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Results from Internship Conducted at DLR of a Berthing Maneuvers Simulator with the European Proximity Operations Simulator

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Abstract. *This study utilizes the available EPOS (European Proximity Operations Simulator) robots at DLR (German Aerospace Center) to exploit the concepts of hardware-in-the-loop and real-time simulations. Two physical robots play the role of chaser and target satellites involved in a berthing maneuver; the chaser satellite is coupled to a virtual robotic manipulator which is emulated by the implemented software. The developed robotic arm consists of a revolute manipulator with three rotating joints and three degrees of freedom moving in space. Such a configuration allows diverse applications in the accomplishment of On-Orbit Servicing. The experiments validated the developed algorithms and models. It was concluded that this work achieved success in the task of creating a reliable simulator for tests of berthing maneuvers.*

Keywords: Berthing Maneuvers; Hardware-in-the-loop; Space Robotics; On-Orbit Servicing.

1. Introduction

This work can be understood as a natural progress of those outcomes obtained in [Nardin 2015], where it was done an analysis of berthing maneuvers using the elaborated simulator that had its functionalities properly explored.

The work of [Santos 2015] addressed a scenario of a final rendezvous maneuver between spacecrafts. Additionally, it was considered a promising use of the rendezvous and docking simulator with hardware-in-the-loop (HIL) of the German Aerospace Center (DLR), which is called the European Proximity Operations Simulator (EPOS). This maneuver simulator has been used to test and validate proposed models.

The simulator uses two industrial robots to physically simulate the complete translational and rotational movement of two different satellites operating rendezvous and docking maneuvers. Moreover, all the guidance, navigation and control loop elements were developed and implemented in a simulation environment and tested in real-time at EPOS.

One of the robots would act as the actual chaser artificial satellite, equipped with its own control system, which serves as the base to the attached robotic manipulator – which, by its turn, is simulated by the computer-based software, seeking to achieve a target point within its work volume, target satellite, and thus characterizing a berthing maneuver.

In this case, the hardware-in-the-loop concept would be explored, aiming to ascertain the maneuver effectiveness. Results presented here have been shown to the scientific community in the report format [Nardin 2019] with great acceptance.

The aim of this work is to test the developed space environment software simulator for berthing maneuvers through real-time (RT - VxWorks operating system) and hardware-in-the-loop simulations using the European Proximity Operations Simulator (EPOS).

2. Methods

The robotic arm adopted here is an anthropomorphic robot (Torsional – Rotational – Rotational, Figure 1). From which we obtained equations to solve the direct and inverse kinematics, i.e., given the desired position to the end effector we find the joint angles able to take the robot's claw to that position and vice-versa.

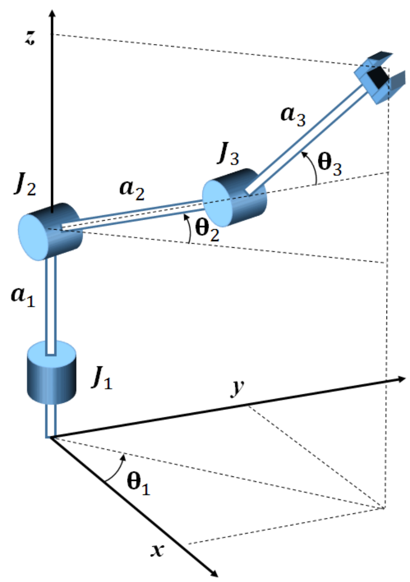

Figure 1. Robotic arm [Nardin 2015].

It is used Equations 1, 2 and 3 for inverse kinematics and Equations 4, 5 and 6 for direct kinematics, considering each joint respectively from 1 to 3.

$$\theta_1 = \arctan \frac{y}{x} \tag{1}$$

$$\theta_2 = \arctan\left[\frac{(z-a_1)(a_2+a_3\cos\theta_3)-\sqrt{x^2+y^2}\,a_3\sin\theta_3}{\sqrt{x^2+y^2}\,(a_2+a_3\cos\theta_3)+(z-a_1)a_3\sin\theta_3}\right] \tag{2}$$

$$\theta_3 = \arccos\left(\frac{x^2 + y^2 + (z - a_1)^2 - a_2^2 - a_3^2}{2a_2 a_3}\right) \tag{3}$$

$$x = [a_2 \cos\theta_2 + a_3 \cos(\theta_2 + \theta_3)]\cos\theta_1 \tag{4}$$

$$y = [a_2 \cos\theta_2 + a_3 \cos(\theta_2 + \theta_3)]\sin\theta_1 \tag{5}$$

$$z = a_1 + a_2 \sin\theta_2 + a_3 \sin(\theta_2 + \theta_3) \tag{6}$$

It is used the iterative Newton-Euler to calculate torques along the manipulator movement. The algorithm works in two stages: Outward and inward [Craig 2005] and [Ellery, 2000]. Equations for Outward:

$${}^{i+1}\vec{\omega}_{i+1} = {}^{i+1}_{i}\mathbf{R}\,{}^{i}\vec{\omega}_i + \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} \tag{5}$$

$${}^{i+1}\dot{\vec{\omega}}_{i+1} = {}^{i+1}_{i}\mathbf{R}\,{}^{i}\dot{\vec{\omega}}_i + {}^{i+1}_{i}\mathbf{R}\,{}^{i}\vec{\omega}_i \times \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} + \ddot{\theta}_i\,{}^{i+1}\hat{Z}_{i+1} \tag{6}$$

$${}^{i+1}\dot{\vec{v}}_{i+1} = {}^{i+1}_{i}\mathbf{R}({}^{i}\dot{\vec{\omega}}_i \times {}^{i}\vec{P}_{i+1} + {}^{i}\vec{\omega}_i \times ({}^{i}\vec{\omega}_i \times {}^{i}\vec{P}_{i+1}) + {}^{i}\dot{\vec{v}}_i) \tag{7}$$

$${}^{i+1}\dot{\vec{v}}_{C_{i+1}} = {}^{i+1}\dot{\vec{\omega}}_{i+1} \times {}^{i+1}\vec{P}_{C_{i+1}} + {}^{i+1}\vec{\omega}_{i+1} \times ({}^{i+1}\vec{\omega}_{i+1} \times {}^{i+1}\vec{P}_{C_{i+1}}) + {}^{i+1}\dot{\vec{v}}_{i+1} \tag{8}$$

$${}^{i+1}\vec{F}_{i+1} = m_{i+1}\,{}^{i+1}\dot{\vec{v}}_{C_{i+1}} \tag{9}$$

$${}^{i+1}\vec{N}_{i+1} = {}^{C_{i+1}}I_{i+1}\,{}^{i+1}\dot{\vec{\omega}}_{i+1} + {}^{i+1}\vec{\omega}_{i+1} \times {}^{C_{i+1}}I_{i+1}\,{}^{i+1}\vec{\omega}_{i+1} \tag{10}$$

Equations for Inward*:*

$${}^{i}\vec{f}_i = {}^{i}_{i+1}\mathbf{R}\,{}^{i+1}\vec{f}_{i+1} + {}^{i}\vec{F}_i \tag{11}$$

$${}^{i}\vec{n}_i = {}^{i}\vec{N}_i + {}^{i}_{i+1}\mathbf{R}\,{}^{i+1}\vec{n}_{i+1} + {}^{i}\vec{P}_{C_i} \times {}^{i}\vec{F}_i + {}^{i}\vec{P}_{i+1} \times {}^{i}_{i+1}\mathbf{R}\,{}^{i+1}\vec{f}_{i+1} \tag{12}$$

Figure 2 presents the ensemble formed by cubic shape base satellite plus robotic manipulator. The physical characteristics of each manipulator's link and satellite are provided by Table 1.

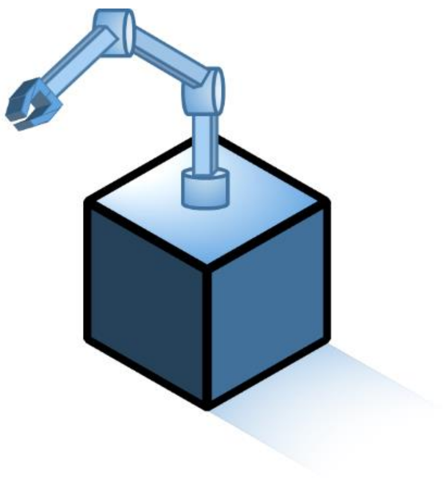

Figure 2 - Ensemble arm and satellite (out of scale) [Nardin 2015].

Table 1. Physical characteristics [Nardin 2015].

	Length(m)	Width (m)	Height (m)	Mass (kg)
Link 0	0.5	0.1	0.1	40
Link 1	1	0.1	0.1	20
Link 2	1	0.1	0.1	20
Satellite	2	2	2	500

The EPOS facility comprises two industrial robots. They are separated by 0 to 25 meters, which are utilized on realistic simulations of rendezvous and docking process, Figure 3. In general, experiments of integration, testing and verification are performed in the Hardware-In-the-Loop EPOS at the German Aerospace Center (Deutsche Zentrum für Luft-und Raumfahrt - DLR) in Oberpfaffenhofen, Germany.

This facility has been described as an important tool and its potential has been exploited through many tests campaign, including end-to-end simulation environment for rendezvous maneuvers [Benninghoff et al. 2018].

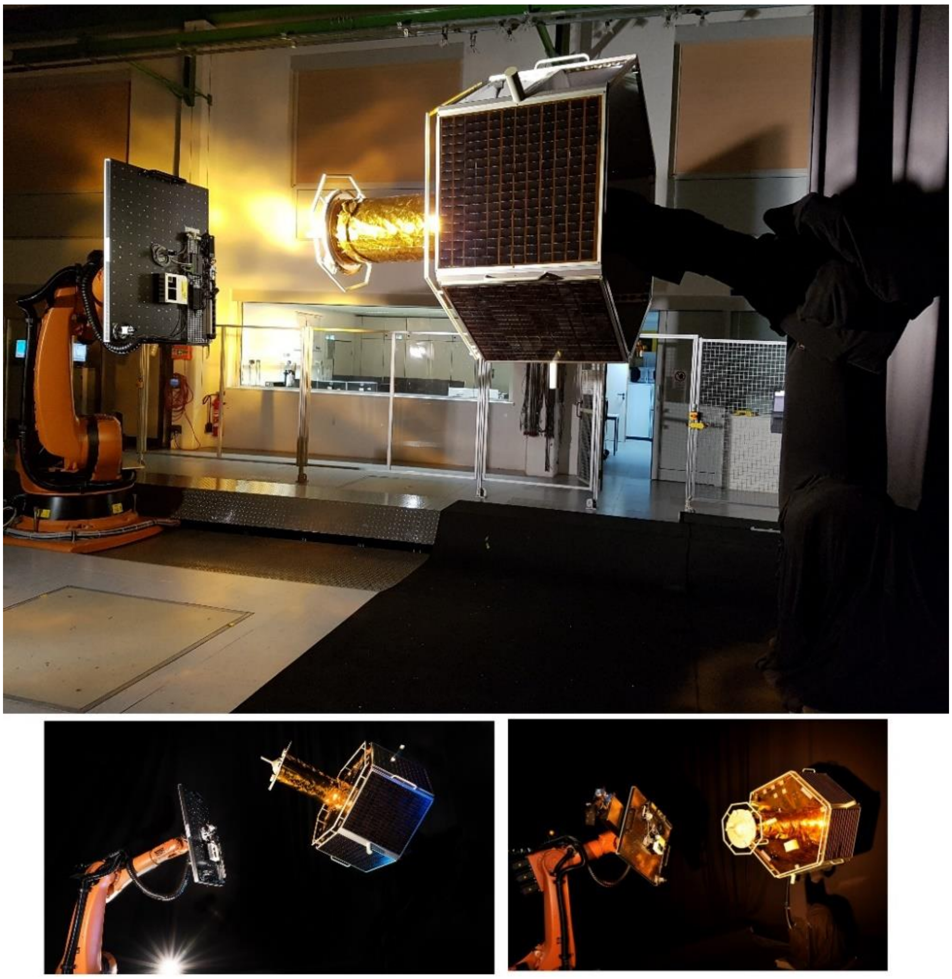

Figure 3 - EPOS Robots.

3. Results and Discussion

Results discussed here can be found in the internship report [Nardin 2019] as part of the outcomes presented to the funding agency.

Figure 4 shows the triggers when the target vector was defined to be inside the virtual manipulator workspace to demonstrate that it was able to reach such a point.

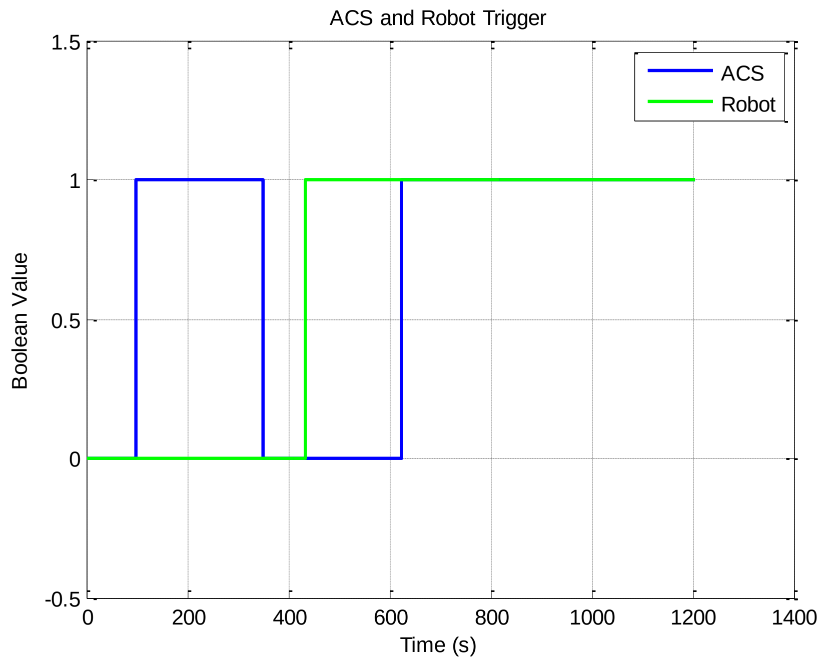

Figure 4 - ACS and robot trigger with target in workspace.

To prove the target point was reached by the virtual manipulator end effector, we can see in Figure 5 the distance error tending to zero. That means the algorithm worked correctly, this can be confirmed by Figure 6 where the joints velocities are presented and at some point, all joints had null velocity at the same time.

To evaluate the satellite control system, Figure 7, 8 and 9 show its behavior along time due to multiple triggers. Figure 10 presents in a tridimensional space how the arrangement center of mass has changed along the simulation.

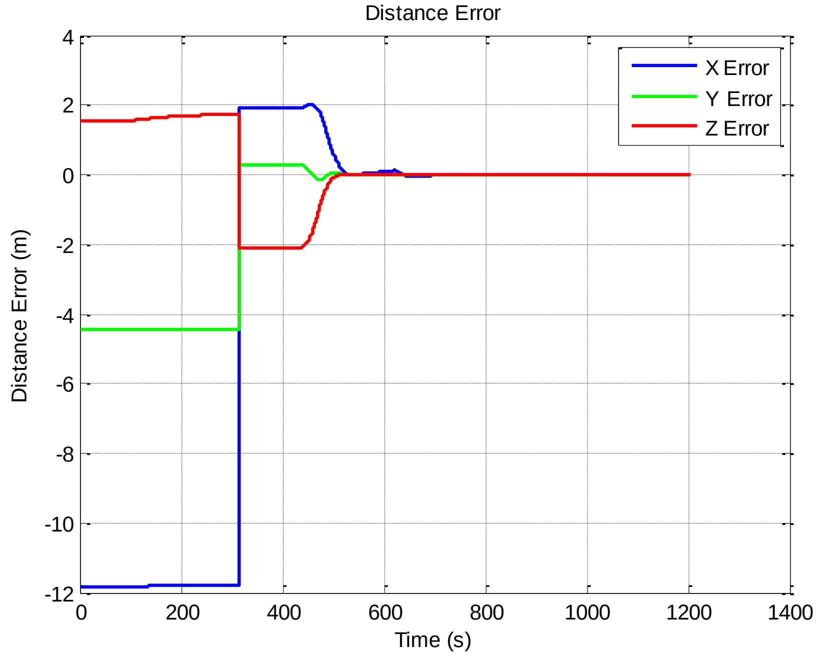

Figure 5 - Distance error to the target.

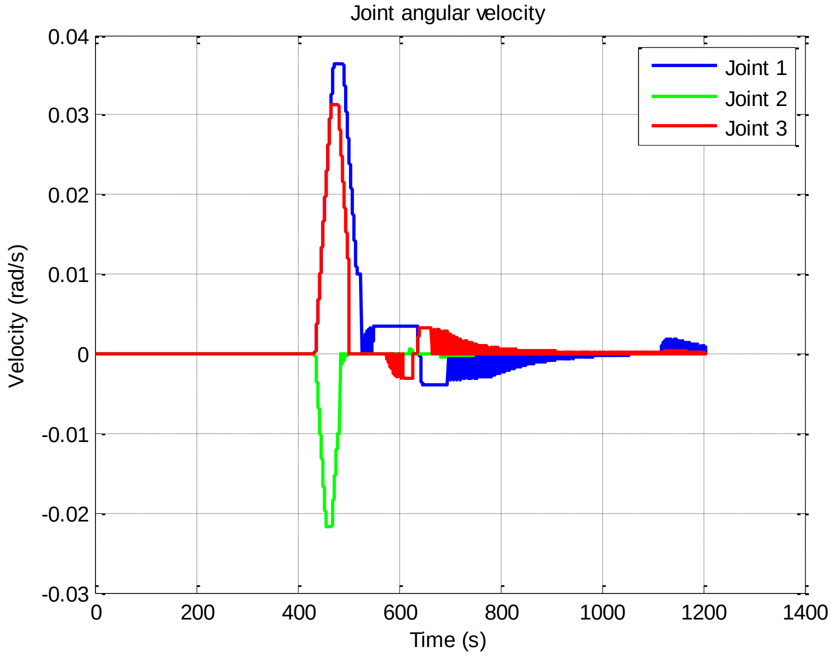

Figure 6 - Joint angular velocities.

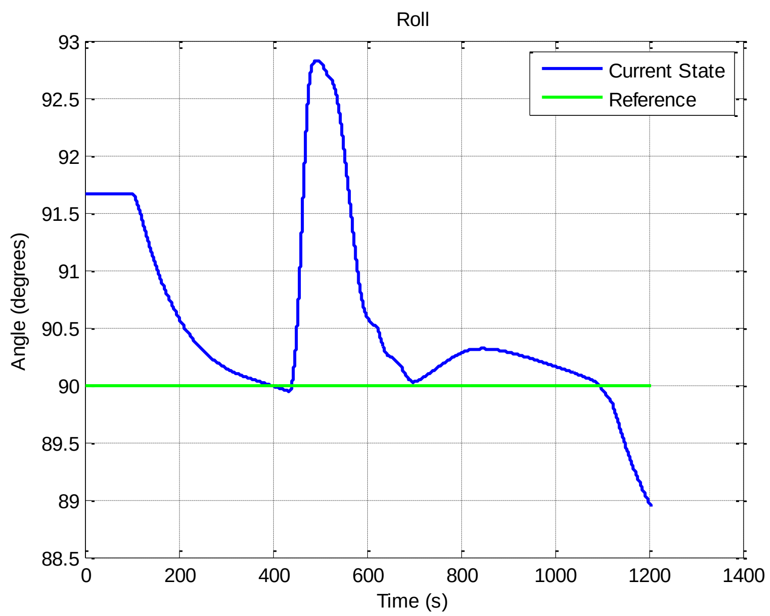

Figure 7 - Angle in roll.

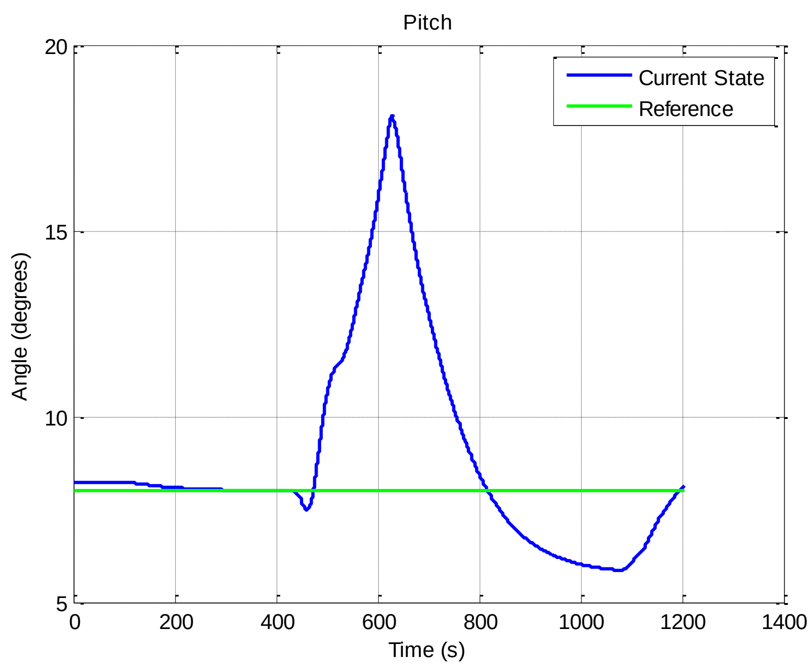

Figure 8 - Angle in pitch.

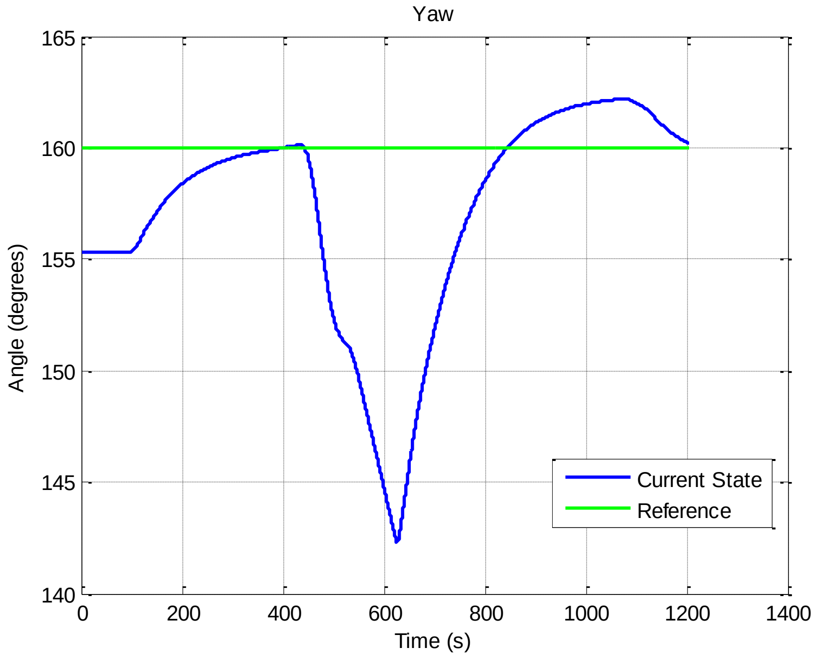

Figure 9 - Angle in yaw.

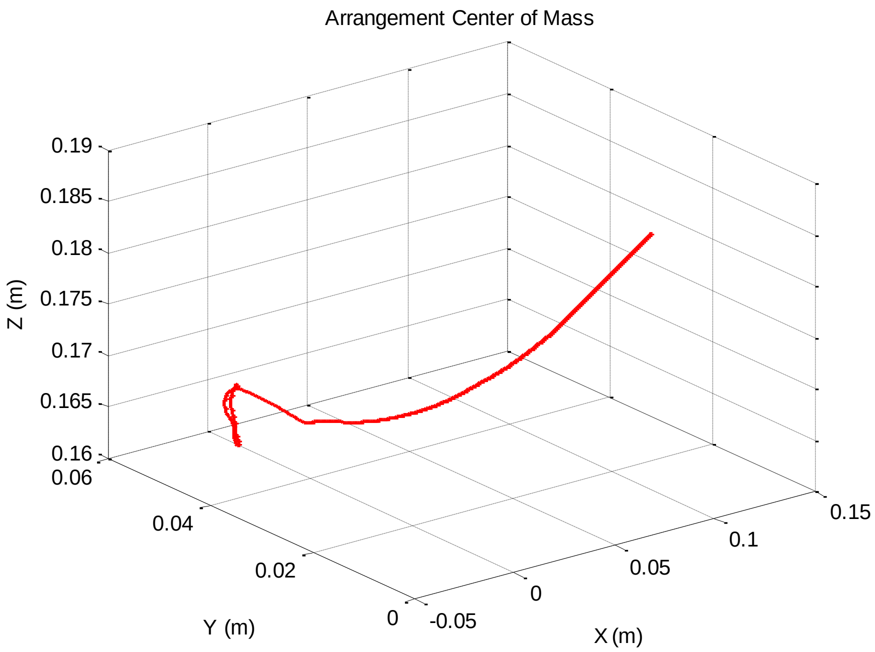

Figure 10 - Arrangement center of mass in 3D.

4. Conclusions

The experiments described were useful to prove the validity of the developed algorithms and inspired the creation of a concept of "Phantom Limb" for spacecrafts endowed with robotic manipulators when tested in these circumstances since at some point we could see the robot, which played the role of a chaser satellite, moving despite its propulsion and control system was turned off. We can conclude that such movement was due to the virtual manipulator, which was not there physically, displacement along time.

After all tests and simulations described, we can say this work achieved complete success in the task of creating a reliable software environment for tests of berthing maneuvers to be executed together with EPOS robots at DLR.

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