HUMAN-ROBOT COLLABORATIVE CONTROL FOR HANDLING AND TRANSFER OBJECTS

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Departamento De Eléctrica Y Electrónica

Carrera De Ingeniería En Electrónica E Instrumentación

Artículo académico, previo a la obtención del título de Ingeniero en Electrónica E Instrumentación

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24 de Agosto del 2021

Human-Robot Collaborative Control for Handling and Transfer Objects

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Abstract. The document proposes the development of a 3D virtual environment, oriented to the common work activities between a unicycle type mobile manipulator robot and a human operator, in collaborative tasks. This strategy is focuses on the incorporation of virtual reality (VR), in which the operator will have access to visualize in an immersive way the behavior of the mobile manipulator robot in common tasks where the human being and the mobile manipulator robot interact. For the interaction between the human operator and the mobile manipulator robot, the graphic engine Unity 3D is used, which exchanges information with the mathematical software Matlab, in order to execute the control algorithm through the use of shared memories. The Novint Falcon haptic device allows human-robot interaction, which provides the operator with force feedback on what is happening in the virtual environment generated by the Unity 3D software and the interaction it has with the mobile manipulator. The HTC Vive immersion device allows the operator to visualize the virtual environment created for the execution of the task. In this work, the design and simulation of the locomotion system of a mobile manipulator robot is carried out for manipulation and object transfer tasks together with the human operator. Finally, the simulation results that validate the proposed control strategy are presented and discussed.

Keywords: Virtual reality · Mobile manipulator · Collaborative control · Matlab · Unity 3D

1 Introduction

Immersive technology, together with the development and technological advances in the last decade, focuses on different applications, in which a distributed group of users share a common 3D virtual environment [1]. It has Virtual Reality (VR) and Augmented Reality (AR) technology, where the development of virtual environments allows an intuitive interaction through input and output devices, in which several senses of human perception are used, this allows to have an immersion and interaction with the virtual environment as the manipulation of bodies, so it is possible to handle or operate different materials, with the purpose of performing tasks and meet achievable goals [2]. Within this scope, virtual reality (VR) allows to create realistic environments that acquire sensorial information for the interaction with the 3D virtual model [3].

M. Botto-Tobar et al. (Eds.): ICAT 2020, CCIS 1388, pp. 96–110, 2021.
https://doi.org/10.1007/978-3-030-71503-8_8

The applications of VR in different training areas motivate the user to learn new skills or get involved in different fields of knowledge, e.g., engineering where it is possible to learn different control techniques in industrial processes [4], medicine where students and doctors can practice hundreds of times a surgical intervention [5] and education where students with sensory and psychological skills improve their learning level [6], this great advance allows the development of society in different fields.

In recent years, the advance of technology has made virtual reality (VR) a completely new world [7], where the user experiences the impression of being immersed in a different environment [8], which is possible through haptic devices such as, e.g., Novint Falcon allowing the movement of the upper extremities [9], or Oculus Rift immersion technologies, HTC VIVE facilitating further perception of interaction within the virtual environment [10, 11]; these devices allow for an increased sense of human presence. In education areas it is used to train professionals in different fields, engineering [12], medicine [13], etc. this technology is used as an innovative strategy in the students' formation process, within the engineering area there are diverse applications oriented to the automation, control and instrumentation field [14], with environments where it is interacted with the measurement equipment allowing to make instrument calibration tasks, P&ID diagrams recognition, etc.

Virtual reality within robotics has generated great developments such as mapping of environmental variables [15], interfaces for mobile robots [16] and industrial manipulators [17]. Within the area of robotics there is a well-known field of service robotics that allows the introduction of autonomous robots to execute collaborative tasks with humans, such as the tele-operation of robots [18], or the cooperative control of mobile manipulators [19], making it easier for people to expand their capabilities and take on relatively heavy tasks, providing greater flexibility in production and increasing the efficiency of work done together. Virtual reality applications in collaborative tasks between different users allows the manipulation of virtual objects in the same environment, e.g., in [20]; students and surgical instructor perform collaborative training within a shared virtual environment.

As described above, this paper presents a virtual reality application developed in the Unity 3D graphic engine, as an intuitive tool that allows collaborative tasks between the human operator and mobile manipulator robot, through Novint Falcon haptic device allowing force feedback for the manipulation and transfer of objects, so the immersion device HTC Vive provides visualization of the virtual environment and human-robot interaction, the collaborative control is designed in Matlab mathematical software which allows to determine the control errors that occur when performing the common task.

This paper is divided into 5 Sections, including the Introduction. Section 2 describes the formulation of the problem. Section 3 includes the description of the virtual environment. Section 4 describes the control structure used. Section 5 discusses the experimental results obtained. Finally, Sect. 6 presents the conclusions of the implemented application.

2 Problem Formulation

Technological trends increasingly include human-robot interaction, either in a teleoperated form, i.e. the robot is controlled remotely by an operator, or the robot operates autonomously to execute a defined task. In complex tasks the integration of the mobile manipulator generates advantages thanks to the mobility offered by a mobile platform and the skill offered by the manipulator. This dedicates an unlimited workspace to the manipulator, making it possible to execute any task set by the user.

The interaction between human-robot is increasingly common in the social aspect, entertainment, among others, as the best known assistant robots, however at the time of conducting experimental tests to evaluate control algorithms in different works with a mobile manipulator robot is essential con-tar with the physical prototype, due to high investment costs in covering certain needs of the robot from the physical structure, acquisition of programming licenses and maintenance. In such a way it is added the inconveniences caused by climatic factors, where the experimental tests are carried out between the human operator and the mobile manipulator robot, the climatic conditions of the environment tend to affect significantly the tests with the robot. Under the following mentioned limitations, it is added the fact that the mobile manipulator robot is being experimented with, so it runs the risk of affecting its physical integrity and functionality. Taking into account the problems generated when performing experimental tests between man-robot, it is feasible to evaluate the control algorithm in a 3D virtual simulator, which allows to incorporate the characteristics and configurations of the mobile manipulator robot, allowing to analyze the functionality of the control algorithm, when performing collaborative man-robot tasks [21].

In the Fig. 1, describes the proposed scheme of the application from hardware and software used to the management of input/output devices Novint Falcon and HTC Vive, which provides the user to experience in a more intuitive way the immersion in the 3D virtual environment, the scenario contains 3D models that allow to create the virtual simulation environment in such a way that several elements are typical of Unity's assets, while the mobile manipulator robot is made in a CAD software (Computer Aided Design) which allows to make the 3D design of the mobile manipulator robot keeping all the mechanical characteristics of it among the most important elements are the wheels, chassis, robotic arm. The CAD design is exported to a 3D modeling, animation and rendering software, allowing to preserve all the physical characteristics of the robot before being imported to the Unity 3D graphic engine as an extension (*.fbx), the conditions of the environment are pre-established, this allows the user to have a better interaction allowing him to observe the velocities of the links that make up the robotic arm and the velocity at which the platform moves.

The Matlab mathematical software has the control algorithms that allow the mobile manipulator to correct errors during Human-Robot interaction, it receives the data sent by the graphic engine that allows the operator to perform the force feedback. The input

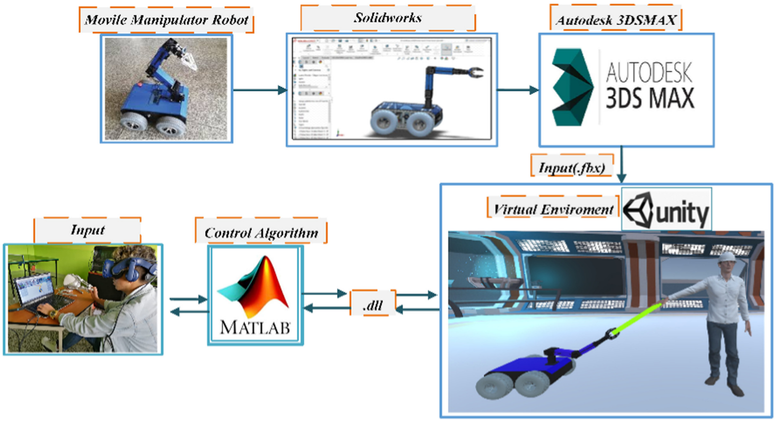


Fig. 1. Proposed outline for the development of the virtual environment

consists of Novint Falcon haptic devices that allow the operator to manipulate the virtual environment and HTC Vive that allows him to visualize the interaction with the avatar, the same one that will execute the collaborative tasks with the robot.

3 Virtual Environment

In this section describes the working methodology for the development of the application see Fig. 2, the stages that make it up are; *i) 3D Design* of the mobile manipulator robot from a CAD software, *ii) Virtual environment*, developed in the Unity 3D graphic engine, incorporating characteristics to the CAD model, *iii) Script block*, allows the control of each system block that interacts with the virtual environment, *iv) Input and output devices*, cooperate to the development of the environment, *v) Mathematical Software*, executes the control algorithm to be implemented.

3.1 CAD Design

The design is make in a CAD tool Fig. 3, so the software used in this design stage is Solidworks. It is oriented to 3D CAD design, allowing the creation of 3D solid models, assemblies, etc. It provides an easy to use design and powerful tools for engineers allowing them to create solid objects to be assembled and obtain complete 3D models. The mobile manipulator robot developed in the CAD software, has all the features and appropriate configurations that a real mobile manipulator has.

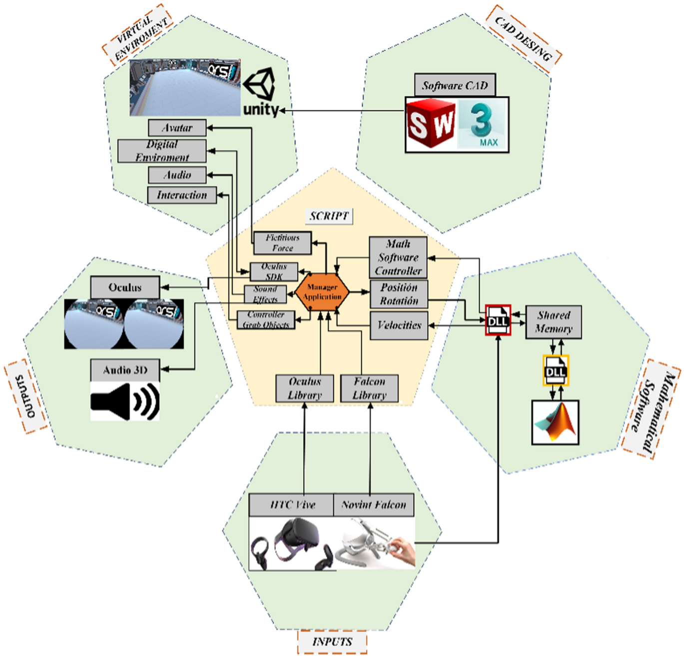


Fig. 2. Structural diagram of the interrelationship between the components

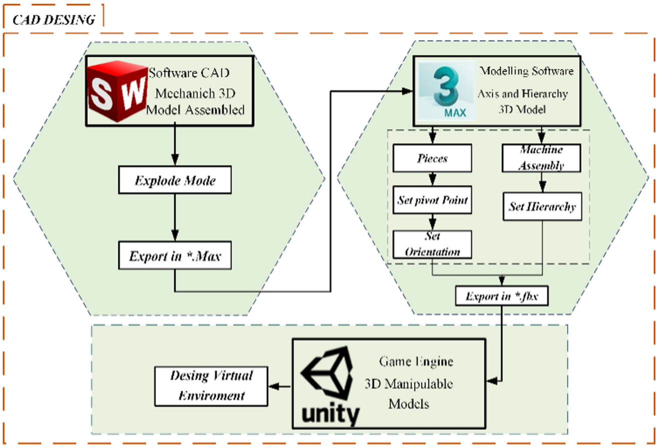


Fig. 3. Stages of CAD design

3.2 Virtual Environment Development

The virtual environment represents the attributes that make up the virtual environment developed in the Unity 3D graphic engine, among the most relevant are mentioned. *i) 3D models*, are the objects that are loaded into the environment including the mobile manipulator; *ii) UI Avatar*, is responsible for interacting with the robot within the virtual environment, providing the user the ability to intervene in the tasks to be performed. *iii) Interaction*, allows the user to link the virtual environment, configured by Grab Object Controller. The environment created allows the sensory and motor immersion of the user in tasks to be performed in collaboration with the mobile manipulator robot. In Fig. 4, it shows the creation of the virtual environment from the migration of elements of 3DS Max and its migration to the Unity 3D graphic engine. The tool MonoDevelop which allows to use the text editor which allows to create the scripts, allowing to make the respective animations of the environment, man-robot displacement, generate environmental sounds, etc. in order to provide a more intuitive immersion to the user.

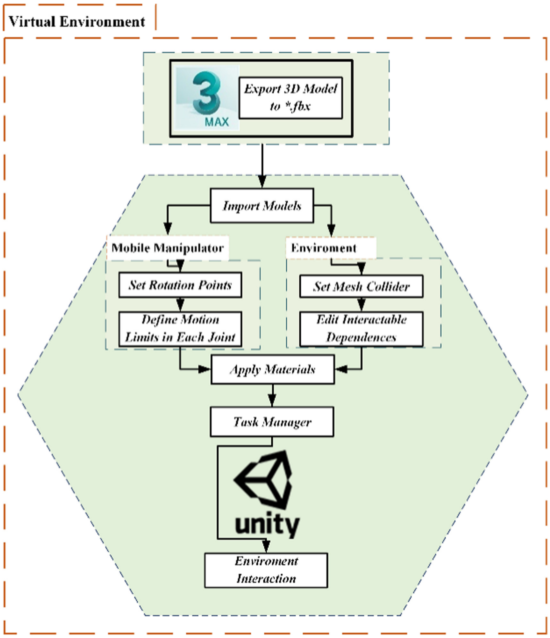


Fig. 4. Creation of the virtual environment

3.3 Block Scripts

In this stage the set of scripts is in charge of communicating Unity 3D between the input and output devices through code blocks. For the interaction with the virtual reality input device, the devices own library is used, which allows the communication with the computer to be executed to provide audio and visual feedback on the execution of the task. Finally the mathematical software by means of the use of the dynamic link library (DLL), which generates a shared memory (SM) for the exchange of data between different software. Through the SM the control actions are entered into the mobile manipulator. In Fig. 5, scheme of the script block. The data of position, rotation and velocity are read and sent to the mathematical software, later to obtain the control errors.

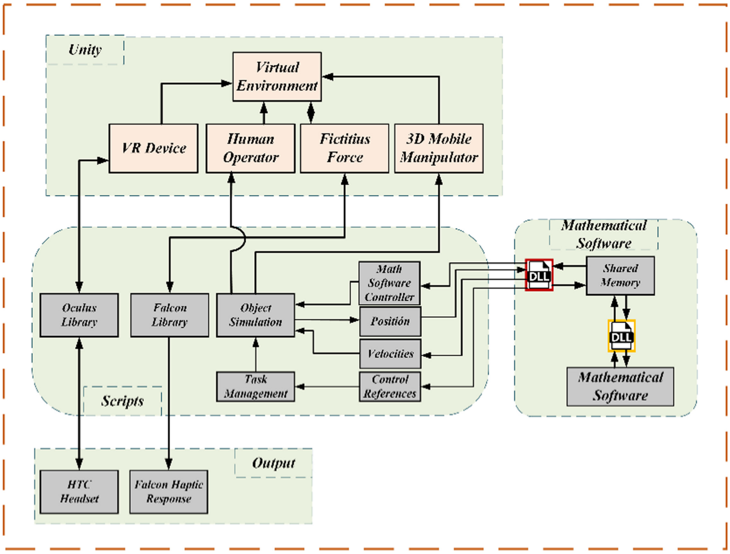


Fig. 5. Description of the Scritps block

3.4 Inputs and Outputs

The inputs and outputs seen in Fig. 2, corresponds to: the immersion device: *i) HTC Vive*, allows the user to enter the designed virtual environment, and interact with the mobile manipulator robot. Connecting the device to the HDMI port making it possible to add the visualization of the environment, the communication is established by means of the Steam VR software and the respective libraries, *ii) Novint Falcon*, is a haptic device capable of generating forces in the X-Y-Z plane of the reference system with a magnitude between 0 and 2.5 lbf, whose work area comprises a spherical region of 10 cm radius.

3.5 Mathematic Software

The mathematical software seen in Fig. 2. Structural diagram of the interrelationship between the components, has control algorithms to control the errors during the Human-Robot interaction, which receives the data sent by the graphic motor to make the calculations and determine a new value of position, orientation and velocity for the mobile manipulator robot, the signals are sent to the graphic motor causing the mobile manipulator robot to change its conditions thus obtaining an application that evolves over time.

4 Control Structure

4.1 Impedance Control

The forces that are generated at the operating end of the robot are obtained from the position of the human operator's arm Fig. 6, the mechanical impedance relationship is given in (1) between the force and velocity of the system.

$$Z(s) = \frac{F(s)}{V(s)} \tag{1}$$

Where $F(s)$ represents the external force applied to the operating end of the robot which is defined by:

$$F(s) = MXs^2 + DXs + KX \tag{2}$$

Where M is the mass, D the damping, K the stiffness and X represents the position of the system, Therefore the velocity and mechanical impedance is given by (3):

$$Z(s) = \frac{MXs^2 + DXs + KX}{Xs} = Ms + D + \frac{K}{s} \tag{3}$$

The force that feels the operating end of the robot represented by (2) allows to determine the position and desired velocity of the operating end, then the respective controller is applied, the external force **F** exerted by the human operator:

$$\mathbf{F} = \mathrm{M} \cdot \mathbf{a} \tag{4}$$

The acceleration vector is obtained from the external force applied obtaining the following one:

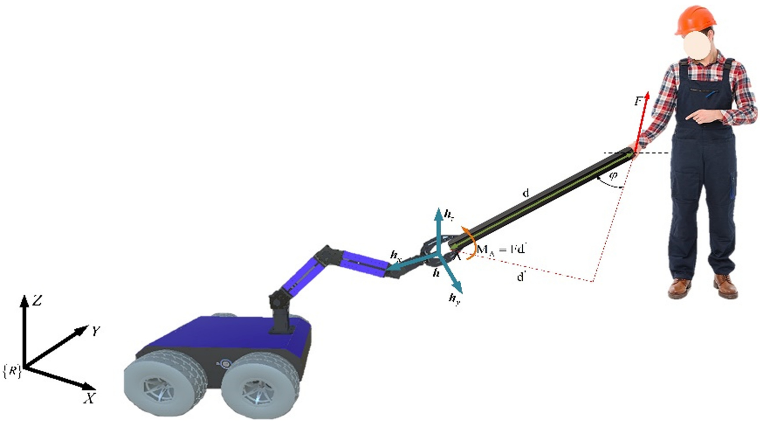


Fig. 6. Human-Robot reference system

$$\mathbf{a} = s^2 + \frac{DsX(s+K)}{M} \tag{5}$$

By integrating (5) the desired velocity of the operating end of the mobile manipulator robot is obtained:

$$\dot{\mathbf{h}}_\mathrm{d} = s\left(s^2 + \frac{DsX(s+K)}{M}\right) \tag{6}$$

To obtain the desired position of the operating end of the robot we integrate (6):

$$\mathbf{h}_\mathrm{d} = s^2\left(s^2 + \frac{DsX(s+K)}{M}\right) \tag{7}$$

4.2 Modeling Kinematic and Dynamic

A. Kinematic Modeling

The kinematic model of the mobile manipulator gives the location of the end effector, depending on the location of the unicycle-type dolly and the configuration of the 4DOF robot arm, as shown in Fig. 7. The mobile manipulator is guided through a u which represents the linear velocity of the moving platform; ψ represents the orientation of the vehicle with respect to $\{R\}$; angular velocity ω, represents the rotation of the dolly in relation to the axis z; l_1, l_2, l_3 y l_4 are the dimensions of the joints of the robotic arm; q_1, q_2, q_3 y q_4 are the angles of rotation for each degree of freedom of the manipulator robot [22].

$$\dot{\mathbf{h}}(t) = \mathbf{J}(\mathbf{q})\mathbf{v}(t) \tag{8}$$

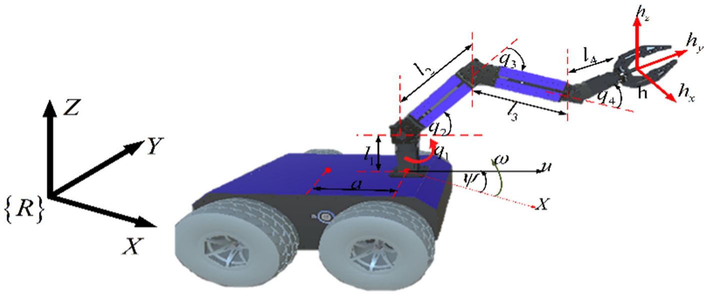


Fig. 7. Mobile robot manipulator

Where $\mathbf{J}(\mathbf{q}) \in \Re^{mxn}$ with $m = 3$y $n = 6$ represents the Jacobian matrix that defines a linear mapping between the velocity vector of the mobile manipulator $\mathbf{v} \in \Re^n$ where $\mathbf{v}(t) = [\,u \quad \omega \quad \dot{q}_1 \quad \dot{q}_2 \quad \dot{q}_3 \quad \dot{q}_4\,]^T$ and the velocity vector of the operating end $\dot{\mathbf{h}} \in \Re^m$ where $\dot{\mathbf{h}}(t) = [\,\dot{h}_x \quad \dot{h}_y \quad \dot{h}_z\,]^T$

B. Dynamic Modeling

The dynamic model of the mobile manipulator robot is applied the Euler-Lagrange method, this is the energy balance equation since it is more suitable to analyze the displacements of the links that limit each other, the dynamic equation of the mobile manipulator can be represented as follows [22].

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \mathbf{v}_{ref}(t) \tag{9}$$

Where $\mathbf{M}(\mathbf{q})$ is the inertial matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the matrix of centripetal and Coriolis forces, $\mathbf{g}(\mathbf{q})$ represents the gravitational forces of the mobile manipulator, $\mathbf{v}_{ref}(t)$ it is the vector of the velocity control signals.

4.2.1 Kinematic Controller

The design of the kinematic controller of the mobile manipulator robot is based on the kinematics of the robot (8). The velocity (6) and position (7) required is obtained as a function of the force felt by the operating end of the robot, detected through the sensors, product of the movement of the object that is generated by the person. Therefore, the following control law is proposed for the mobile manipulator:

$$\mathbf{v_c} = \mathbf{J}^{\#}\left(\dot{\mathbf{h}}_\mathbf{d} + \mathbf{L_K}\tanh(\tilde{\mathbf{h}})\right) + \left(\mathbf{I} - \mathbf{J}^{\#}\mathbf{J}\right)\mathbf{L_D}\tanh(\boldsymbol{\eta}) \tag{10}$$

Where, $\mathbf{J}^{\#} = \mathbf{W}^{-1}\mathbf{J}^T\left(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}^T\right)^{-1}$ with $\mathbf{W}$ positive symmetrical matrix that weighs the control actions of the system, $\dot{\mathbf{h}}_\mathbf{d}$ is the desired velocity vector of the end-effector $\mathbf{h}_\mathrm{d}$; $\tilde{\mathbf{h}}$ it's the vector that contains the control errors $\tilde{\mathbf{h}} = \mathbf{h}_\mathrm{d} - \mathbf{h}$; $\mathbf{L_K}$ and $\mathbf{L_D}$ these are defined positive diagonal gain matrices, and $\boldsymbol{\eta}$ is a vector allows the configuration of the arm to be at maximum manipulability [22].

4.2.2 Dynamic Compensation

Dynamic compensation controller, whose main objective is to compensate the dynamics of the mobile manipulator, thus reducing the velocity error. This controller receives as inputs the desired velocities $\mathbf{v_c}$ calculated by the kinematic controller (10), and generates velocity references $\mathbf{v_{ref}}$ for the mobile manipulator. If there is no perfect velocity tracking, the velocity error is defined as $\tilde{\mathbf{v}} = \mathbf{v_c} - \mathbf{v}$. Therefore, the following control law is proposed.

$$\mathbf{v_{ref}} = \mathbf{M}(\mathbf{q})\boldsymbol{\sigma} + \mathbf{C}(\mathbf{q}, \mathbf{v})\mathbf{v_c} + \mathbf{g}(\mathbf{q}) \tag{11}$$

Where, $\mathbf{v_{ref}} = \begin{bmatrix} u_{ref} & \omega_{ref} & \dot{q}_{1ref} & \dot{q}_{2ref} & \dot{q}_{3ref} & \dot{q}_{4ref} \end{bmatrix}^T$ is the control action and $\boldsymbol{\sigma} = \dot{\mathbf{v}}_\mathbf{c} + \mathbf{L_v}\tanh(\tilde{\mathbf{v}})$ where $\mathbf{L_v}$ a defined positive matrix.

4.3 Stability Analysis

The control error $\tilde{\mathbf{h}} = \mathbf{h_d} - \mathbf{h}$ is analyzed assuming perfect velocity tracking $\mathbf{v} \equiv \mathbf{v_c}$, thus substituting (10) in (8) we have:

$$\dot{\tilde{\mathbf{h}}} + \mathbf{L_K}\tanh\left(\tilde{\mathbf{h}}\right) = 0 \tag{12}$$

The following Lyapunov function is considered for stability analysis [22]:

$$\mathrm{V}\left(\tilde{\mathbf{h}}\right) = \frac{1}{2}\tilde{\mathbf{h}}^{T}\tilde{\mathbf{h}} \tag{13}$$

Where the time derivative is located in the system trajectories is:

$$\dot{\mathrm{V}}\left(\tilde{\mathbf{h}}\right) = \tilde{\mathbf{h}}^{\boldsymbol{T}}\mathbf{L_K}\tanh\left(\tilde{\mathbf{h}}\right) \tag{14}$$

The closed-loop control system (10) is asymptotically stable, so that the position error of the end-effector $\tilde{\mathbf{h}}(t) \rightarrow 0$ is asymptotically, with $t \rightarrow \infty$.

5 Experimental Results

This section presents the virtual scenarios created in the Unity 3D graphic engine, where the human operator has the option to select three test environments through the menu in Fig. 8 are *i) Laboratory, ii) Closed Hangar, iii) Factory*, in the virtual environment will perform the simulation of the collaborative task Man-robot.

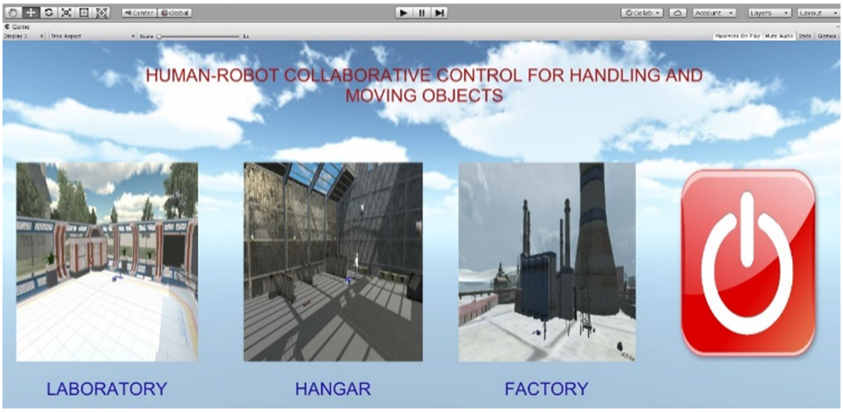
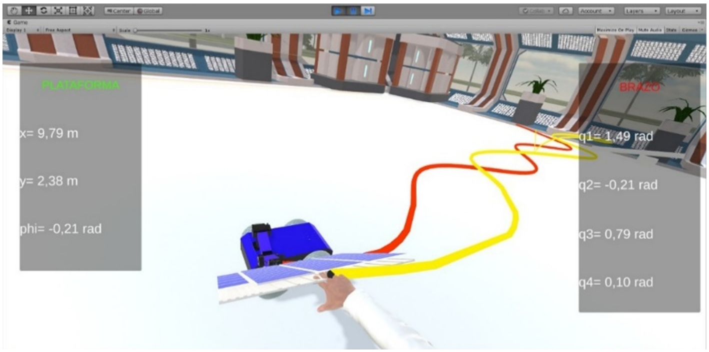


Fig. 8. Start menu of the virtual environment

Once the scene is selected, the communication is linked to the Matlab software to evaluate the performance of the control algorithm applied to the mathematical model of the robot, which approaches and holds the different objects, for which the movement of the avatar's hand will be represented through a Novint Falcon haptic device that perceives the operator's input signal, the received signal is send to the virtual environment and the actuators of the haptic device are used to physically convert sensations to the human operator show in Fig. 9.

Fig. 9. Human operator interaction test

The task executed of manipulation and transport of the object, in which the avatar is interacting with the object coupled to the operative end of the robot see Fig. 10, as time passes the control evolves in such a way that the robot modifies the positions of its links to continue with the collaborative task as it is shown in Fig. 11.



PLATAFORMA
x= 9,79 m
y= 2,38 m
phi= -0,21 rad

BRAZO
q1= 1,49 rad
q2= -0,21 rad
q3= 0,79 rad
q4= 0,10 rad

Fig. 10. Initiation of control for the collaborative task

PLATAFORMA
x= 9,96 m
y= 2,26 m
phi= -0,48 rad

BRAZO
q1= 1,48 rad
q2= -0,19 rad
q3= 0,75 rad
q4= 0,08 rad

Fig. 11. Man-robot collaborative object transport

The results obtained from the development of the collaborative task between man-robot through the interaction of the operator with the haptic device, you can see how the stability of the controller evolves over time, through the control actions of the mobile platform shown in Fig. 12, the velocities of each link of the robot arm in Fig. 13 and in Fig. 14 you can see the positioning errors of the operating end of the mobile manipulator robot.

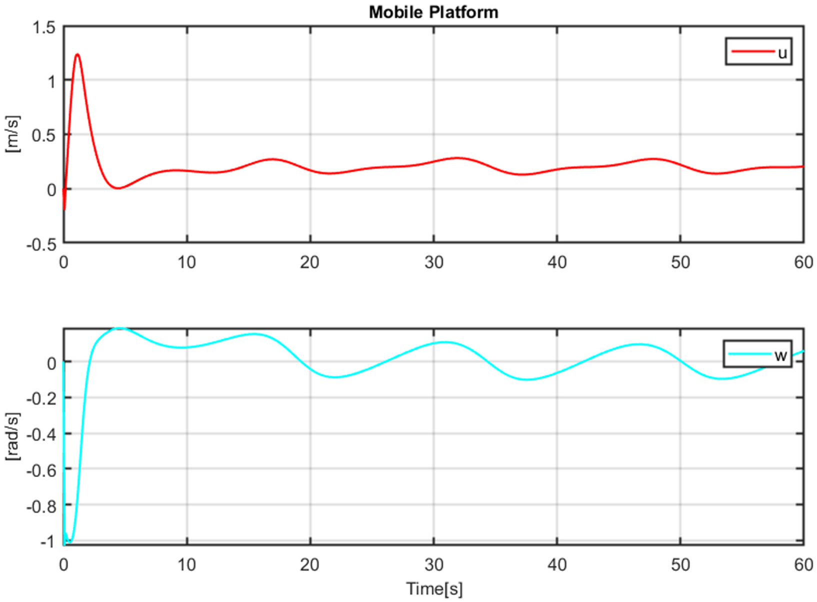


Fig. 12. Unicycle platform control actions

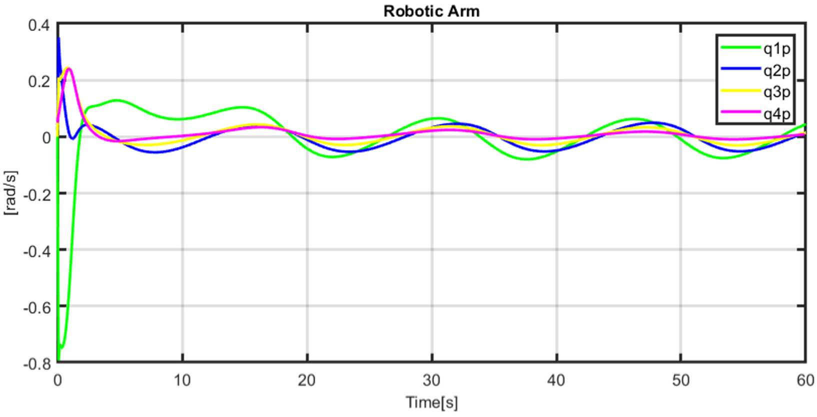


Fig. 13. Angular velocities of the robotic arm

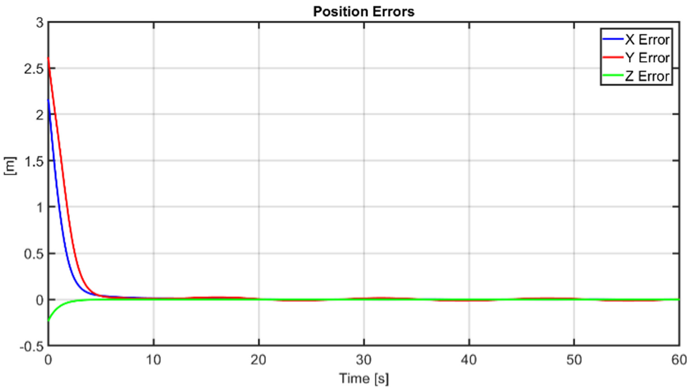


Fig. 14. Position errors of the operating end of the robot

6 Conclusions

In this paper the Human-Robot interaction carried out in Unity 3D virtual environment and the execution of the control algorithm implemented in the mathematical software allow to obtain a better interaction. In the application it allows the human operator to interact with the mobile manipulator robot through the haptic device Novint Falcon which allows to make force feedback. The development of the virtual environment in conjunction with the haptic device allows to generate an immersive environment of interaction Man-Robot and the controller implemented to meet the collaborative task.

Acknowledgements. The authors would like to thank the Corporación Ecuatoriana para el Desarrollo de la Investigación y Academia - CEDIA for their contribution in innovation, through the CEPRA projects, especially the project CEPRA-XIV-2020–08-RVA “Tecnologías Inmersivas Multi-Usuario Orientadas a Sistemas Sinérgicos de Enseñanza y Aprendizaje”; also the Universidad de las Fuerzas Armadas ESPE and the Research Group ARSI, for the support for the development of this work.

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