Teleoperation of an Aerial Manipulator Robot with a focus on Teaching – Learning Processes

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Latacunga

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Abstract. This paper presents a bilateral teleoperation scheme for the aerial manipulator consisting of a 3DOF robotic arm on a six-propeller unmanned aerial vehicle (Matrix 600 Pro), which allows the operator to perform complex tasks in partially structured environments. The development of the controller is based on the kinematic model of the aerial manipulator, which allows precise control of its movements in relation to the use of a haptic device (Falcon Novint), which allows a feedback of forces from the operator environment. In addition, a teleoperation control scheme is proposed that performs actions in: *i) Locomotion mode*, this allows the manipulation and navigation of the robot's movement; *ii) Navigation mode*, which allows transmitting the desired movement of the UAV by means of speed signals; and *iii) Manipulation mode,* allows to transmit the desired movement of the robotic arm through positions. Tests were performed in a virtual reality environment, in order to test control algorithms and perform simulations that resemble the conditions of a real environment, in addition experimental tests of the proposed teleoperation scheme were performed, obtaining an optimal behavior of the aerial manipulator robot. Finally, simulation results will be presented to validate and test the teleoperation scheme.

Keywords: aerial manipulator, kinematics, bilateral teleoperation, haptic device, virtual reality.

1 Introduction

Robotics is a discipline that has experienced growth in recent years and has gained great importance in different fields of application. This discipline presents sustainable solutions to solve problems in various areas such as industry, military, medicine and education [1] [2]. Therefore, Robotics and automation are important topics in modern industry in the development of technological advances, which allow robots to excel in industrial automation for quality improvement and increased production [3]. During the technological evolution robots leave industrial environments to perform activities in partially structured spaces taking the name of service robot. In general, service robots have the potential to improve the quality of life for humans by providing assistance with tasks that are difficult or impossible for them to perform on their own. As technology continues to advance, service robots are likely to become increasingly common in a variety of industries and applications [4]. In addition, there is a field that focuses on the design and development of autonomous and tele-operated robots to assist humans in various tasks. These robots can be terrestrial, aerial or marine and their mobility can vary from legs, wheels or propellers, for which their capacity to provide services depends largely on their mechanical design and their ability to adapt to different environments [5]. While aerial manipulators can be considered as the natural evolution of mobile robotics, adding manipulation capabilities to the versatility and agility of UAVs. This will undoubtedly improve the quality of many workers operating in hazardous conditions and situations [6] [7].

One of the key aspects of intelligent control is machine learning, which enables robots to learn and adapt to their environment. In addition, advanced sensors are being used to detect and respond to changes in the environment [5]. On the other hand, the control of an aerial manipulator robot is a complex problem if the dimensions and weight of the robotic arm are relevant with respect to the weight of the UAV [8] [9]. In fact, there are several ways to study and control these systems; *i*) *decoupled system*, i.e., the kinematic model of the UAV and the robotic arm is made, also the control of each of these parts is made, therefore, the point of interest of the kinematic analysis of the UAV is made with respect to the center of mass and the point of interest of the kinematic analysis of the robotic arm is made with respect to the operating end; *ii*) *coupled system*, i.e., the kinematic modeling and control is done for the system as a whole, for the modeling and control of this system is done with respect to the end-effector of the air manipulator. [10] [11]. Finally, the difficulty of executing tasks that require high precision may make it necessary to merge teleoperated controls and automatic control [12]. In another aspect, virtual environments with the progressive advance of virtual reality (VR) focused on the teaching-learning process must have computer generated real life scenes present, allowing robot-human interaction, ensuring educability in students where they can obtain a better performance and solve their concerns, also the virtual simulator allows interaction with the virtualized robot for future proposals of advanced control algorithms [3] [13].

Today there are teleoperated robots that allow users to perform object manipulation tasks in inaccessible or dangerous environments [14]. As teleoperated robots are capable of performing tasks in hazardous environments and can be operated from a secure location [15]. In other words, teleoperation could be defined as a remote operation or manipulation of a system to perform specific tasks in any environment with a high degree of reliability and therefore no failures or serious consequences [16]. On the other hand, teleoperation is a technique that allows human operators to control robots remotely via an interface. This interface can handle a large amount of information in real time, which means that the information must be processed quickly in order to make decisions and take actions at the right time [17] [18].

This work focuses on the development of a bilateral teleoperation scheme that allows a human operator to perform complex tasks in a remote environment with an aerial manipulator. It is divided into the following stages: i) *Local Site*, is mainly composed by the human operator who in turn can monitor and control an aerial manipulator robot. For which, a Human Machine Interface (HMI) is considered where the human operator will interact with the aerial manipulator robot, allowing to execute navigation and manipulation tasks. In addition, a 3DOF haptic device is considered at the local site that considered through the haptic device; ii) *Remote Site*, is composed of an aerial manipulator robot consisting of an unmanned aerial vehicle with six rotating propellers and a 3DOF robotic arm, in order to perform navigation and manipulation tasks in partially structured environments. It is worth mentioning that the aerial manipulator robot is equipped with proprioceptive sensors that will allow defining the position and velocity of the robot with respect to an inertial reference system. At the same time, the imple-mentation of exteroceptive sensors that will allow monitoring the interaction of the aer-ial manipulator robot with the environment is considered. For the motion control of the aerial manipulator robot, the implementation of a control algorithm that generates the maneuverability signals for both the unmanned aerial vehicle and the robotic arm is considered. In addition, the control algorithm is based on the nonlinear model of the aerial manipulator robot; iii) *Comunication Channel*, transfers the bilateral information between the local site and the remote site through a local wireless network with the objective of reducing communication delays, considering negligible delays and finally iv) *Experimental Tests*, several experimental tests are carried out in order to validate the bilateral teleoperation scheme. Therefore, the present work is composed of 6 sections, including the introduction, which presents the state of the art of tele-operation of an aerial manipulator robot, in section II the methodology and digitalization detailing the stages of development of a virtual environment that allows the validation of the bilateral teleoperation scheme and the experimentation tests; Section III presents the mathematical modeling of the aerial manipulator which is performed separately respectively; In section IV, the design of the teleoperation scheme including the advanced control will be carried out, which allows the stability analysis. Section V presents the analysis and results obtained and finally, Section VI presents the conclusions of the research work.

2 Methodology and Digitization

This section describes the methodology to be implemented, which details the technique to generate the solution of a bilateral teleoperation scheme, in addition, there is the digitization of the work environment in which the experimentation of the real aerial manipulator and the virtualized environment are carried out.

2.1 Methodology

Figure 1 shows the methodology of the development stages for the implementation of a Human Machine Interface (HMI) in the Unity3D simulator in order to perform experimental tests in a real way and at the simulation level.

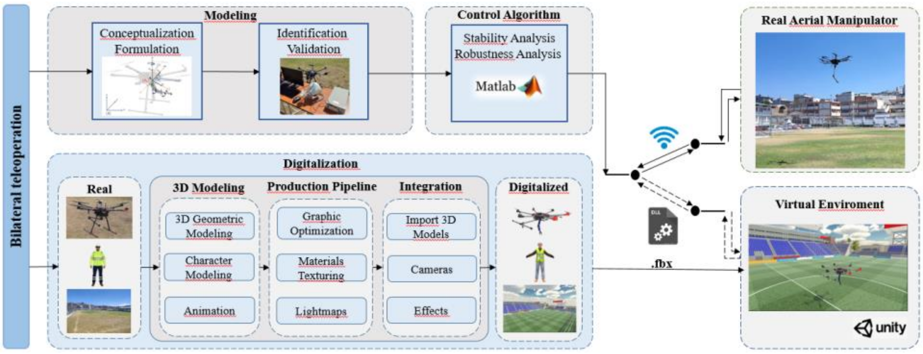

Figure 1. Methodology for the control and digitalization of the aerial manipulator.

The proposed scheme is based on four main stages: *i) Modeling*, the mathematical model is made with the purpose of simulating the behavior of the aerial manipulator in a virtual environment. In addition, a kinematic model that represents the characteristics and restrictions of movement of an unmanned aerial vehicle and a robotic arm is also considered. It is also considered the identification and validation of the parameters through experimental tests; ii) *Control Algorithm*, the proposal of a bilateral teleoperation scheme is developed, which allows the execution of navigation and manipulation tasks, which will be evaluated through stability and robustness analysis, this control algorithm is implemented in MatLab software; iii) *Experimental Tests*, real tests are carried out by means of wireless communication and simulation tests in which a virtual environment is created that considers the reconstruction of external resources and processes; iv) *Digitization*, Both the aerial manipulator and the environment where the different tests are performed, for which these are modeled using CAD tools, considering their real shapes in order to have immersion and interaction. In addition, we simulate disturbances and different weather conditions that affect the navigation and manipulation of the aerial manipulator robot at the time of executing the defined tasks. And finally, using 3DS Max software (Autodesk, FreeCAD, SolidWorks), files compatible with Unity 3D software is exported [3].

2.2 Virtual Environment

Virtual environments allow to carry out strengthening activities in teaching-learning processes, with the objective of evaluating the performance of a control algorithm. It is for this reason that it is necessary to have an environment to experiment the performance of robots before they perform any task in a real environment. For this reason, this section describes the development of a 3D virtual simulator that allows to verify the performance of an aerial manipulator robot.

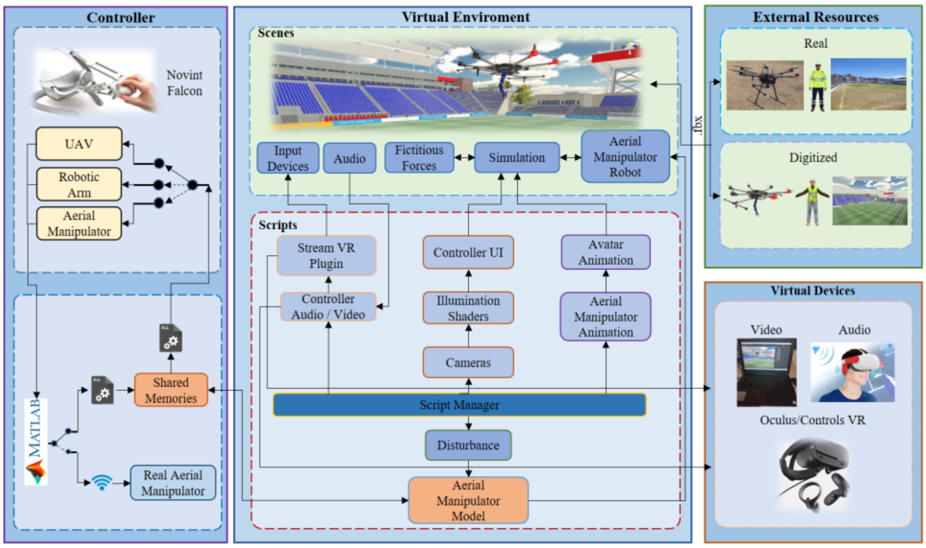

Figure 2. Proposed outline of the virtual environment.

The implementation scheme of the virtual simulator of the aerial manipulator robot and its environment is shown in Figure 2, which consists of three main stages: *i) External Resources*, comprises all the elements immersed in the virtual environment, these elements are the following; virtualized scenario, aerial manipulator robot and avatar; *ii) Virtual Environment*, has implemented a real time graphic representation system, for the development of the process it is organized in two groups: *a)* Scenario, contains the implementation of CAD models, audios and other elements; *b) The Scripts*, are programmed by code blocks that allow the exchange of information between the input and output devices connected to the system, it is also possible to emulate the real behavior of an unmanned aerial vehicle in conjunction with a robotic arm. These scripts allow the management of the libraries (SDK) focused on the virtual input devices, which enable the interaction and communication between them. The remaining scripts manage the other components involved in the virtual scenery, such as: the model of the aerial manipulator, the user interface, the lighting, the camera selection, the audio control and the weather disturbances. Finally, *iii) The Controller*, allows the implementation of advanced control algorithms capable of controlling the aerial manipulator robot in order to perform navigation and manipulation tasks [3] [19]. Therefore, through the haptic device is considered a force feedback to the human operator where through its buttons will control UAV, robotic arm and aerial manipulator. From the MatLab software, the tests are performed experimentally by controlling the real aerial manipulator through wireless communication and through bilateral communication where the information is shared through Dynamic Link Library (DLL) in which the method of shared memories is implemented to the simulated aerial manipulator through the virtual environment.

3 Robot Kinematic Model

This section describes the kinematic modeling of the aerial manipulator consisting of an unmanned aerial vehicle with six rotating propellers and a 3 DOF robotic arm. Therefore, the kinematic model can be used to simulate and analyze the behavior of the robot under different conditions, to design control strategies that allow the robot to perform specific tasks autonomously, semi-autonomously or teleoperated.

3.1 Robotic Arm

Figure 3 shows the configuration of the kinematic model that consists of the relationship between the position and orientation of the end-effector of the robotic arm and the configuration variables of the robotic arm, which allows the precise control of the movement in front of the desired task [20]. Therefore, the manipulator provides the deriva-tive of the end-effector position as a function of the derivatives of the robotic arm in which Eq. (1) is detailed.

$$\dot{\boldsymbol{h}}_a(t) = \boldsymbol{J}_a\big(\boldsymbol{q}_a(t)\big)\dot{\boldsymbol{q}}_a(t) \tag{1}$$

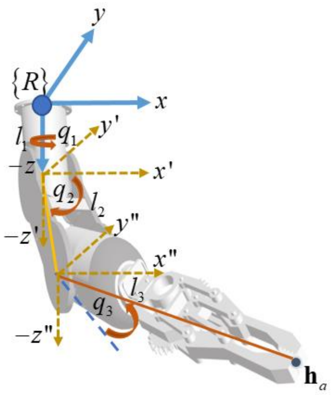

Figure 3. Kinematic diagram of the robotic arm.

where, $\dot{\boldsymbol{h}}_a(t)$ is the velocity vector of the end-effector, $\boldsymbol{J}_a\big(\boldsymbol{q}_a(t)\big)$ is the Jacobian matrix of the robotic arm and $\dot{\boldsymbol{q}}_a(t)$ is the vector of joint velocities of the manipulator.

3.2 Unmanned Aerial Vehicle (UAV)

The kinematic model of the UAV refers to the mathematical representation of the robot's motion in the workspace. The robot considered in this work (hexacopter) has four maneuverability velocities represented in the reference frame $\{R_D\}$, these velocities allow the robot to move in the work space. Figure 4 shows the kinematic variables of a hexacopter in the fixed reference frame $\{R\}$.

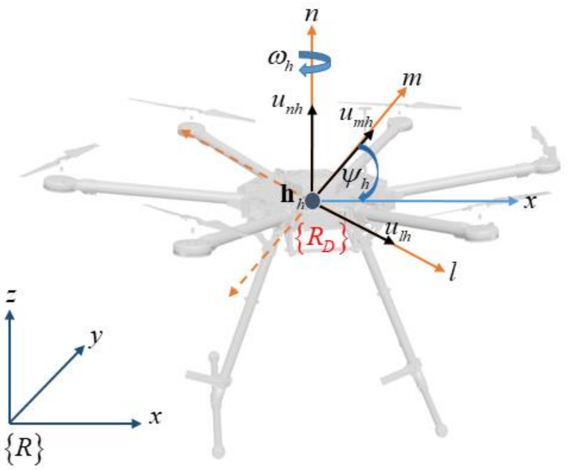

Figure 4. UAV kinematic diagram.

The kinematic model of the UAV is expressed in Eq. (2) as follows:

$$\dot{\boldsymbol{h}}_h(t) = \boldsymbol{J}_h\big(\psi_h(t)\big)\boldsymbol{u}_h(t) \tag{2}$$

where, $\dot{\boldsymbol{h}}_h = [\dot{x}_h \quad \dot{y}_h \quad \dot{z}_h \quad \dot{\psi}_h]^T$ is the velocity vector in the fixed reference frame $\{R\}$, $\boldsymbol{J}_h\big(\psi_h(t)\big)$ is the matrix that transforms the control velocities into the velocities of the reference system and $\boldsymbol{u}_h = [u_{lh} \quad u_{mh} \quad u_{nh} \quad \omega_h]^T$ represents the vector of control velocities of the UAV [2] [21].

3.3 Aerial Manipulator

The kinematic model is an important component of the aerial manipulators, since it allows to motion control and position control of the end-effector, taking into account that $\boldsymbol{h} = f(\boldsymbol{q}_u, \boldsymbol{q}_a)$ is a function of the UAV and the robotic arm configuration respectively. Therefore, the kinematic model of the aerial manipulator is detailed in Eq. (3).

$$\dot{\boldsymbol{h}}(t) = \boldsymbol{J}\big(\boldsymbol{q}(t)\big)\boldsymbol{v}(t) \tag{3}$$

where, $\boldsymbol{J}\big(\boldsymbol{q}(t)\big)$ is the Jacobian matrix that defines a linear mapping between the vector of the robot arm velocities $\boldsymbol{v}(t) = [u_l \quad u_m \quad u_n \quad \omega \quad \dot{q}_1 \quad \dot{q}_2 \quad \dot{q}_3]^T$ and the end-effector velocity vector $\dot{\boldsymbol{h}}(t) = \big[\dot{h}_x \quad \dot{h}_y \quad \dot{h}_z\big]^T$ [2] [21].

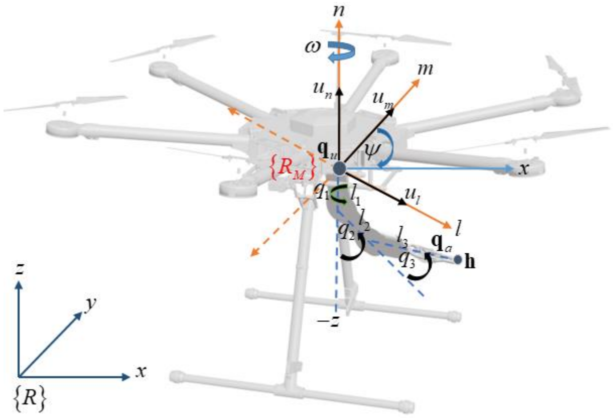

Figure 5. Kinematic diagram of the aerial manipulator.

4 Teleoperation Scheme

Figure 6 shows the proposed teleoperation scheme, which is divided into the following stages: *i) Local Site*, is mainly composed by the human operator who in turn can monitor and control an aerial manipulator robot. For which, a Human Machine Interface (HMI) is considered, where the human operator will interact with the aerial manipulator robot, allowing to execute navigation and manipulation tasks. In addition, a 3DOF haptic device is considered at the local site that will allow transmitting the desired motion through the position and velocity of the aerial manipulator robot. In addition, a force feedback to the human operator will be considered through the haptic device; *ii) Remote Site*, is composed of an aerial manipulator robot consisting of an unmanned aerial vehicle with six rotating propellers and a 3DOF robotic arm, in order to perform navigation and manipulation tasks in partially structured environments. It is worth mentioning that the aerial manipulator robot is equipped with proprioceptive sensors that will allow defining the position and velocity of the robot with respect to an inertial reference system. For the motion control of the aerial manipulator robot, the implementation of a control algorithm that will generate the maneuverability signals for both the unmanned aerial vehicle and the robotic arm will be considered. Furthermore, the control algorithm is based on the nonlinear model of the aerial manipulator robot; and finally *iii) Communication Channel*, transfers bilateral information between the local site and the remote site through a local wireless network with the objective of reducing communication delays, considering negligible delays.

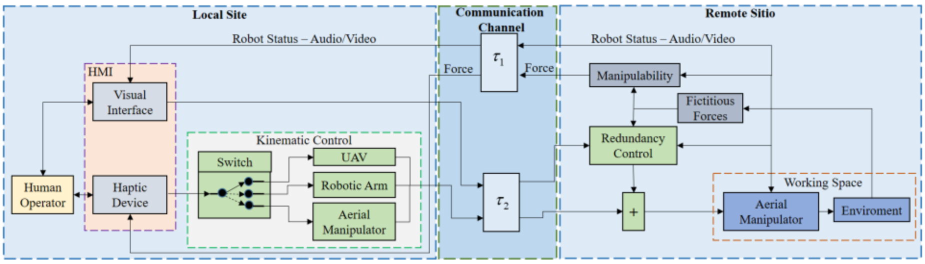

Figure 6. Bilateral teleoperation scheme.

4.1 Robotic Arm Controller

The human operator controls the robotic arm by means of position errors through the Falcon Novit device, these signals are transformed into position commands and sent to the remote site, which will be executed by the robotic arm [19]. On the other hand, from the point of view of control theory, the end-effector must follow a desired trajectory for which the following nonlinear control law has been proposed and is expressed in Eq. (4).

$$\boldsymbol{u}_{ref\_a} = \boldsymbol{J}_a^{-1}\left(\boldsymbol{L}_K\, tanh\left(\boldsymbol{L}_K^{-1}\boldsymbol{K}\tilde{\boldsymbol{h}}_a\right)\right) \tag{4}$$

where, $\boldsymbol{J}_a^{-1}$ is the inverse matrix of $\boldsymbol{J}_a$, $\tilde{\boldsymbol{h}}_a$ is the vector of control errors defined as $\tilde{\boldsymbol{h}}_a = \boldsymbol{h}_{ad} - \boldsymbol{h}_a$, $\boldsymbol{K}$ y $\boldsymbol{L}_K$ are diagonal matrices that weight the vector $\tilde{\boldsymbol{h}}_a$. However, in order to include an analytical saturation of velocities in the robotic arm, we propose the use of the function $\boldsymbol{tanh}(.)$, which saturates the errors $\tilde{\boldsymbol{h}}_a$ [19].

4.2 UAV Controller

By means of the kinematic model of the UAV, an advanced control algorithm is implemented to perform navigation tasks, this algorithm considers a control law, which implements trajectory tracking, which is generated by the operator and is defined by:

$$\boldsymbol{u}_{ref\_h} = \boldsymbol{J}_h{}^{-1}\left(\dot{\boldsymbol{h}}_{hd} + \boldsymbol{K}_h\, tanh\left(\tilde{\boldsymbol{h}}_h\right)\right) \tag{5}$$

where, $\boldsymbol{J}_h{}^{-1}$ is the inverse matrix of $\boldsymbol{J}_h$; $\dot{\boldsymbol{h}}_{hd}$ is the vector of velocities generated by the haptic device. These velocities occur in the fixed reference system $\{R\}$, because the return information to the operator is the position of the UAV in the system; $\boldsymbol{K}_h$ is the positive diagonal matrix that weights the control error and $\tilde{\boldsymbol{h}}_h$ is the position of the error [21] [22].

4.3 Aerial Manipulator Controller

The proposed control algorithm for the execution of manipulation and navigation tasks must be implemented according to the technique to be used. That is, for the technique of a bilateral teleoperation scheme, a different mathematical software hosted on the same computer is considered [2]. On the other hand, the proposed control algorithm will consider a nonlinear control law based on the kinematic mode of an aerial manipulator robot, which is expressed in Eq. (6).

$$\boldsymbol{u}_{ref\_m} = \boldsymbol{J}^{\#}\dot{\boldsymbol{h}}_d + (\boldsymbol{I} - \boldsymbol{J}^{\#}\boldsymbol{J})\boldsymbol{L}\,tanh(\boldsymbol{L}^{-1}\boldsymbol{B}\Lambda) \tag{6}$$

where $\boldsymbol{J}^{\#} = \boldsymbol{W}^{-1}\boldsymbol{J}^T(\boldsymbol{J}\boldsymbol{W}^{-1}\boldsymbol{J}^T)^{-1}$; being $\boldsymbol{W}$ a positive definite matrix that weights the control actions of the system; $\dot{\boldsymbol{h}}_d$ is the vector of desired end-effector velocities; $\boldsymbol{L}$ y $\boldsymbol{B}$ are positive definite diagonal matrices which weight the vector Λ. On the other hand, we represent the projection on the null space of $\boldsymbol{J}$, where Λ is an arbitrary vector containing the velocities associated with the air manipulator. Therefore, any value given to Λ will have effects only on the internal structure of the air manipulator and thus will not affect the control of the end-effector [20].

To evaluate the behavior of control errors control $\tilde{\boldsymbol{h}}$ stability analysis is performed using the Lyapunov theory considering the Lyapunov candidate function as $\boldsymbol{V}(\tilde{\boldsymbol{h}}) = \frac{1}{2}\tilde{\boldsymbol{h}}^T\tilde{\boldsymbol{h}}$, which is derived by obtaining $\dot{\boldsymbol{V}}(\tilde{\boldsymbol{h}}) = \tilde{\boldsymbol{h}}^T\dot{\tilde{\boldsymbol{h}}}$ [10]. On the other hand, perfect tracking of the velocity is considered, *i.e.*, $\boldsymbol{v} = \boldsymbol{u}_{ref\_m}$. Substituting the controller (6) in the kinematic model of the manipulator (3), we obtain the closed-loop equation $\dot{\tilde{\boldsymbol{h}}} = 0$. Finally, re-placing the closed-loop equation in the evolution of the Lyapunov candidate function results that:

$$\dot{\boldsymbol{V}}(\tilde{\boldsymbol{h}}) < 0 \tag{7}$$

As (7) is negative definite, therefore, the control error converges to zero, then the system is asymptotically stable.

Remark: It should be noted that for each of the cases of the control algorithms for the robotic arm, UAV and aerial manipulator proposed, the stability analysis is similar to that performed previously, therefore, it is concluded that the control errors converge to zero and therefore the systems are asymptotically stable.

On the other hand, for this case, the internal configuration of the air handler is considered as a secondary objective, defined as $\Lambda = [0 \quad 0 \quad 0 \quad \tilde{\boldsymbol{q}}_1 \quad \tilde{\boldsymbol{q}}_2 \quad \tilde{\boldsymbol{q}}_3]$, where $\tilde{\boldsymbol{q}}_i = \bar{\boldsymbol{q}}_{di} - \boldsymbol{q}_i$ with $i = 1,2,3$, corresponds to the internal configuration of the desired arm.

5 Analysis and Results

This section describes the behavior of a bilateral teleoperation scheme for an aerial manipulator, in which the following aspects are considered: *i) Simulator*, using the working environment developed in Unity 3D, which receives the behavioral signals of the proposed control algorithm; and ii) E*xperimental Tests*, with the aerial manipulator consisting of the UAV (Matrix 600Pro) and a 3DOF robotic arm, which receive force feedback signals through a haptic device.

A. Virtual Simulator

The behavior of the proposed control scheme is tested by means of a virtual working environment where the virtualization of the aerial manipulator is considered, for which force feedback signals are sent through the Falcon Novint device as shown in Figure 7. While in Figure 8, the behavior of the aerial manipulator to execute manipulation and navigation tasks in partially structured environments is shown.

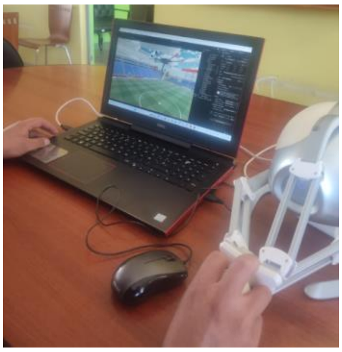

Figure 7. Human Operator at the local site.

Figure 8. Movement of the robot in the virtual environment.

B. Experimental Tests

In this experiment the controller is run from Matlab, however, the operator generated data from the local site is sent to the robot via wireless communication, the robot receives the operator generated reference commands and executes the task. The experiment consists of three stages: i) the operator has to position the UAV to a desired position; ii) once the UAV is positioned, the operator performs a task only with the robotic arm using the haptic device; and iii) finally the operator generates references for the entire air handler, controlling the operating end. Figure 9 shows the remote site and Figure 10 shows the robot executing the task in the real partially structured environment.

Figure 9. Remote Site.

Figure 10. Motion tests of the real aerial manipulator.

Figure 11 shows the evolution of the UAV, it is observed how the robot reaches the desired position, by means of the operator at the remote site. Figure 12 indicates the control errors; in this case the control change is made when the three position errors are at zero or very close to zero.

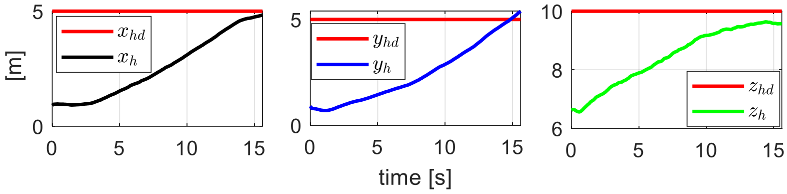

Figure 11. Evolution of the UAV.

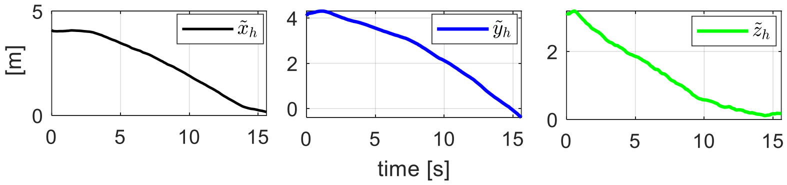

Figure 12. UAV control errors.

Figure 13 indicates the desired position generated by the operator and the evolution of the robotic arm position. It can be seen how the arm follows the references generated by the haptic device. And Figure 14 indicates the control errors of the robotic arm, it can be seen how the errors tend to be close to zero, i.e., the end of the robotic arm follows the reference position generated by the operator at the local site.

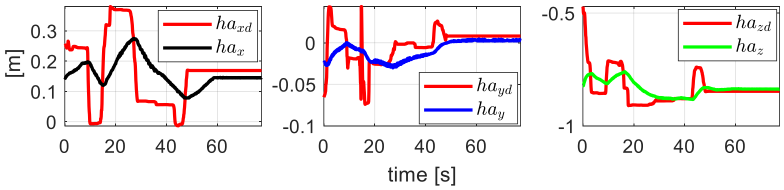

Figure 13. Desired position generated by the operator and the evolution of the robotic arm position.

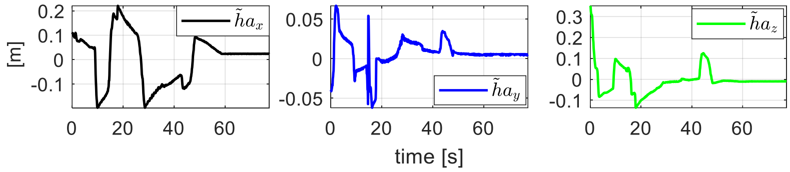

Figure 14. Robotic arm control errors.

Finally, in the final stage of the experiment, the entire robot, i.e. the operating end, is controlled. Figure 15 indicates the desired position generated by the operator (red line) and the evolution of the operating end. And Figure 16 indicates the control errors, it can be seen how the control errors of the operating end of the robot tend to be zero, i.e., the operating end follows the references generated by the operator at the local site.

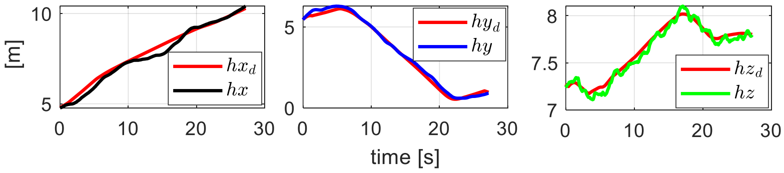

Figure 15. Desired position generated by the operator and the evolution of the operating end.

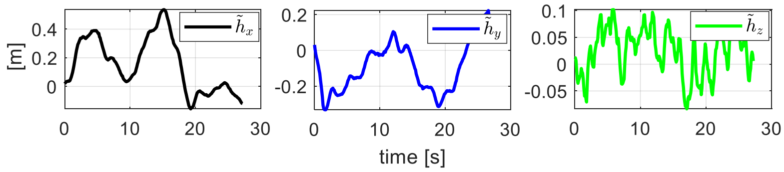

Figure 16. Operating end control errors.

6 Conclusions

This paper proposes a virtual environment that is used to simulate the bilateral teleoperation of an aerial manipulator. The Virtual environment developed is highly integrated with Matlab, allowing control commands to be sent. By integrating the virtual environment with the controller, the teleoperation scheme can be evaluated in a simulated manner, allowing the controller gains to be adjusted and allows the operator to become familiar with the haptic device. Therefore, the simulation of the virtual environment allows the human operator to test advanced control algorithms and evaluate their performance before implementing them in the real world. Experimental results show how the operator generates reference commands by means of the haptic device and the real robot executes them. The scheme allowed separate control of the UAV and the robotic arm, in order to perform tasks with higher pressure. Firstly, by positioning the UAV to subsequently execute a manipulation or object grasping tare with the robotic arm. Finally, the control of the operating end of the robot was evaluated jointly. With the evaluated control scheme, for future work it is proposed to add the dynamics of the robot to the control scheme to compensate the dynamics of the whole system.

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