



Bilateral Tele-Operation of an Unmanned Aerial Vehicle: Teaching and Learning Priority.

Cumbicos Jiménez, Richard Hernán

Departamento de Eléctrica, Electrónica y Telecomunicaciones

Carrera de Ingeniería en Electrónica e Instrumentación.

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Mgs. Ortiz Moreano, Jessica Sofía

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Richard Cumbicos, and Jessica S. Ortiz

Universidad de las Fuerzas Armadas ESPE, Latacunga-Ecuador.
{rhcumbicos, jsortiz4}@espe.edu.ec.

Abstract. The present work presents a bilateral tele-operation scheme for a rotary propeller UAV. The development of the controller is based on the kinematic model of the UAV, and the use of a haptic device for the feedback of forces from the environment to the operator. A learning system is presented to test the controller within a virtual reality environment. The virtual reality environment will allow to evaluate the performance of the robot as close as possible to reality, therefore, it is provided within the development of the virtual reality environment to have the UAV digitized and with all the characteristics of kinematic and dynamic movement; and with a partially structured environment with obstacles present in the environment that allow to evaluate the operation of the controller by simulation and finally test the tele-operation control experimentally with the rotating propeller robot.

Keywords: kinematic, learning system, virtual reality, tele-operation.

1 Introduction

Robotics is a field that has made significant progress in recent years. Robots have become more precise, intelligent and versatile, and their use has expanded to a wide range of applications in various fields [1]. From manufacturing industry within industrial robotics to medicine and space exploitation in service robotics. With technological advancement different robots can perform a wide variety of tasks, from cleaning and security to medical care and education [2]. Robots are now safer and more accessible, making them more useful and beneficial to society at large. One such robot that has recently shown significant benefits are those known as Unmanned Aerial Vehicle (UAV) or more commonly known as drones.

UAVs or drones are increasingly being used in service robotics as they are robots that can move from one place to another in the air, with no restrictions on movement. Drones are used for package delivery, drones for inspection of structures and crops, drones for mapping and surveying, drones for monitoring and prevention of natural disasters, drones for search and rescue operations, smaller drones that can be used for surveillance and security in buildings and public events and among other applications that benefit people to perform a task with the minimum possible time and accuracy [3][4]. Most of these tasks can be executed autonomously, semi-autonomously. One of the most widely used techniques for semi-autonomous control of a robot is tele-operation.

Tele-operation is a control technique that allows a robot to be remotely operated while receiving sensory feedback from the environment. This is achieved through communication between the operator and the robot. This control technique is useful in situations where the work environment is dangerous or impossible for a human to reach, such as exploration work, handling toxic materials, in hostile environments or in emergency situations. In the literature there are developed schemes of robot tele-operation, *e.g.*, in [5] they present a tutorial of bilateral tele-operation for nonlinear systems, they have the Lyapunov theory with slight modifications that allows to analyze the stability. In [6] they present a bilateral teleoperation scheme for a mobile robot with a robotic arm. The scheme they present allows the operator to receive force feedback from the remote location using a haptic device, allowing the human operator to perform complex tasks in remote environments. The scheme uses the model of the robot in order to propose the control structure. In [7] present obstacle avoidance for tele-operation of a UAV, the authors consider wave variables to increase operator performance within the bilateral tele-operation scheme with time delays. They describe the theoretical analysis of the use of variables within a UAV obstacle avoidance system, allowing to reduce the number of collisions, the workload on the operator and the haptic activity during task execution. Usually these bilateral tele-operation schemes need the kinematic or dynamic model of the robot to design the controller [8][9]. The mathematical models of the robots contain the characteristics and/or motion constraints that can be used for both simulation and experimentation.

Usually the control schemes for implementation require to be tested at laboratory level, *i.e.*, simulate the control scheme to adjust the gains or variables that allow the correct operation of the robot during the task [10]. This type of simulators is usually of mathematical type since they need to perform complex and high-speed calculations continuously [11]. However, in order to simulate teleoperation schemes it is helpful to have a virtual work environment that allows to evaluate the performance of the robot and the user when interacting with the environment. Currently, there are simulation software for robots that allow the evaluation of the robot's performance in a 3D environment, such as: V-rep [12], Robot Operating System (ROS) [13], Gazebo [14], and among other software that allow testing of robots in 3D environments. Most of these types of simulators allow creating the environment and adding the robots that are available within the software. Nowadays, thanks to the diversity of 3D software, it is possible to have virtual environments that allow the immersion of the user to generate greater resemblance with reality, there are works that allow the incorporation of robots within these environments. In [15] they create a virtual reality environment in Unity 3D to test the teleoperation scheme of an aerial manipulator robot with two robotic arms, the environment has the digitization of a physical environment and the robot. However, they only simulate the execution of the task and no experimental tests of the proposed scheme are performed.

This work proposes the development of a virtual reality environment in Unity 3D to evaluate the teleoperation system of a rotary propeller UAV. The virtual reality environment will allow users to incorporate the UAV with all the movement characteristics (robot dynamics) to emulate the behavior of the real drone. The environment has obstacles and also allows communication with Matlab software. This software is in charge

of executing the tele-operation control of the robot and transmitting the data, *i.e.*, the environment allows to simulate as close as possible to the real thing and to adjust the controller, with the objective of proceeding to perform the experimentation with the physical robot. Therefore, the system used to evaluate the controller allows to interact in the virtual environment or with the physical robot. This work is divided into seven sections, including the Introduction. In Section II, the conceptualization of the process is presented, while in Section III the kinematic model and the teleoperation control scheme are presented. The development of the virtual environment for simulation is presented in Section IV. The results obtained are presented in Section V. In Section VI the discussion is presented and finally, Section VII presents the conclusions of the work.

2 Process Conceptualization

Figure 1 shows the proposed scheme for the development of the virtual reality simulator to evaluate the tele-operation control of an aerial robot.

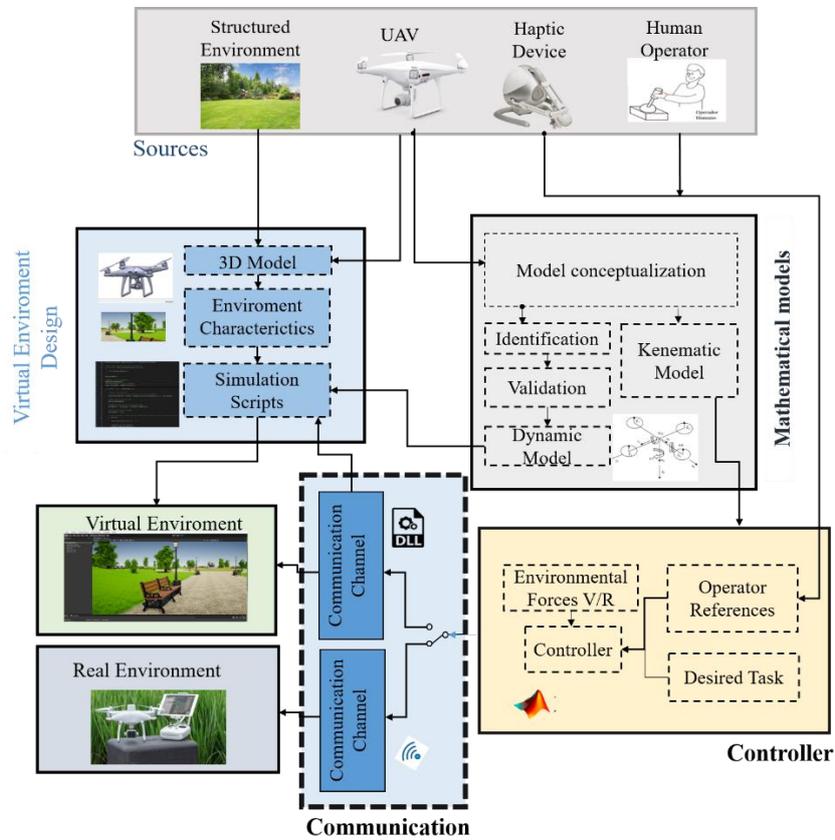


Fig. 1. Process Conceptualization.

Sources. The sources are the essential elements for the development of the environment and the UAV tele-operation control, including: *i*) the type of structured environment to be incorporated into the virtual environment; and *ii*) the rotary wing UAV to be controlled and digitized to be incorporated into the simulation environment.

Design of the virtual environment. In this stage the creation of the 3D models of the virtual environment and the 3D model of the UAV is developed. Here the characteristics of the environment and objects that will intervene in the simulation are assigned. It also consists of a block which has the necessary scripts to recreate the environment, to send and receive data from the controller and to animate the robot within the virtual environment.

Mathematical models. To establish the control of the UAV it is necessary to have the mathematical model of the robot. The kinematic and dynamic model of the robot allows to assign the characteristics and movement of the robot, thus allowing to emulate the real behavior within the virtual reality environment. For the dynamic model of the robot it is necessary to obtain the parameters that make up the model, therefore, the model is subjected to the process of identification and validation of parameters.

Controller. In this stage the tele-operation control is designed, which receives the references from the human operator through a haptic device and generates the feedback to the human operator. This allows to give information about the state of the robot within the real or virtual environment. The control scheme allows to send the reference data to the physical robot or to the virtual robot through a specific communication channel for each environment. In this block there are two types of communication: *i*) the communication channel between the mathematical software where the tele-operation control is executed and the virtual reality environment; and *ii*) the communication channel between the physical UAV within the real environment and the local site where the operator is located which is where the tele-operation control is executed.

Environments. The virtual environment is designed to emulate the behavior of the real robot and to be able to evaluate the teleoperation controller by simulation, it has objects in the environment which allow to validate the performance of the control and the feedback of forces to the human operator. In the real environment the UAV robot tele-operation control is tested experimentally.

3 Kinematic Model of an Unmanned Aerial Vehicle

The mathematical model allows to describe the relationship between the control inputs, such as velocity and orientation, and the UAV outputs, such as position and velocity. The kinematic model can be used to simulate and analyze the behavior of the UAV in different situations, to design control strategies that allow the UAV to perform specific tasks autonomously or semi-autonomously. Figure 2 shows the kinematic scheme of the rotating propeller UAV robot within the workspace.

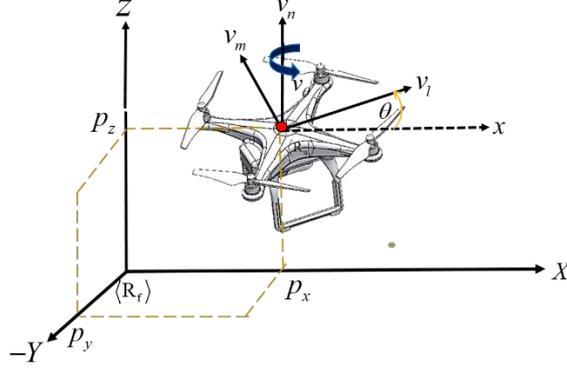


Fig. 2. UAV configuration in XYZ space.

The direct kinematics of the robot locates the position of the robot control point of interest, such as the location of a sensor, location of a camera, center of mass of the robot. In this case the center of mass of the robot is considered as the point of interest to control and the orientation around the Z axis. The kinematics are the operational coordinates of the robot defined as:

$$\mathbf{p}(t) = [p_x \ p_y \ p_z \ p_\theta]^T \quad (1)$$

where, $\mathbf{p} \in \mathbb{R}^4$ is the position and orientation vector of the robot within the fixed reference system $\langle R_f \rangle$. In order to relate the robot maneuverability velocities to the robot workspace velocities, we obtain the instantaneous kinematic model of the robot defined as:

$$\dot{\mathbf{p}}(t) = \mathbf{J}(\theta)\mathbf{v}(t) \quad (2)$$

where, $\dot{\mathbf{p}}(t) \in \mathbb{R}^4$ is the vector containing the velocities in the workspace $\langle R_f \rangle$ and is defined as $\dot{\mathbf{p}}(t) = [\dot{p}_x \ \dot{p}_y \ \dot{p}_z \ \dot{p}_\theta]^T$; $\mathbf{v}(t) \in \mathbb{R}^4$ is the vector containing the robot's maneuverability velocities within the moving reference system $\langle R_u \rangle$. The robot used in this work has four maneuverability velocities, three linear velocities and one angular velocity. The vector of maneuverability velocities is defined as $\mathbf{v}(t) = [v_l \ v_m \ v_n \ v_\theta]^T$. Where, v_l is the frontal linear velocity of the robot; v_m is the lateral linear velocity of the robot; v_n is the elevation velocity of the UAV; and v_θ is the angular velocity that allows the robot to rotate around the Z axis. Finally, $\mathbf{J}(\theta) \in \mathbb{R}^{4 \times 4}$ is the Jacobian matrix of the system, this matrix transforms the maneuverability velocities of the moving frame $\langle R_u \rangle$ to the velocities in the fixed reference system $\langle R_f \rangle$. The differential kinematic model of the robot is defined as:

$$\begin{bmatrix} \dot{p}_x \\ \dot{p}_y \\ \dot{p}_z \\ \dot{p}_\theta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 & 0 \\ \sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_l \\ v_m \\ v_m \\ v_\theta \end{bmatrix} \quad (3)$$

Remark. In the process of obtaining the differential kinematic model, we consider that the velocities to be worked with are small, i.e., that at small velocities the roll ($\phi \approx 0$) and pitch ($\varphi \approx 0$) angles are zero, therefore, only the UAV yaw angle is considered.

3.1 Tele-Operation Scheme

The Figure 3 shows the proposed scheme for the teleoperation of a UAV, the scheme contemplates the local site and the remote site.

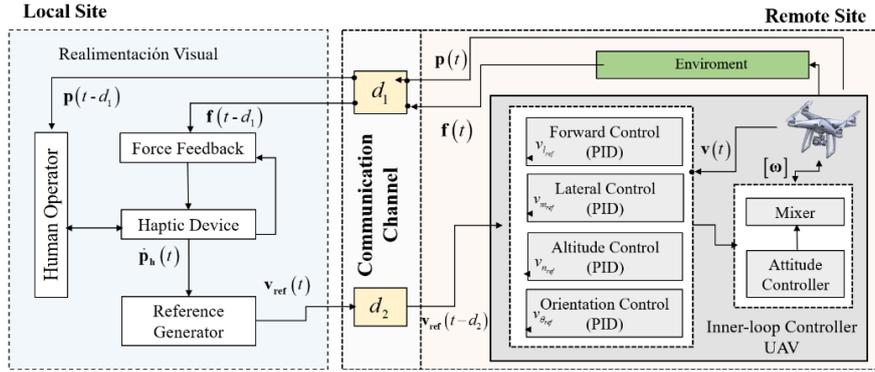


Fig. 3. Schematic diagram for UAV tele-operation.

In the local site, the human operator is considered with the haptic device that generates the velocity references to the robot $\mathbf{v}_{ref}(t)$. The controller for the reference generator is defined according to the robot kinematics (2). Control law implemented is trajectory tracking, the trajectory is generated in real time by the operator and is defined by:

$$\mathbf{v}_{ref}(t) = \mathbf{J}^{-1}(\theta)(\dot{\mathbf{p}}_h(t) + \mathbf{K}_1 \tanh(\tilde{\mathbf{p}}(t))) \quad (4)$$

where, $\dot{\mathbf{p}}_h(t) \in \mathbb{R}^4$ is the vector of velocities generated by the operator by the haptic device. These velocities are given in the fixed reference frame, because the feedback to the operator is the robot position into $\langle R_f \rangle$; $\tilde{\mathbf{p}}(t) \in \mathbb{R}^4$ is the position error determined by $\tilde{\mathbf{p}}(t) = \mathbf{p}_h(t) - \mathbf{p}(t - d_1)$, where $\mathbf{p}_h(t)$ is the desired robot position at instant t ; $\mathbf{p}(t - d_1)$ is the robot position observed by the operator at $(t - d_1)$ and d_1 is the time delay in which the operator perceives the robot position at the local site; $\mathbf{K}_1 \in \mathbb{R}^{4 \times 4}$ is diagonal positive matrix that weights the control error; and $\mathbf{J}^{-1}(\theta)$ is the inverse matrix of $\mathbf{J}(\theta)$ the robot.

In teleoperation of manipulators the operator senses the force of the contact objects, while in teleoperation of a mobile robot the operator senses the force of the environment to navigate safely and not to collide. In this case force feedback through position error is considered. Therefore, the calculation of the fictitious force components in space is determined by:

$$f_x = -k_x \tilde{p}_x \quad f_y = -k_y \tilde{p}_y \quad f_z = -k_z \tilde{p}_z \quad (5)$$

where, k_x , k_y and k_z are proportional gains to generate the fictitious feedback force; \tilde{p}_x , \tilde{p}_y and \tilde{p}_z are the positional errors of the aerial robot.

4 Virtual Environment Development

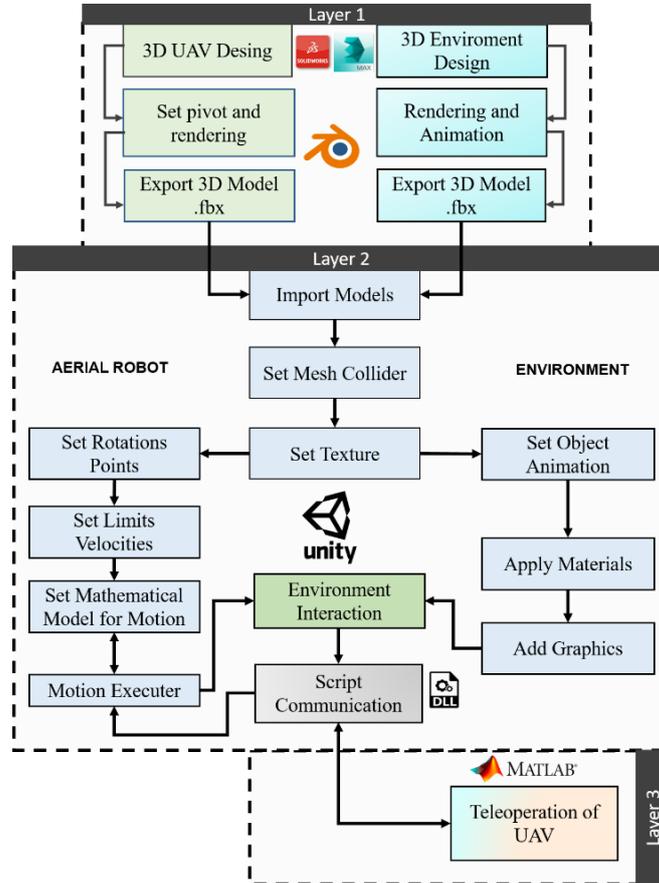


Fig. 4. Multilayer Diagram of the 3D Simulator Design.

Figure 4 shows the procedure for the development of the simulation environment for UAV teleoperation

Layer 1. In the first instance, the 3D models of the UAV and the 3D design of the environment are developed. For the UAV model is made in CAD software, in this case SolidWorks is considered for the modeling of the robot. The CAD model of the robot is assigned the motion properties to perform the motion animation according to its actual configuration, this is done in Blender software, which is suitable for rendering and adding animations. Similarly, the 3D environment is rendered and the respective animations are assigned to recreate the environment. Finally, the models are exported in

*.fbx format to be used in UNITY, Figure 5 shows the export procedure of the UAV model.

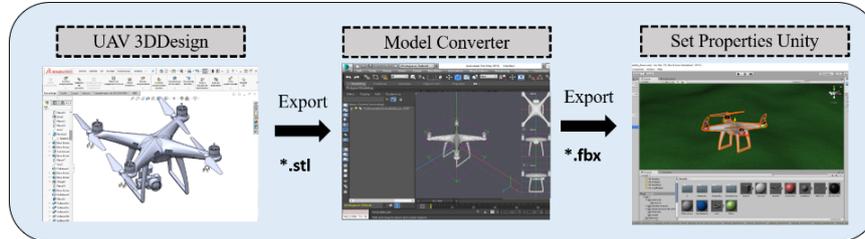


Fig. 5. UAV 3D digitalization.

Layer 2. In this layer the UNITY programming for the simulator is developed. The imported models are used and the characteristics are assigned to each 3D model. For the aerial robot an animation script is created according to the robot behavior, in other words, the dynamic model is used to execute the movements according to the velocities given by the operator. For the environment, the animation programs of the objects are added. The communication script is created to send and receive data from the human operator. A Dynamic Link Library (DLL) is used for communication between Matlab and Unity.

Layer 3. This is the final stage in which the Matlab software communicates with the virtual environment to perform the tele-operation simulation, in Matlab the control script is created to send the maneuverability velocities by means of a DLL and receive the data for remote monitoring and control of an unmanned aerial vehicle.

5 Results

In order to validate the virtual simulator and the tele-operation scheme, we performed tests with the Unity virtual environment and experimentally with the robot. The robot considered in this work is a DJI phantom (Figure 6). Figure 7 shows the human operator with the haptic device and Figure 8 shows the human operator in the experiment.



Fig. 6. Phantom 4 used for tele-operation.

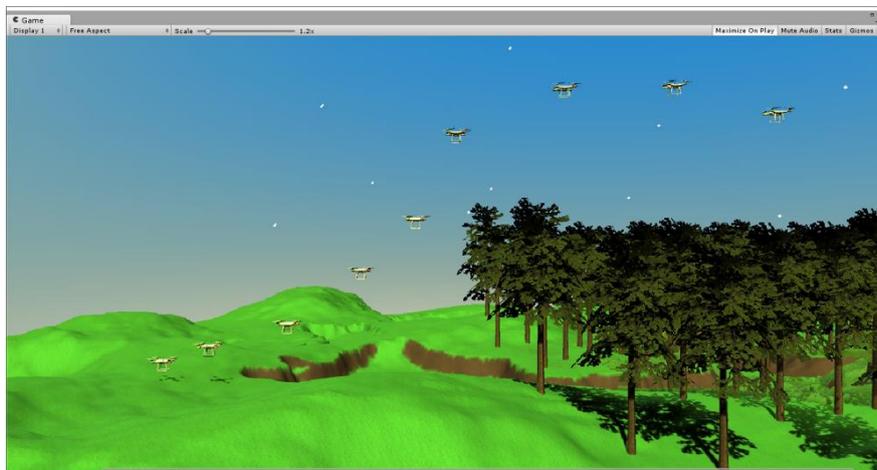


Fig. 7. Human operator at the local site.

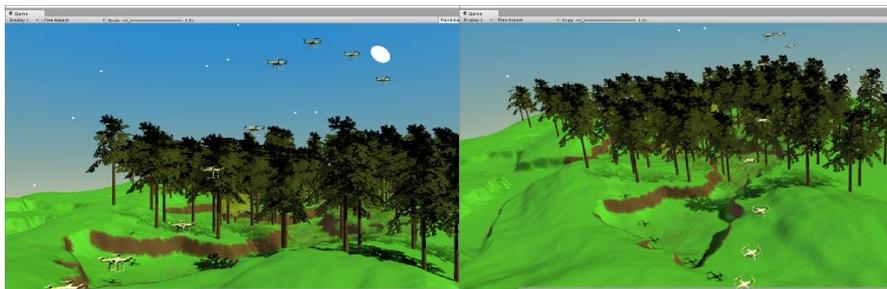


Fig. 8. Human operator on local site (Experiment).

The first test is performed with the virtual reality environment. Figure 9 shows the tests performed with the virtual simulator.



a) Lateral view of drone movement.



b) Perspective and top view of the movement executed by the drone.

Fig. 9. Motion of the robot in the virtual environment.

For experimental validation of the tele-operation scheme, we proceed to perform the test with the physical robot. In this experiment, as in the previous one, the Matlab control is executed; however, now the data generated by the operator at the local site are

sent to the robot via wireless. Figure 10 shows the movement executed by the robot in the environment; in this case, fixed obstacles are inserted in the environment.

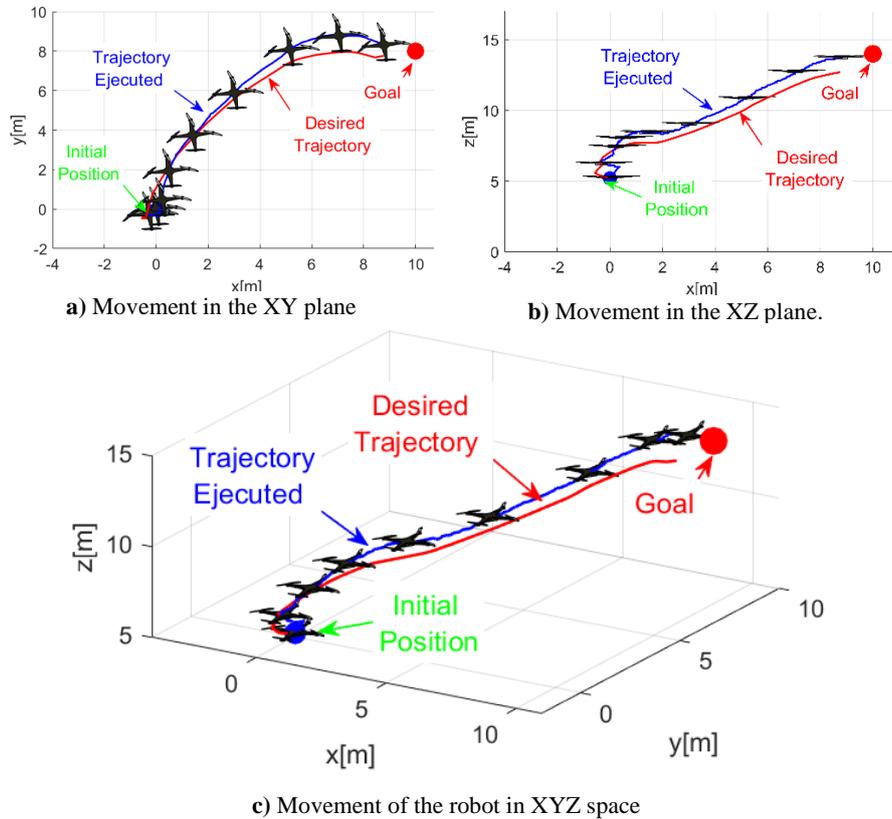


Fig. 10. Executed movement of the physical robot in the real experiment.

Figure 11 shows the fictitious forces generated towards the operator when the robot is close to an obstacle.

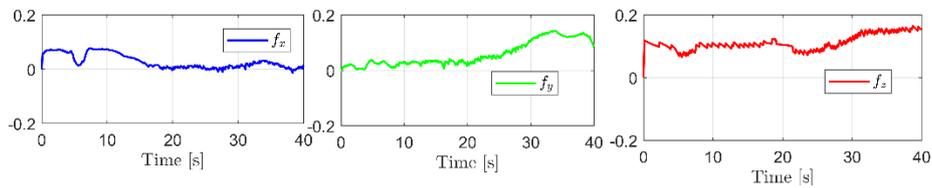


Fig. 11. Fictitious forces generated to the operator.

Finally, the Figure 12 shows the control errors that exist at the desired point to which the operator must drive the robot. And the Figure 13 shows the velocities generated by the operator and those generated by the robot. As can be seen, there is a minimum error in these velocities, due to the disturbances introduced by the wind.

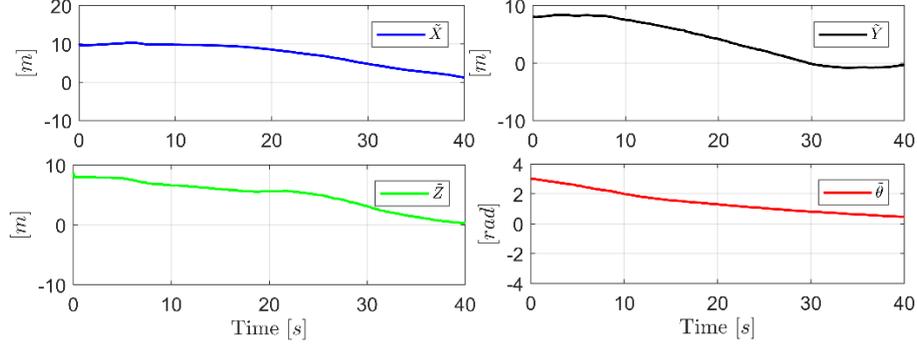


Fig. 12. Errors in the working space between the robot and the target to be reached.

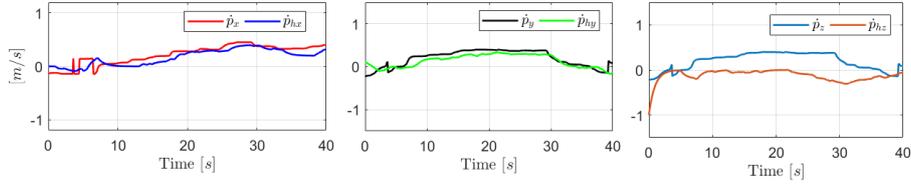


Fig. 13. Reference velocities generated by the operator and velocities executed by the robot.

6 Discussion

The experimental results of the work developed with respect to the control with tele-operation have presented advantages for the control of the UAV from a remote location, through the results obtained can be observed as the user takes the robot to the desired target. To meet the objective, the user perceives the environment and especially the control error through the force feedback, this allows the operator through the feedback to perceive if he is taking the robot to the desired point. The force feedback to the operator may vary depending on the working environment of the robot, i.e., in an environment with high disturbances (wind) the control error will increase and therefore, the force perceived by the human operator will increase (view Figure 11).

7 Conclusions

The virtual environment is developed with the objective of simulating the tele-operation of an aerial robot, the environment allows to integrate the control from Matlab and emulate the behavior of the robot in a virtual environment. The virtual environment also allows testing other algorithms since the control algorithm is done in Matlab and additional tasks can be implemented, such as autonomous robot control. Once the simulation is executed with the virtual environment, experimental tests can be performed with the physical robot, avoiding damage to the physical robot by adjusting the gains and training the operator to tele-operate the robot through the virtual environment. The

behavior of the virtual and real robot is very similar because the dynamic model of the robot in Unity is used to execute the movements. Based on the results obtained, future work is proposed on the cooperative control of several aerial robots through teleoperation, allowing more complicated objectives to be met, e.g., transporting hazardous cargo between UAVs.

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