibody software and Matlab/Simulink control software to develop an environment for human-in-the-loop simulator for ROV's pilots training. MSC.Adams/View is an open environment for multibody applications and it is possible to construct a very complex mechanical model with few clicks on the mouse using the MSC.Adams/View graphical interface.

### 2. ROV MODEL

The dynamics of ROVs are highly nonlinear due to the coupling between the ROV's dynamics and the hydrodynamics forces on the vehicle. ROVs have similar velocities along all three axes and control techniques using linearization of the equations of motion about one forward velocity do not work effectively as they can with aircraft and submarines. Therefore, it is important to consider the nonlinear equations of motion in modeling the ROVs dynamics and all the hydrodynamics forces (Yuh, 1990).

The hydrodynamics coefficients can be calculated based on the geometry of the ROV. Added mass and drag forces are the most important hydrodynamics forces and using the tabulated data we can estimate the hydrodynamics coefficients (Fossen, 1994).

A nonlinear multibody model of the ROV was built using MSC.Adams/View software. In this model, we included the rigid body model of the ROV with six degrees of freedom, the hydrodynamics forces, the manipulator model, the thruster model and a discretized model of the tether cable. In this work we modeled the tether cable using the lumped parameter approach, dividing it into small pieces and connecting these pieces by means beam elements. For each piece of the tether cable we can apply the hydrodynamics forces due to maritime sea current.

Using the ROV's manipulator and the control thrusters the pilot can perform the desired task for a specific mission. There are many types and configurations of these manipulators on the market. One of the MSC.Adams advantage is that the development team can model a new type of manipulator in a very short time.

In this work we modeled a ROV with six degrees of freedom and with two manipulators with six and four degrees of freedom. The tether cable was discretized into two hundred small pieces.

Figure 1 shows the Fugro ROV which this work is based on. Tab. 1 shows the ROV parameters, based on the Fugro Manual of Operation.



Figure 1: ROV model Fugro G3 used in this work (Porto de Vila Velha-ES – 13/02/2007)

Table 1: ROV's parameters

<b>Length</b>	2925 mm
<b>Width</b>	2050 mm
<b>Height</b>	1725 mm
<b>Mass</b>	3300 kg
<b>Longitudinal Velocity</b>	3.5 knts - 1.8 m/s
<b>Lateral Velocity</b>	2.8 knts - 1.44 m/s
<b>Vertical Velocity</b>	2.7 knts – 1.39 m/s

## 2.1. ROV equation of motion

The ROV can be treated as a rigid body with six degrees of freedom. The equation of motion of the ROV can be conveniently expressed as:

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau \quad (1)$$

The mass matrix  $M$  accounts for vehicle inertia and added mass, the  $C$  matrix includes the Coriolis and centripetal forces, the  $D$  matrix is the damping matrix due to vortex shedding damping forces, based on Morrison's equation. The  $g$  matrix accounts for gravitational and buoyancy forces. The vector input  $\tau$  is the thruster force applied on the ROV.

In this equation we did not take into account the forces and torques due to tether cable. These forces and torques are modeled as lumped masses connected by means of beam elements into MSC.Adams model. It is an improvement

compared to many other models in the literature where a simplified model of the tether cable is included into the vector input  $\tau$ . Also, Eq. (1) do not take into account the manipulator dynamics.

In MSC.Adams we can construct each subsystem separately and connect them via joints and force elements. It is not necessary to write all the equations by hand in order to obtain a full equation of motion of the entire model. The hydrodynamics forces and torques are applied on the ROV using general forces elements.

In order to reproduce the external world and hence, improve the reality of the simulator a CAD geometry can be imported into the MSC.Adams model using standard formats (STEP, PARASOLID, IGES). The pilot will train for the mission in a environment that s/he will see in the physical location.

The ROV's model built on MSC.Adams, including the geometry of the external world, can be seen in Fig. 2

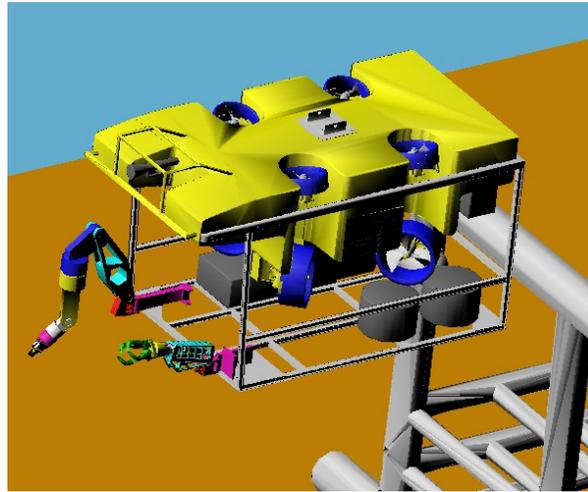


Figure 2: ROV model on MSC.Adams/View software

## 2.2. Hydrodynamic forces

The hydrodynamics forces acting on the ROV are described assuming an irrotational fluid with longitudinal velocity of current equal to  $U_f$ . The relative velocity between the ROV and fluid is:

$$U_r = U - U_f \quad (2)$$

Where:

$U$  = ROV longitudinal velocity, m/s

$U_f$  = fluid velocity, m/s

$U_r$  = ROV relative velocity, m/s

The hydrodynamics forces and moments on the ROV can be linearly superposed. Considering the three components (Fossen, 1994):

- 1) Added mass due to inertia of the surrounded fluid
- 2) Damping force due to vortex shedding (Morrison's equation)
- 3) Restoring forces (weight and buoyancy)

The added masses are additional inertia terms introduced into the ROV model in order to account for the effective mass of surrounding fluid that must be accelerated with the ROV. We assumed constant coefficients for the added masses.

Figure 3 shows the mesh generated using the WAMIT software. WAMIT is a radiation/diffraction program developed for the analysis of the interaction of surface waves with offshore structures ([www.wamit.com](http://www.wamit.com)), the bodies may be located on the free surface, submerged, or mounted on the sea bottom. The calculated added masses can be seen in Tab. 2.

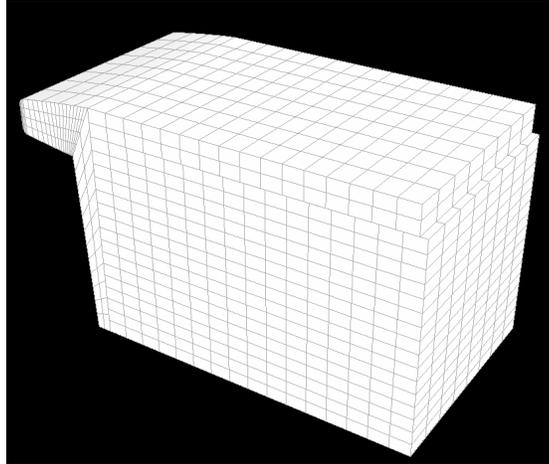


Figure 3: ROV mesh generated in the WAMIT.

Table 2: Calculated added masses for the ROV.

	10m deep			50m deep			100m deep			unit
	5s	15s	25s	5s	15s	25s	5s	15s	25s	
surge	2885	2888	2887	2886	2886	2886	2886	2886	2886	kg
sway	5511	5515	5514	5512	5512	5512	5512	5512	5512	
heave	5636	5643	5642	5638	5638	5638	5638	5638	5638	
roll	861	861	861	861	861	861	861	861	861	kg.m <sup>2</sup>
pitch	2477	2477	2477	2476	2476	2476	2476	2476	2476	
yaw	1697	1697	1697	1697	1697	1697	1697	1697	1697	

In a viscous fluid the frictional forces are presented that the system is not conservative. The viscous damping forces acting on the ROV were modeled using Morrison's equation:

$$F_d = \frac{1}{2} C_d \rho_w A U_r |U_r| + C_m \rho_w A \dot{U} \quad (3)$$

Where  $C_d$  is the damping coefficient,  $\rho_w$  is the density of the sea water;  $A$  is the projected area of the ROV,  $U$  and  $\dot{U}$  are the relative velocities and accelerations between the ROV and the fluid.

The restoring forces are the gravitational and the buoyance forces. The buoyance force is equal to the weight of fluid displaced by the ROV and is given by:

$$F_B = \rho_w g V \quad (4)$$

Where  $V$  is the volume of fluid displaced by the ROV and  $g$  is the acceleration of gravity.

These forces are implemented into the MSC.Adams/View via general forces applied at the ROV center of mass. These forces can be seen in Fig. 4

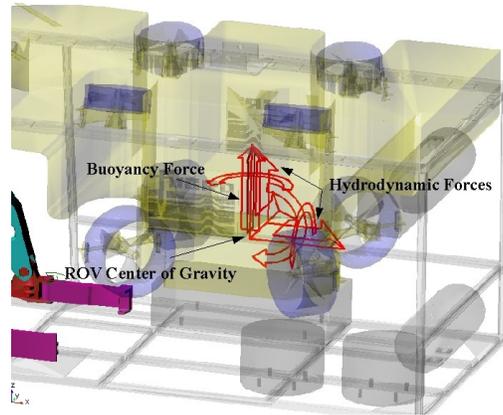


Figure 4: Hydrodynamics forces applied on the ROV model.

### 2.3. Thruster model

A first order model approximation of the propeller thrust  $T$  is used. This approach was taken by Blanke (1981) who used lift forces calculations as the basis for approximation of the open propeller diagram. The performance of the propeller will be a function of the speed of water, propeller revolutions per second  $n$  and propeller diameter  $D$ . The non dimensional open water characteristics are defined in terms of the open water advance coefficient (Fossen, 1991):

$$J_0 = V_a / (nD) \quad (5)$$

The relative speed of water going into the propeller is given by:

$$V_a = (1 - \omega)U \quad (6)$$

Where  $\omega$  is the wake fraction number (0.1 – 0.4) and  $U$  is the forward speed of the ROV.

The positive thruster force is given by the following equation:

$$T = \rho_w D^4 K_T (J_0) |n|n \quad (7)$$

The non-dimensional propeller thrust coefficient  $K_T$  is a function of the advance number and can be represented in a graphic like the one in Fig. 5 (Fossen, 1991).

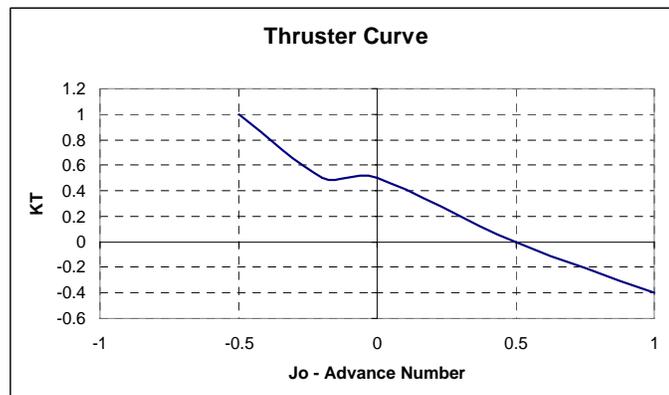


Figure 5: Thruster curve

## 2.4. Manipulator model

Figure 6 shows the multibody model of the ROV's seven function manipulator into ADAMS/View. The manipulator is composed of seven bodies and seven revolute joints. The joints connecting the parts can be seen in Fig. 6. All the parts are connected using revolute joints (one rotational degree of freedom).

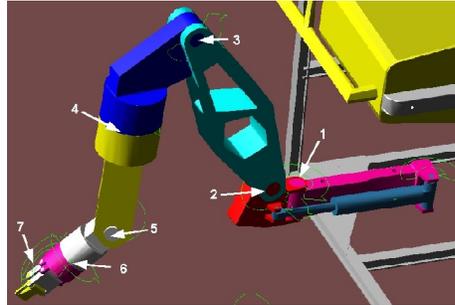


Figure 6: ROV's seven function manipulator.

Figure 7 shows the multibody model of the ROV's five function manipulator into ADAMS/View. This manipulator is composed of five bodies and four revolute joints and one translational joint.

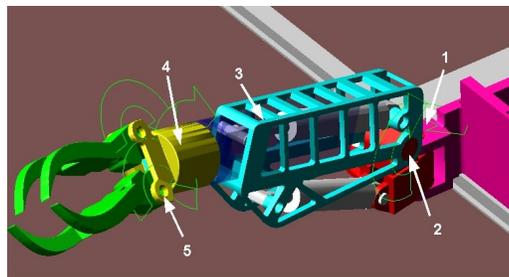


Figure 7: ROV's five function manipulator.

For both manipulators a PID (Proportional, Integral and Derivative) torque controller was developed in order to control the angles (a servo motor control) of the manipulators' arms and grippers.

Figure 8 shows two joysticks used to control the master and slave manipulators.

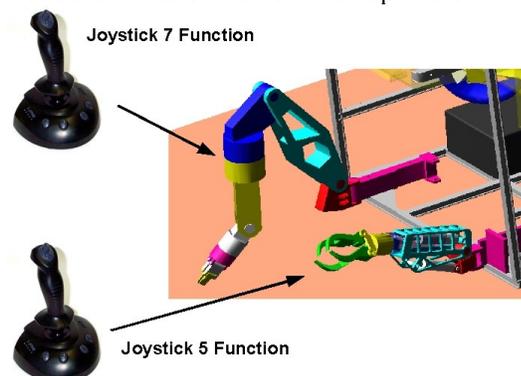


Figure 8: Joysticks to control the manipulators.

## 2.5. Tether model

The tether is a long elastic structural member that can only sustain tensile loads and may have length-varying properties. We represented the tether by a finite element model, dividing it small parts and connecting them via beam

elements. A finite element implementation was chosen because it is versatile and can model the complicated characteristics of tethered cable systems. Figure 9 shows the finite element tether cable and the beam element connecting the parts.

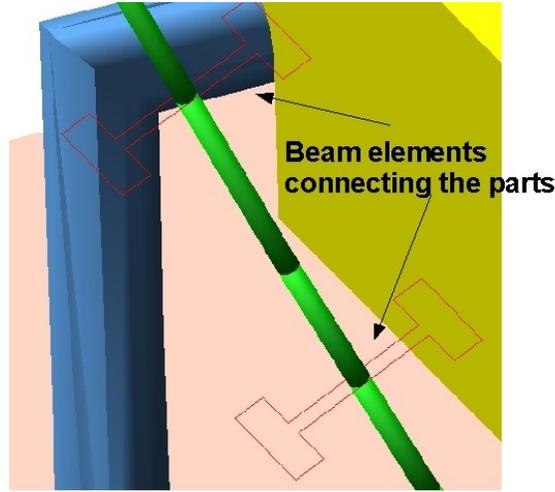


Figure 9: Discretized element model of the tether cable using beam elements.

The following constitutive equations define how MSC.Adams uses the data for a linear beam to apply a force and a torque to the parts. The force and torque it applies depends on the displacement and velocity between two parts. The constitutive equations are analogous to those in the finite element method:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{bmatrix} = \begin{bmatrix} K_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{22} & 0 & 0 & 0 & K_{26} \\ 0 & 0 & K_{33} & 0 & K_{35} & 0 \\ 0 & 0 & 0 & K_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & K_{55} & 0 \\ 0 & K_{62} & 0 & 0 & 0 & K_{66} \end{bmatrix} \begin{bmatrix} x-L \\ y \\ z \\ a \\ b \\ c \end{bmatrix} - \begin{bmatrix} C_{11} & C_{21} & C_{31} & C_{41} & C_{51} & C_{61} \\ C_{21} & C_{22} & C_{32} & C_{42} & C_{52} & C_{62} \\ C_{31} & C_{32} & C_{33} & C_{43} & C_{53} & C_{63} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{54} & C_{64} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{65} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

Each  $K_{ij}$  is defined in the following way:

$$K_{11} = \frac{EA}{LK_{22}} = 12 \frac{EI_{zz}}{[L^3(I + P_y)]}, K_{26} = -6 \frac{EI_{zz}}{[L^2(I + P_y)]}, K_{33} = 12 \frac{EI_{yy}}{[L^3(I + P_z)]}, K_{35} = 6 \frac{EI_{yy}}{[L^2(I + P_z)]} \quad (8)$$

$$K_{44} = \frac{GI_{xx}}{L}, K_{55} = \frac{(4 + P_z)EI_{yy}}{[L(I + P_z)]}, K_{66} = \frac{(4 + P_y)EI_{zz}}{[L(I + P_y)]}$$

Where:

$$P_y = 12 \frac{EI_{zz}}{(GAL^2)} ASY, P_z = 12 \frac{EI_{yy}}{(GAL^2)} ASZ \quad K_T \quad (9)$$

The parameters ASY and ASZ are the correction factor for shear deflection in the y and z direction respectively.

## 2.5. Human interface

The ROV simulator has a human interface to exchange the data inputs from joysticks and the MSC.Adams model. This human interface was implemented using the Virtual Toolbox available on MATLAB/Simulink software. This toolbox has a library that reads inputs from joysticks via USB port.

When the simulation runs MSC.Adams solver resolves the dynamic equations of the plant. The plant input and output are the variables that come back into MSC.Adams and the variables that go to the MATLAB/Simulink. These definitions are made a priori inside the MSC.Adams model.

Two joysticks are used: one is used to control the thrusters of the ROV and the other is used to control the manipulator and the gripper. Fig. 10 shows the configuration of MATLAB/Simulink and MSC.Adams models. The thruster model was included into the MATLAB/Simulink because it is more convenient to test the thruster parameters and, in the future, implement a thruster controller.

As can be seen in the Fig. 10 the outputs are position, longitudinal velocity, acceleration, forces and torques. The outputs variables are visualized in real time through the charts inside the MSC.Adams/View. Also, the output data are recorded on the MATLAB workspace for further analysis.

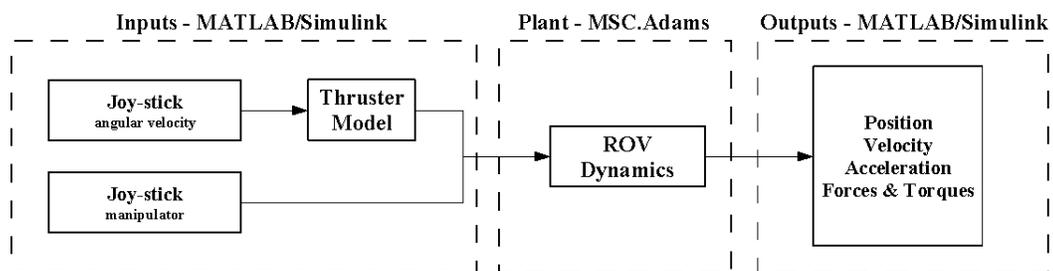


Figure 10: Co-simulation between MATLAB/Simulink and MSC.Adams.

## 3. RESULTS

The simulator can be seen in Fig. 11, which is composed of two joysticks for the manipulators (left and right) and one joystick for controlling the thrusters. Two persons are necessary to control the ROV (manipulator plus thrusters). Four LCD displays are implemented and they show simultaneously the operation.

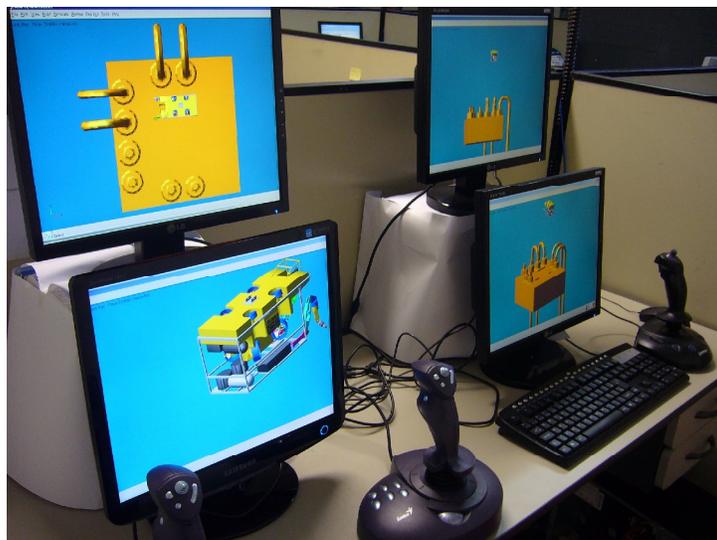


Figure 11: Simulator with 4 LCD displays and three joysticks (2 for ROV manipulators and 1 for control of the thrusters)

An experimental validation was performed based on experimental data supplied by Petrobras in the Campos Basin. The trajectory of the ROV is shown in Fig 13. The simulator performed very well (in a real time simulation) using a desktop computer with Pentium IV microprocessor, 2.6 GHz, dual core with 8 GB RAM and two accelerated board graphics display GEFORCE.

Figures 14, 15 and 16 show the yaw angle, heave and surge displacements of the ROV. Red line is simulated and the blue line is the experimental data. The simulated and experimental data are very close, showing that the virtual model has a dynamic behavior very close to the real ROV. The corresponding angle and displacement of the ROV can be seen in Fig. 12.

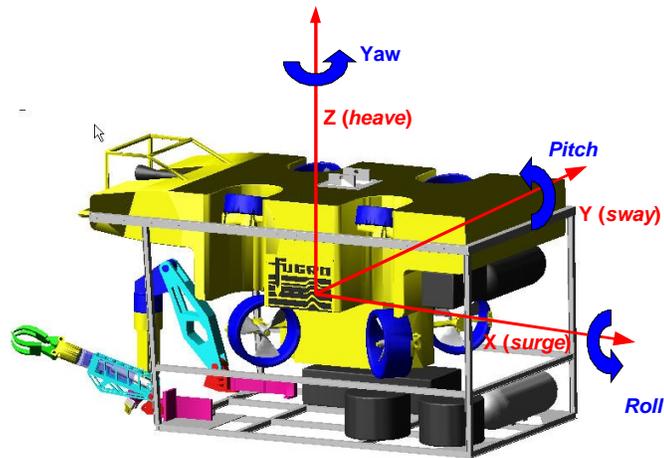


Figure 12: ROV angles and displacement convention

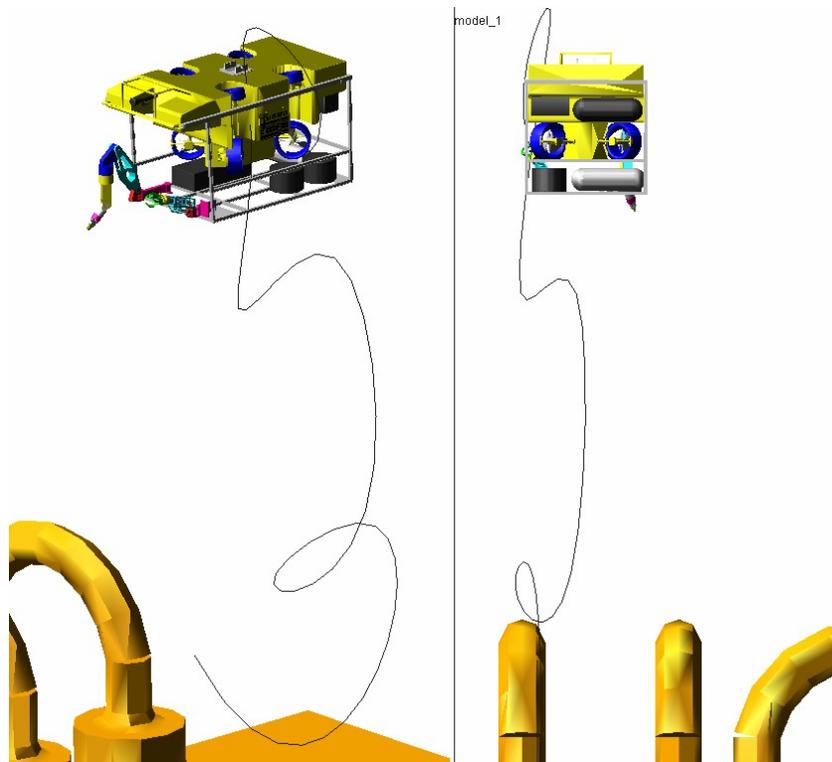


Figure 13: Experimental trajectory performed by the ROV. Data supplied by Petrobras, Campos Basin.

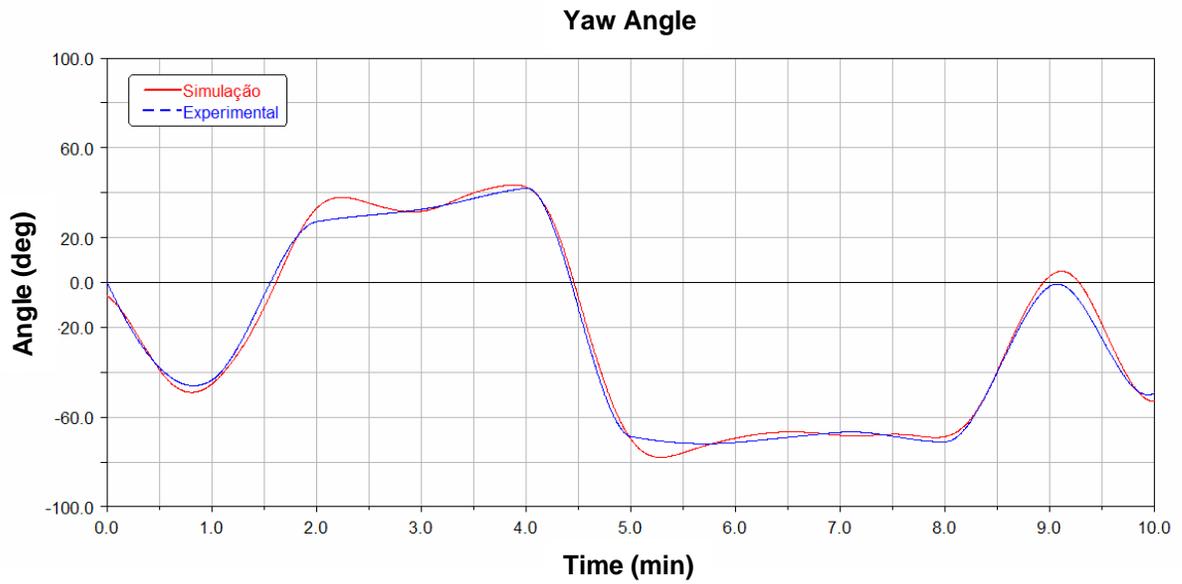


Figure 14: Yaw angle of the ROV during the simulation.

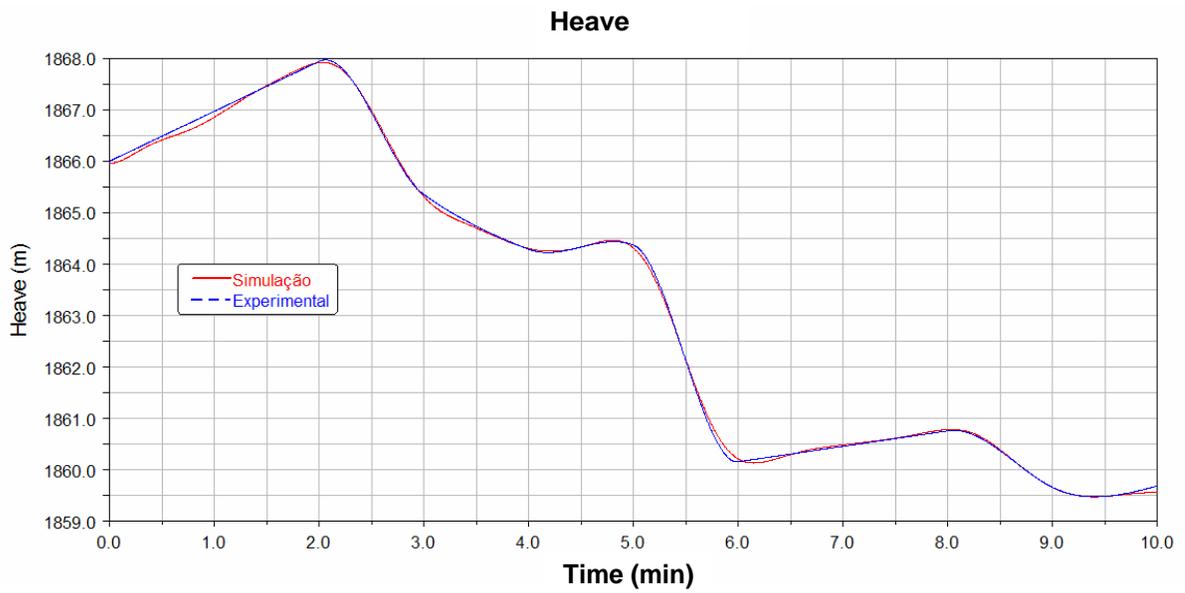


Figure 15: Heave displacement of the ROV during the simulation.

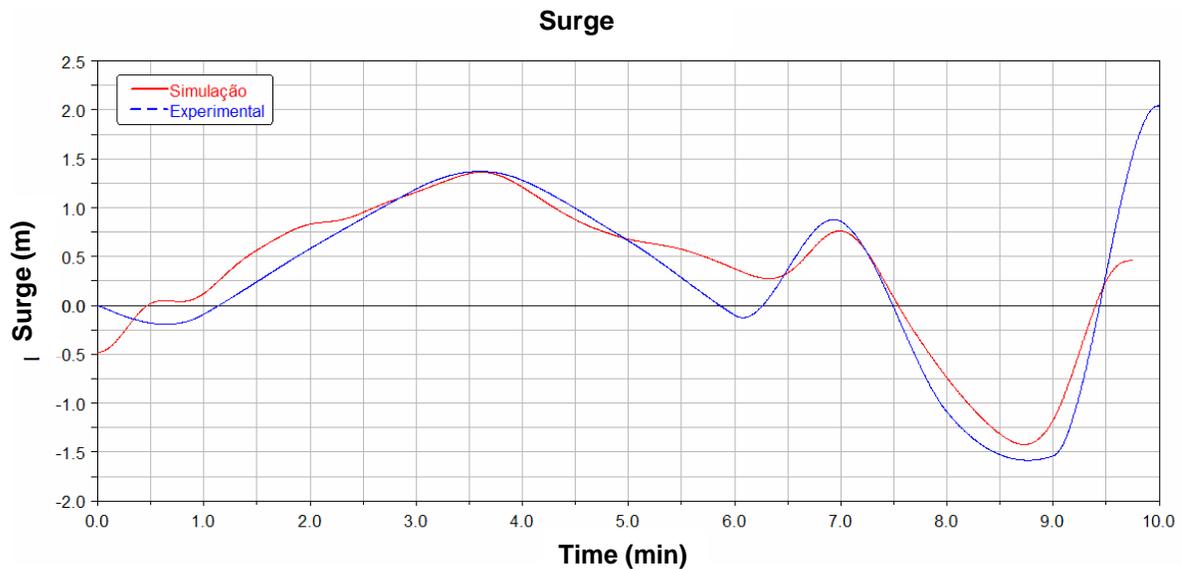


Figure 16: Surge displacement of the ROV during the simulation.

#### 4. CONCLUSIONS

The ROV's simulator implemented in this work used a general multibody software and it is a new approach in real-time applications. The toolboxes available on the market use proprietary and hand written equations of the ROV and manipulators and any modifications you need to do, like a new ROV or a new manipulator, you will need to contact the company and pay for this new development. Besides, these software do not use an open architecture and the data exchange with other software is very difficult.

MSC.Adams is a well known software for multibody applications and can exchange data with many softwares on the market. The co-simulation analysis using MSC.Adams and Matlab/Simulink is very versatile because the user can develop your own model of the ROV and can build a very complex system, including a complex model of the manipulator and the thrusters. Also, the thruster controls can be developed inside the Matlab/Simulink.

The validation presented in this work is very simple but it demonstrates the feasibility of developing real time applications using commercial software that are very powerful in dynamic modeling (MSC.Adams) and controls (Matlab/Simulink).

#### 3. ACKNOWLEDGEMENTS

We want to acknowledge the financial support from FAPESP (Fundação de Amparo a Pesquisa do Estado de São Paulo), Petrobras (Cesar de Souza Lima and Ricardo Capplonch from Submarine Technology Group - TS), which help this work supplying ROV data and their technical knowledge.

#### 4. REFERENCES

- Driscoll, F.R., Lueck, R.G and Nahon, M. , 2000, "Development and Validation of a Lumped-Mass Dynamics Model of a Deep-Sea ROV System", Applied Ocean Research, Vol.22, pp. 169-182.
- Blanke, M. 1981, "Ship Propulsion Losses Related to Automated Steering and Prime Mover Control", PhD thesis, The Technical University of Denmark, Lyngby.
- Fossen, T.I. 1994, "Guidance and Control of Ocean Vehicles", Ed. John Wiley & Sons, Baffins Lane, Englando, 480 p.
- Gomes, R.M.F., Sousa, J.B., Pereira, F.L., 2003, "Modeling and Control of the IES Project ROV". <http://paginas.fe.up.pt/~lsts/draft/2003/74.pdf>
- Ridao, P., Ribas, D., Batlle and Hernández, E., 2004, "Simulation of Physical Agents. An Application to Underwater Robots", <http://www.xsens.com/download/papers/Simulation%20of%20physical%20agents.%20An%20application%20to%20Underwater%20robots.pdf>.
- Yuh, J., 1900, "Modeling and Control of Underwater Robotic Vehicles", IEEE Transactions on Systems, Man, And Cybernetics, Vol.20, No. 6, November, December, pp. 1475-1990..

## **5. RESPONSIBILITY NOTICE**

The authors are the only responsible for the printed material included in this paper.