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# TEMA: MOBILE MANIPULATOR ROBOT CONTROL THROUGH VIRTUAL HARDWARE IN THE LOOP

**AUTORES:**

**Byron Stalin Jorque Rea**
**Jéssica Daniela Mollocana Jiménez**

**TUTOR:**

**Ph.D Víctor Hugo Andaluz Ortiz**

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# Mobile Manipulator Robot Control Through Virtual Hardware in the Loop

Byron S. Jorque(✉), Jéssica D. Mollocana(✉), Jessica S. Ortiz(✉),
and Víctor H. Andaluz(✉)

Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador
{bsjorque,jamollocana,jsortiz4,vhandaluz1}@espe.edu.ec

**Abstract.** This article focuses on the implementation of the Hardware-in-the-Loop technique to evaluate advanced control algorithms to a mobile manipulator robot that comprised of 3DOF anthropomorphic type robotic arm mounted on a unicycle type platform. The implementation of HIL includes the use of Unity 3D graphic engine for the development of a virtual environment that allows to visualize the execution of the movements of the robot through the implemented control algorithm. In addition, it is considered the kinematic model and dynamic model of the robot that represent the characteristics and restrictions of movement of the mobile manipulator robot. Finally, experimental results achieved through the implementation of the HIL technique are presented, in which the behavior of the robotic system and the evolution of control errors when executing locomotion and object manipulation tasks can be verified.

**Keywords:** HIL · Mobile Manipulator · Algorithm controller · Kinematic · Dynamic

## 1 Introduction

Robotics have evolved in the last decades to the point that it is essential in the industry for the automation of production lines. Autonomous robots execute repetitive tasks with great velocity and precision [1, 2]. However, the current challenge in robotics is to transcend from industrial robotics to service robotics, in which robots are specifically designed for the service of mankind [3]. Service robotics is a field that focuses on assisting humans outside the industrial environment. For instance, they can perform domestic, security, surveillance, and transportation tasks. Service robotics is additionally an active field of research due to its numerous personal and professional applications. For example, they can be used as servants, company robots, and nursing aid robots [6]. Other uses of service robots may use multiple actuators; for instance, the cooperative control of mobile manipulators [4], or human - robot collaboration [5]. Finally, there are robots specifically designed for a task. In this way, robots can be aerial, aquatic, and terrestrial, and they can move using wheels, legs, fins, and propellers [7].

There are complex tasks that require both locomotion and manipulation. That is why new kinds of robots are being developed, which combine both functionalities; they are

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called mobile manipulators [10]. In other words, a mobile manipulator is a mechanic structure comprised of a robotic arm coupled with a locomotion system [8]. This kind of robots, therefore, combine the dynamic aspect of the platform with the ability of object manipulation of the arm [8]. This in turn makes the robot more versatile since it has more work range and flexibility [9]. Nowadays, mobile manipulators are used in several fields, providing services like domestic cleaning, personal assistance [11], and working in the construction and mining industries [12].

Between the techniques used to control a mobile manipulator robot is the execution of the complete simulation, construction of the robot and the implementation of the controller in hardware and that developed in recent years; Hardware in the Loop. HIL is a new alternative for the control of complex physical systems [13], which includes the development of a real time simulation environment to test processes. For the development of a HIL environment it is essential to incorporate into software the mathematical models that represent a physical system and physical hardware devices that act as controllers [14]. In this way, simulation platform is obtained that emulates a real process and at the same time provides the control unit, electrical signals similar to those obtained from a real process.

There are several control techniques for mobile manipulators, such as complete simulation, mechanical construction, and Hardware in the Loop (HIL), which is the most recent one. The later one is a new alternative for the development of simulation environments, and the control of complex physical systems [13]. This technique is not limited to the software representation of the system or the complete implementation, which can be expensive, but rather it combines the advantages of both techniques. HIL incorporates the mathematical models that represent a physical system with the hardware that control the behavior of the robot [14]. HIL also allows including additional physical devices that interact with the simulated environment [15]. In this way, a robust simulation platform is obtained, which emulates a real process and provides control units with electrical signals that are similar to those of a real process.

In this paper we present the implementation of the technique of Hardware in the Loop for the autonomous control of a mobile manipulator robot that comprised of a robotic arm mounted on a mobile platform type unicycle. For the implementation of the Hardware in the Loop technique, the development of a virtual environment in the Unity 3D graphic engine is considered [16, 17] that allows to visualize the behavior of the robot when executing autonomous tasks. The proposed control scheme considers a cascade system consisting of 2 subsystems. The first subsystem considers a kinematic controller, while the second subsystem comprises a dynamic compensation to decrease the velocity and tracking error. Also, it is analyzed the stability and robustness of the control algorithm proposed through Lyapunov's theory considering as perturbations errors in the maneuvering velocities. Finally, several results obtained by implementing the HIL technique are presented, evaluating the behavior of the control algorithms and the evolution of control errors, which converge asymptotically to zero when there are no disturbances and is limited when considering disturbances in the maneuverability commands.

This article is presented in 6 sections, including the Introduction. In the second section, the structure of the HIL environment can be appreciated, as well as the communication channels. Section 3 shows the kinematic and dynamic modeling of the mobile manipulator, considering its characteristics and movement restrictions. Section 4 details the design of the control algorithm, as well as the stability and robustness analysis for the validation of the controller. Experimental results are shown in Sect. 5, and finally Sect. 6 shows the conclusions.

## 2 System Structure

In this section, the structure of the implemented HIL environment is detailed. Figure 1 shows the HIL scheme, which is comprised of three blocks: real time simulation, communication channel and end hardware.

HIL environment is carried out in the Unity-3D graphic engine, as well as external resources such as the CAD software, and additional input and output devices. The CAD software contains the configurations of the real robot and the 3D models of the environment that resembles a factory where the robot is tested. The virtual environment then allows visualizing the locomotion and object manipulation actions taken by the robot.

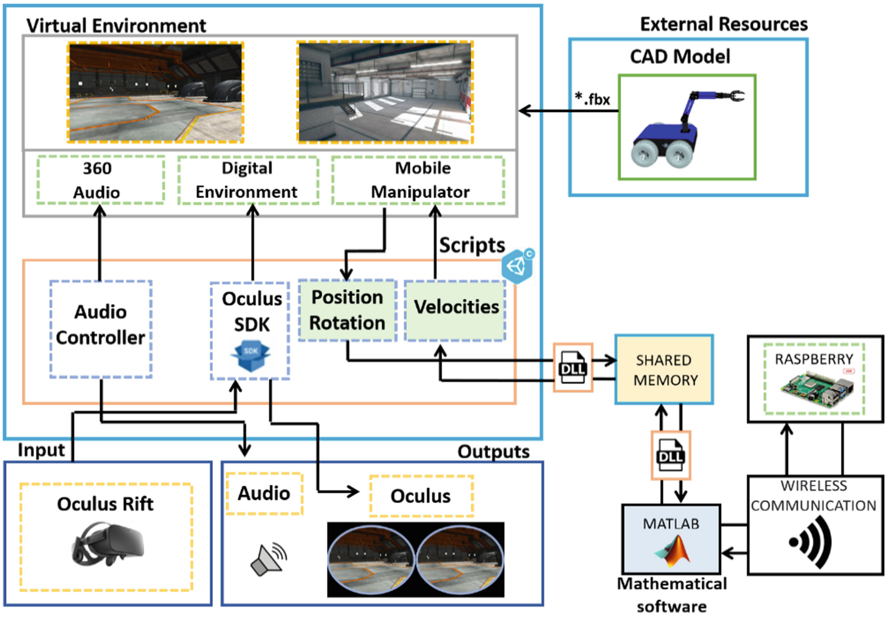


Fig. 1. Hardware in the loop.

Hill technique also allows connecting the virtual environment with additional I/O devices using a set of scripts. The purpose of the I/O devices is to have visual and auditive feedback of the proper functionality of the robot. The control algorithm is embedded in a low-cost Raspberry-Pi board, which executes and sends the control actions wirelessly using the ZigBee protocol to Matlab.

The link with Matlab is carried out using a Dynamic Link Library (DLL), which allows different software to exchange information through shared memory. This memory enables introducing the control actions of the mobile manipulator inside the simulation environment. In this way, the controller sends the proper control actions at a given time, and receives feedback from the simulation to compute the corresponding error.

## 3 Mobile Manipulator Robot

This section shows the kinematic and dynamic modeling of a mobile manipulator robot. The robot is comprised of a mobile platform and a robotic arm, which are considered as a single robotic system. Those elements also determine restriction and motion characteristics of the robot.

The kinematics of a robot is given by its position and orientation with respect to its working environment, the geometrical relationship between its components, as well as motion restrictions [18]. Figure 2 illustrates the configuration of the mobile manipulator robot that was used in this work. The point $p$ expresses the position of the robot, $\mathbf{h}$ is the interest point, which represents the position and orientation of the manipulator's end effector with respect to the reference frame $\{R\}$.

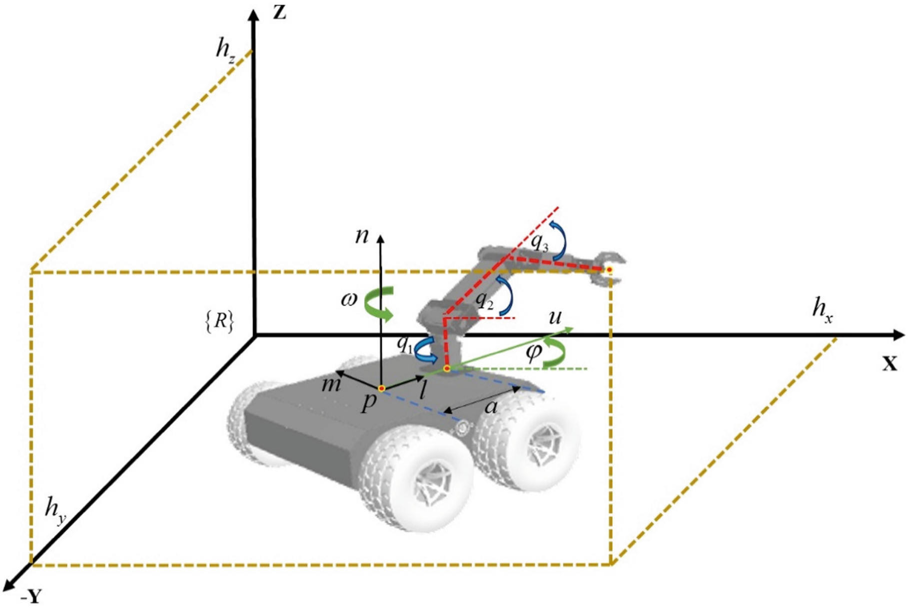


**Fig. 2.** Configuration of the mobile manipulator robot.

The kinematic model of the robot is obtained by applying the derivative to the end effector. The position and orientation of the end effector are expressed as a function of the position of the mobile platform and the configuration of the robotic arm.

$$\dot{\mathbf{h}}(t) = \mathbf{J}(\mathbf{q})\mathbf{v}(t), \tag{1}$$

where $\mathbf{v} = \begin{bmatrix} \dot{h}_x\ \dot{h}_y\ \dot{h}_z \end{bmatrix}^T$ is the end effector's velocity vector, $\mathbf{v} = \begin{bmatrix} \mu\ \omega\ \dot{q}_1\ \dot{q}_2\ \dot{q}_3 \end{bmatrix}^T$ is the robot's velocity vector, $\mathbf{q} = \begin{bmatrix} x\ y\ \varphi\ q_1\ q_2\ q_3 \end{bmatrix}$ is the position vector, and $\mathbf{J}(\mathbf{q})$ is the Jacobian matrix that stablishes a linear relationship between velocities, and is based on the rotation angles of the joints in the manipulator [18].

Robot characteristics and motion restrictions are represented by the Jacobian matrix. For instance, motion restrictions are given by:

$$\dot{x}\sin(\varphi) - \dot{y}\cos(\varphi) + a\omega = 0, \tag{2}$$

where $\dot{x}$ and $\dot{y}$ are the velocities of the mobile platform over the $x$ and $y$ axis, $a$ is a constant that defines the distance between the base of the robotic arm and the mobile platform point $p$ of coordinates $(x, y)$, and $\omega$ represents the angular velocity of the mobile platform with respect to the $z$ axis. All of this in relationship with the reference frame $\{R\}$.

On the other hand, in order to determine the motion characteristics of the mobile manipulator at executing tasks, it is important to define the dynamics of the robotic system. This is carried out using the Euler-Lagrange proposal, given by:

$$L = K - P, \tag{3}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\mathbf{q}}}\right) - \frac{\partial L}{\partial \mathbf{q}} = \boldsymbol{\tau}, \tag{4}$$

where $L$ is the Lagrange function, which defines the balance between kinetic and potential energies of the different elements of the robot, and $\tau$ is the torque vector applied to the robot, i.e. the torque due to the translation and rotation of the robot. By associating (3) and (4), the matrix model (5) is obtained. It contains all the forces generated by the robot:

$$\mathbf{M}(\mathbf{q})\dot{\mathbf{v}}(t) + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\mathbf{v}(t) + \mathbf{g}(\mathbf{q}) = f(t), \tag{5}$$

using (5), the motion equations of the actuators are included, as well as the robot's configuration. In this way, the expression for the dynamical model is derived:

$$\mathbf{M}(\mathbf{q})\dot{\mathbf{v}}(t) + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\mathbf{v}(t) + \mathbf{g}(\mathbf{q}) = \mathbf{v}_{ref}(t), \tag{6}$$

where $\mathbf{M}(\mathbf{q})$ is the Inertial matrix; $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the matrix of centripetal force and Coriolis, $\mathbf{g}(\mathbf{q})$ is the gravitational vector, which represents the effects of gravity on the robot's components, and $\mathbf{v}_{ref}(t)$ is the vector of control velocity.

## 4 Control Scheme

This section presents the design of the control algorithm, which is comprised of a kinematic control and a dynamic compensator. The former is based on the robot´s kinematics while the later has the objective to reduce the velocity error by compensating its dynamics. Additionally, the stability and robustness of the proposed controller is analyzed in this section. Figure 3 illustrates the control scheme for the mobile manipulator robot implemented using HIL.

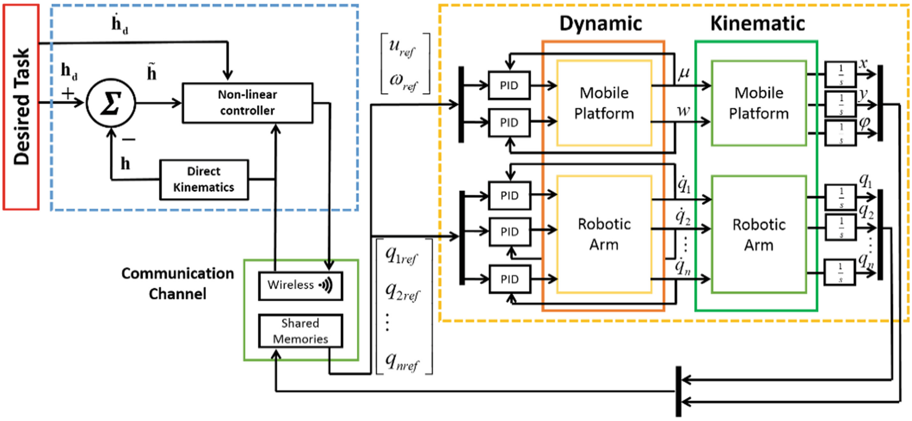


**Fig. 3.** Autonomous control scheme.

## 4.1 Kinematic Control

The kinematic model of the robotic mechanism (1) contributes to the development of the kinematic controller. The velocity vector of the robot can be expressed as the velocity vector of the end effector using the pseudo-inverse of the Jacobian matrix.

$$\mathbf{v}(t) = \mathbf{J}^{\#}(\mathbf{q})\dot{\mathbf{h}}(t) \tag{7}$$

where, $\mathbf{J}^{\#}(\mathbf{q}) = \mathbf{W}^{-1}\mathbf{J}^{T}\left(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}^{T}\right)^{-1}$ and $\mathbf{W}$ is a positive symmetric matrix that exerts the control actions. Thus, the velocity vector is given by:

$$\mathbf{v}(t) = \mathbf{W}^{-1}\mathbf{J}^{T}\left(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}^{T}\right)^{-1}\dot{\mathbf{h}}(t) \tag{8}$$

Therefore, the control law that commands the velocities of the manipulator, as well the desired trajectory of the robot, is formulated:

$$\mathbf{v}_c = \mathbf{J}^{\#}\left(\dot{\mathbf{h}}_{\mathrm{d}} + \mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right)\right) + \left(\mathbf{I} - \mathbf{J}^{\#}\mathbf{J}\right)\mathbf{D}\tanh(\boldsymbol{\eta}) \tag{9}$$

where, $\mathbf{h}_{\mathrm{d}}$ is the vector of desired positions, $\dot{\mathbf{h}}_{\mathrm{d}}$ is the vector of desired velocities at operative extreme, $\tilde{\mathbf{h}}$ represents the control error given by $\tilde{\mathbf{h}} = \mathbf{h}_{\mathrm{d}} - \mathbf{h}$; $\mathbf{K}$ and $\mathbf{D}$ are defined positive gain matrices, and finally $\boldsymbol{\eta}$ defines the position error vector of the robotic arm, its function is to obtain maximum manipulability [19].

Once the control law based on the kinematic model has been established, it is important to grant its stability. For this purpose, the behavior of error control $\tilde{\mathbf{h}}$ is carried out, considering a perfect velocity tracker $\mathbf{v} = \mathbf{v}_c$. By replacing (9) in (1), the following expression is obtained:

$$\dot{\tilde{\mathbf{h}}} + \mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right) = 0 \tag{10}$$

For the stability analysis, the following function is considered a candidate Lyapunov $V\left(\tilde{\mathbf{h}}\right) = \frac{1}{2}\tilde{\mathbf{h}}^T\tilde{\mathbf{h}}$; where its first time derivate in defined as $\dot{V}\left(\tilde{\mathbf{h}}\right) = \tilde{\mathbf{h}}^T\dot{\tilde{\mathbf{h}}}$. Now replacing (10) in the Lyapunov candidate function is obtained:

$$\dot{V}\left(\tilde{\mathbf{h}}\right) = \tilde{\mathbf{h}}^T\mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right) \tag{11}$$

this equation implies that the closed loop control system is asymptotically stable; such that $\tilde{\mathbf{h}}(t) \to 0$ con $t \to 0$.

## 4.2 Dynamic Compensation

The dynamic compensation block has as objective reducing the velocity tracking error by compensating the dynamics of the system. The desired velocities $\mathbf{v}_c$ are fed to the controller for the dynamic compensation, and they originate the reference velocity for the mobile manipulator robot $\mathbf{v}_{ref}$. Thus the dynamic compensation is given by:

$$\mathbf{v}_c = \mathbf{J}^{\#}\left(\dot{\mathbf{h}}_{\mathrm{d}} + \mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right)\right) + \left(\mathbf{I} - \mathbf{J}^{\#}\mathbf{J}\right)\mathbf{D}\tanh(\boldsymbol{\eta}) \tag{12}$$

where, $\mathbf{v}_{ref} = \left[\begin{array}{ccccc} \mu_{ref} & \omega_{ref} & \dot{q}_{1ref} & \dot{q}_{2ref} & \dot{q}_{3ref} \end{array}\right]^T$ represent the control action; $\tilde{\mathbf{v}}$ defines the velocity error given by $\tilde{\mathbf{v}} = \mathbf{v}_c - \mathbf{v}$, and finally, $\dot{\mathbf{v}}_c$ is the vector accelerations.

Following the procedure, previously stablished in the stability analysis of the kinematic controller, and considering a Lyapunov candidate function as the quadratic error, it is possible to determine that $\tilde{\mathbf{v}}(t) \to 0$ asymptotically, when $t \to \infty$. This grants the stability of the proposed control law.

Similarly, performing a robustness analysis is a fundamental part of the implemented controller. This allows determining the validity of the control errors. Thus, we have that:

$$\dot{V}\left(\tilde{\mathbf{h}}\right) = \tilde{\mathbf{h}}^T\delta_{\dot{\tilde{\mathbf{h}}}} - \tilde{\mathbf{h}}^T\mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right) \tag{13}$$

where, $\delta_{\dot{\tilde{\mathbf{h}}}}$ is the variation difference between the desired velocity and the real ones. This is under the condition of perfect tracking defined as $\delta_{\dot{\tilde{\mathbf{h}}}} = \dot{\mathbf{h}}_d - \dot{\mathbf{h}}$.

In order for $\dot{V}\left(\tilde{\mathbf{h}}\right)$ to be negative, the following expression must be true:

$$\left|\tilde{\mathbf{h}}^T\mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right)\right| > \left|\tilde{\mathbf{h}}^T\delta_{\dot{\tilde{\mathbf{h}}}}\right|, \tag{14}$$

for $\tilde{\mathbf{h}}$ with high values, $\mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right) \approx \mathbf{K}$; Therefore $\dot{V}\left(\tilde{\mathbf{h}}\right)$ will be negative only if $\|\mathbf{K}\| > \left\|\delta_{\dot{\tilde{\mathbf{h}}}}\right\|$. In this way the error $\tilde{\mathbf{h}}$ diminishes. On the other hand, $\tilde{\mathbf{h}}$ with low values, $\mathbf{K}\tanh\left(\tilde{\mathbf{h}}\right) \approx \mathbf{K}\tilde{\mathbf{h}}$. In this case, (13) is written as:

$$\left\|\tilde{\mathbf{h}}\right\| > \left\|\delta_{\dot{\tilde{\mathbf{h}}}}\right\| / \lambda_{\min}(\mathbf{K}) \tag{15}$$

implying that the error $\tilde{\mathbf{h}}$ is limited by,

$$\left\| \tilde{\mathbf{h}} \right\| \le \frac{\left\| \delta_{\dot{\tilde{\mathbf{h}}}} \right\|}{\lambda_{\min}(\mathbf{K})} \tag{16}$$

And, if $\delta_{\dot{\tilde{\mathbf{h}}}} \neq 0$, $\tilde{\mathbf{h}}(t)$ ultimately limited by (16).

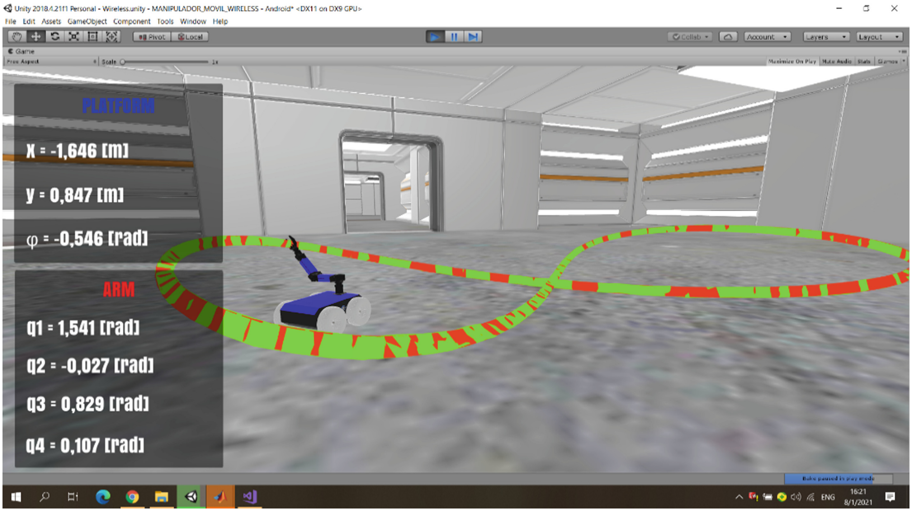
## 5 Experimental Results

This section presents the most relevant experiments and results. They serve to evaluate the behavior of the mobile manipulator robot in the virtual environment. For the experimental tests a laptop containing the mathematical model that simulates in behavior of the robot inside a virtual scenario created in the Unity 3D graphic engine was considered. The computer has 16 GB of RAM memory with a GPU of 6 GB. The controller was implemented in a Raspberry Pi-4 model B of 4 GB of RAM. It represents the hardware component of HIL. Finally, to establish a wireless communication channel, Xbee S2C devices were used. Figure 4 shows the physical implementation of the HIL system.

**Fig. 4.** Physical implementation of the Hardware in the Loop environment.

The experiments carried out recreate the simulation environment of the mobile manipulating robot with the law of control implanted. The mechanical design of the robot in the Unity-3D graphic engine is shown in Fig. 5, as well as the main variables that allow to visualize the displacement of the robot considering an infinite type path in order to excite the dynamics of the robot and to check the evolution of the control algorithm. To achieve the desired trajectory, the following parametric functions are used $h_{xd} = 2.45\cos(0.05t)$, $h_{yd} = 1.35\sin(0.1t)$ and $h_{zd} = 0.6 + 0.2\cos(0.1t)$.

In order to verify the implementation of the HIL technique, the Fig. 6 shows the real-time error variation for the position in the $X - Y - Z$ axis, as well as angular and linear velocity variation of every link in the mobile manipulator robot. Its observed how the



PLATFORM

X = -1,646 [m]

y = 0,847 [m]

φ = -0,546 [rad]

ARM

q1 = 1,541 [rad]

q2 = -0,027 [rad]

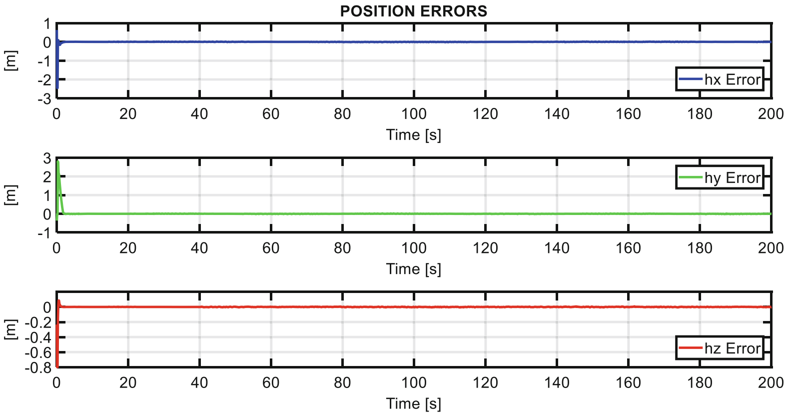
q3 = 0,829 [rad]

q4 = 0,107 [rad]

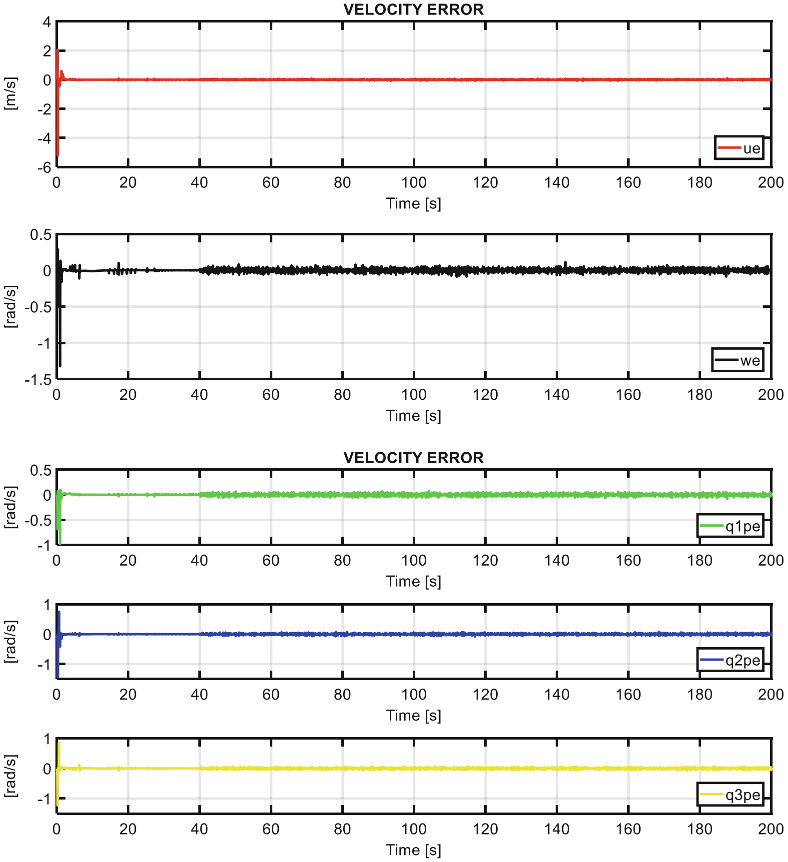
**Fig. 5.** Mobile manipulator movement.

control actions make adjustments in the robot's joints so that the end effector can follow the desired path, even when the robot suffers perturbations. The Fig. 6a shows control errors with perturbations while Fig. 6b shows velocities errors with perturbations. The errors associated with the dynamic function, do not tend to cero, but rather oscillate in a value near cero. However, the system still follows the desired trajectory, which indicates that the controller is indeed robust, as defined in (16). Therefore, by means of the control law, the errors tend to cero in function of the gain matrix **K**.

In this way, the performed tests illustrate how the implementation of a HIL environment constitutes an effective technique to control mobile manipulator robots. This technique allows implementing control algorithms embedded in virtual environments. Unlike alternative techniques, HIL permits incorporating input/output devices in the system. Those devices produce additional visual and auditive feedback of the robot's actions inside the virtual environment, making the system more user friendly. In contrast, physical construction is more expensive and time consuming, and total simulation does not enable incorporating physical components that interact with the mechanism.



a) Mobile manipulator control errors with disturbances.



b) Mobile manipulator velocity error with disturbances.

**Fig. 6.** Control and velocity errors with disturbances.

## 6 Conclusions

Hardware in the Loop is a technique that assist in the development of complex robotic test environments, without the need of building a mechanical system. The virtual environment developed in the graphic engine Unity 3D enables visualizing the robot's motion, which is commanded by the control law implemented in the end hardware. This control unit, through wireless information exchange, performs important parameter control, such as the motion of the joints in the robotic arm and the position of the mobile platform. Obtained results, regarding the robot performing autonomous tasks, validate the efficacy of the implemented technique, as well as the performance of the control law. Steady state errors in these tests tended to cero, as designed.

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Certifico que el trabajo de titulación, **"Mobile Manipulator Robot Control through Virtual Hardware in the Loop"** fue realizado por la señorita Jéssica Daniela Mollocana Jiménez, con cédula de ciudadanía n° 0550121842 y el señor Byron Stalin Jorque Rea, con cédula de ciudadanía n° 0503894164, el cual ha sido revisado y analizado en su totalidad por la herramienta de verificación de similitud de contenido; por lo tanto cumple con los requisitos legales, teóricos, científicos, técnicos y metodológicos establecidos por la Universidad de las Fuerzas Armadas ESPE, razón por la cual me permito acreditar y autorizar para que lo sustente públicamente.

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Firma:

Jéssica Daniela Mollocana Jiménez
C.I. No. 0550121842

byron Jorque

Byron Stalin Jorque Rea
C.I. No.0503894164

## DEPARTAMENTO DE ELÉCTRICA Y ELECTRÓNICA
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