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Simulation of remote control of a hexacopter with force feedback in semi-structured environments

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Abstract: This project simulates the flight of hexacopters in indoor environments. Through the design, modeling, and implementation of environments, it imitates semi-structured environments with static obstacles, including a house, a church, and a supermarket. Each environment displays different levels of difficulty. The application offers a choice between two models of hexacopters, achieving more useful and interactive, and it includes the option of force feedback, implemented with a force feedback joystick, warning the user about possible collisions, and giving the feeling of presence to the operator. The haptic device limits the force applied. The application focuses on three-dimensional scenes in semi-structured indoor environments, reproducing the environment variables (appearance, features, context) of a real system; in this sense, the implementation of the simulator is a low-cost technique that offers several possible scenarios without effects in the real world.

Keywords: hexacopters, haptic device, force feedback, simulation.

Simulación de control remoto de un hexacóptero con retroalimentación de fuerza en entornos semiestructurados

Resumen: Este proyecto simula el vuelo de hexacópteros en ambientes interiores. A través del diseño, modelado e implementación de entornos, imita entornos semiestructurados con obstáculos estáticos, incluyendo una casa, una iglesia y un supermercado. Cada entorno muestra diferentes niveles de dificultad. La aplicación ofrece la posibilidad de elegir entre dos modelos de hexacópteros, consiguiendo ser más útiles e interactivos, e incluye la opción de retroalimentación de fuerza, implementada con un joystick de retroalimentación de fuerza, advirtiendo al usuario sobre posibles colisiones, y dando la sensación de presencia al operador. El dispositivo háptico limita la fuerza aplicada. La aplicación se centra en escenas tridimensionales en ambientes interiores semiestructurados, reproduciendo las variables del entorno (aspecto, características, contexto) de un sistema real; En este sentido, la implementación del simulador es una técnica de bajo coste que ofrece varios escenarios posibles sin efectos en el mundo real.

Palabras clave: hexacópteros, dispositivo háptico, retroalimentación de fuerza, simulación

I. INTRODUCTION

The development of flight simulators is a solution to the education and training of students in various areas of engineering. The advantages of using a flight simulator as a facilitating tool for the experience acquisition are very high. The student can develop his capabilities since high-performance training stimulates the mental, physical, and psychological aspects. In this way, the simulation allows them to obtain skills for a proper flight, a realistic flight experience, and a high confidence level in the flight simulator. [1].

Computer simulation is often used to model systems for which analytical solutions cannot be found [2]. By simulating the teleoperation of a hexacopter, focused on applications of three-dimensional scenarios in internal semi-structured environments, reproducing the environment and its variables (appearance, features, context), constitutes a technique of low cost that offers several possible scenarios without effects in the real world.

We propose the Unity 3D video game engine utilization to simulate semi-structured environments with static obstacles, and two models of hexacopters. In addition, the application has the option to use the feedback force, which is carried out with the Microsoft SideWinder Force Feedback 2 Joystick haptic device; this controller limits the force feedback applied, allowing warn the user about possible collisions, and giving the feeling of presence to the operator. Finally, a series of tests are carried out to evaluate their performance. Initially, menus, scenarios, and maps are validated to continue with the behavior of the hexacopters during their flights, ending with user feedback on the handling of the Flight Simulator, which is done through a survey that complements the previous evaluations.

II. UNMANNED AERIAL VEHICLE

An unmanned aerial vehicle (UAV) is defined as an aircraft without a crew, which may be reusable and can maintain a level of controlled and sustained flight. This vehicle is powered by one or more engines [4].

Advances in UAVs have been significant so their applications increasing with time. One of the main reasons is that they can be used for tasks that involve some difficulty or danger to conventional vehicles crewed by people [5]. Also, UAVs acquire great importance in performing inspection, control, and sensing of high chemical toxicity tasks, thus reducing human exposure. Each of them would imply a high cost and risk to people, and loss of productivity without their use [6].

A. Hexacopter

A hexacopter is a type of UAV that consists of six rotors, arranged in four distinct configurations [7]. Among the main characteristics of this type of vehicle is good stability, due to the opposite direction of rotation of its propellers, which prevents it from rotating on its axis continuously due to the inertia of these. They also have a good time in flight concerning UAVs of the smallest number of rotors, since they can carry larger batteries and their motors work at fewer revolutions. Finally, it is important to emphasize their great power and load capacity [8]. The possible configurations of a hexacopter are: Cross (+), X, Y6, and H (Fig. 1).

"A hexacopter exhibits flight performance comparable to that of a helicopter. It maneuvers by rotating its propellers, which generate the necessary thrust for movement. Each engine can be controlled independently, allowing for various translations and rotations by adjusting the speed of each axis as needed. During a hexacopter's flight, several forces and torques are considered, including gravity, air friction, and the torque produced by the propellers." (Fig. 2) [9].

The simpler movement is the ascent and descent vertical of the aircraft, which is possible with the increase and decrease of the speed of the rotors of form equal and simultaneously [5].

The roll angle represents rotation around the 'x' axis, resulting in left or right movement, as shown in Figure 3a. To move left, the hexacopter decreases the thrust produced by the propellers on the left side while increasing the thrust from the propellers on the right side. Conversely, to move right, the hexacopter reduces the thrust from the propellers on the right side and simultaneously increases the thrust from the propellers on the left side.

The pitch angle represents the "z" axis rotation, and generates the movements back and forth of the aircraft, as shown in Fig. 3b. For forward movement, the hexacopter increases the thrust produced by the propellers on the back and diminishes the thrust produced by the front propellers.

Yaw angle represents a rotation around the axis 'y' and is generated by increasing the thrust produced by the propellers rotating in a clockwise direction, while decreasing the thrust produced by the propellers rotating counter-clockwise, as shown in Fig. 3c. And turn, the opposite direction is achieved by decreasing the thrust produced by the propellers rotating in a clockwise direction, while increases the thrust produced by the propellers rotating counter-clockwise.

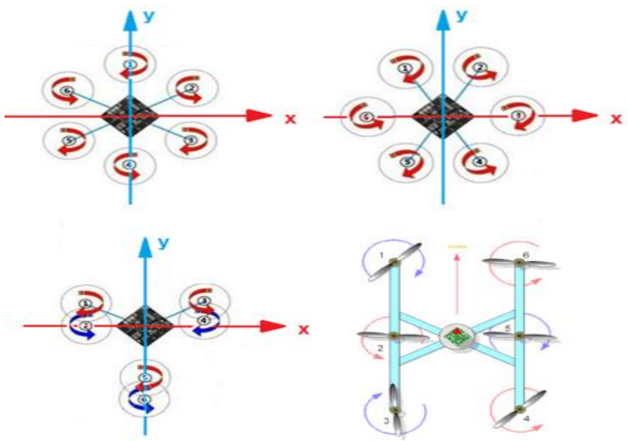


Fig 1. Configurations of a hexacopter: Cross (+), x (x), Y6, and H.

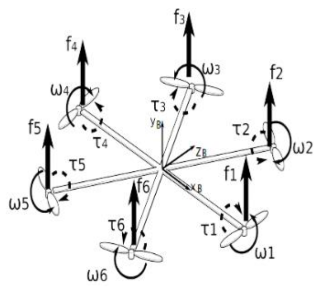
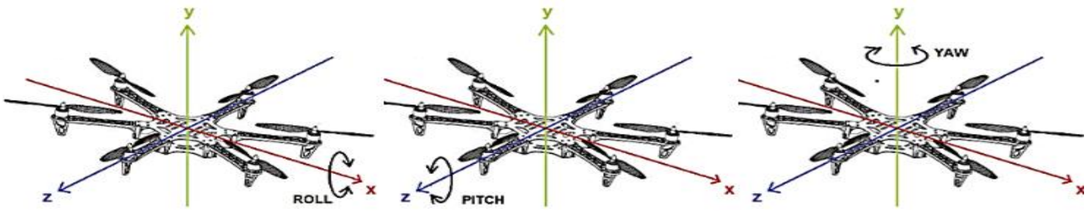


Fig. 2. Thrusts, torques, and angular velocities of a hexacopter [9].



(a) (b) (c)

Fig. 3. Movements of rotation of a hexacopter: a) Roll, b) Pitch, c) Yaw

B. Human machine interface

The human-machine interface (HMI) can be understood as the point of action in which a man comes in contact with a machine [10]. The user can interact with reality, experiencing it and exploring it through different HMI options, such as the force feedback joystick and the keyboard. The last mentioned device is within the classification of haptic devices, since it involves the sense of touch, allowing one to enter a virtual world closer to a real environment, where there is a set of characteristics of objects such as elasticity, viscosity, adhesion, etc., which can be complemented by the force feedback [11].

C. Fictitious forces

Such forces explain the apparent acceleration of a body seen from a non-inertial reference system [12]. One of the objectives pursued by the project is the evasion of static obstacles in semi-structured environments, which proposes the creation of fictitious forces when the aircraft identifies an obstacle between the next two elements: the hexacopter and the obstacle.

The use of fictitious forces is a simple and efficient method, these forces are arranged in such a way that cover the aircraft environment and play the role of repelling any obstacle found in its field, increasing this repulsion always decreases the distance between the two objects. The diameter of the environment of the aircraft is defined considering the dimensions of the hexacopters and the environments, according to the criteria of the author, a length of three times the diameter of the hexacopters, for the evasion of obstacles.

Fig. 4 observes the scheme of evasion of obstacles, where d is the distance in which begins repulsion of the hexacopter towards the obstacle is found, and F is the fictitious force that will be sent as feedback towards the haptic device, delivering the information of change of address to the user. The algorithm for the calculation of this force depends on the magnitude of the distance.

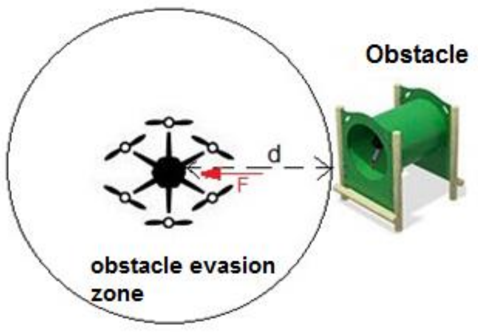


Fig. 4. Scheme of evasion of obstacles

III. HEXACOPTER MODEL

To obtain the dynamic model based on equations that describe the position and orientation of the hexacopters is assumed that each aircraft is a rigid body in space, subject to a main force, which corresponds to the thrust, and three moments, that will generate the movements of the vehicle [13]. This behavior is controlled by adjusting the angular speed of the rotors spinning through electric motors [14]; and the fixed Center of mass and the origin of the coordinate system are considered coincidental, assuming that the structure of the hexacopter is symmetric [13].

To describe the movement of the hexacopter we will need two systems of reference [14]: the earth system and the body system. The Earth system is seen as inertial, which is defined as the absolute linear position of the hexacopter (x, y, z). The body system uses the coordinates of North, East, and South. The origin of this reference system is fixed at a point on the Earth's surface, and the axes are directed in the following way: x - North - and eastward and z - downward. The angular position of the body concerning the inertial system is defined using Euler angles: roll, pitch, and yaw. It is necessary to find the transformations of the body to the inertial system, which is relied on to use the rotation matrix, starting with the rotations around the axes [13].

By rotating each of the angles roll, pitch, and yaw, it gets the matrix of rotation R (1) for the transformation of the system, inertial or fixed to the body, which is an orthogonal system.

$$R(\emptyset)R(\theta)R(\psi) = \begin{bmatrix} \cos\theta\cos\psi & \cos\psi sen\theta sen\emptyset - \cos\emptyset sen\psi & \cos\emptyset\cos\psi sen\theta + sen\emptyset sen\psi \\ \cos\theta sen\psi & \cos\emptyset\cos\psi + sen\theta sen\emptyset sen\psi & \cos\emptyset sen\theta sen\psi - \cos\psi sen\emptyset \\ -sen\theta & \cos\theta sen\emptyset & \cos\theta\cos\emptyset \end{bmatrix} \quad (1)$$

A. Kinematic Model [15]

Taking into account the motion of a rigid body decomposed into translation and rotation, and that the equations governing these movements are the Newton – Euler, that is expressed as a function of the linear speed of each axis of translation, V_x, V_y, and V_z are the entries of the system and the speeds of the aircraft $\dot{x_b}$, $\dot{y_b}$ and $\dot{z_b}$.

With the defined model, the rotation matrix (1) is used as a link between the Centre of mass reference system and the fixed ground system.

$$\begin{bmatrix} \dot{x_E} \\ \dot{y_E} \\ \dot{z_E} \end{bmatrix} = R(\emptyset, \theta, \psi) \begin{bmatrix} \dot{x_B} \\ \dot{y_B} \\ \dot{z_B} \end{bmatrix} \quad (2)$$

Replacing (1) in (2) gets complete kinematic models depending on angles ∅, θ and ψ.

It can be reduced through approximations of small angles, which is convenient in the simplification of the trigonometrical laws, and presents an acceptable accuracy when the angle tends to zero, assuming $\theta \to 0$ and $\emptyset \to 0$, it has $\cos\emptyset \cong 1$, $\cos\theta \cong 1$ and $\sin\emptyset \cong 0$, $\sin\theta \cong 0$, obtaining:

$$\begin{bmatrix} \dot{x_E} \\ \dot{y_E} \\ \dot{z_E} \end{bmatrix} = \begin{bmatrix} \cos(\psi) & -\text{sen}(\psi) & 0 \\ sen(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \quad (3)$$

B. Dynamic Model

A dynamic model is applied to the scheme of the hexacopter of Fig. 5 and it is performed employing Euler-Lagrange equations and Newton's laws [16]. The hexacopter has twelve States, which are [16]:

$$X = [x, \dot{x}, y, \dot{y}, z, \dot{z}, \emptyset, \dot{\emptyset}, \theta, \dot{\theta}, \psi, \dot{\psi}] \quad (4)$$

Where x, y and z are the positions in the X, Y, Z axes; $\dot{x}$, $\dot{y}$ y $\dot{z}$ are the speed in the axes. $\emptyset, \theta, \psi$ are the roll, pitch and yaw euler angles, respectively; $\dot{\emptyset}, \dot{\theta}$ and $\dot{\psi}$ are the speed in the angles.

Euler Lagrange [15]

The Lagrangian is the sum of translational and rotational energy less the potential energy, defined by:

$$L(q, \dot{q}) = Ec_{tras} + Ec_{rot} - Ep \quad (5)$$

Where Ec_{tras} is the kinetic energy of translation, Ec_{rot} is the kinetic energy of rotation, and Ep is the energy potential of the hexacopter.

$$\begin{bmatrix} F_\xi \\ \tau_\eta \end{bmatrix} = \frac{d}{dt}\left(\frac{\partial L(q,\dot{q})}{\partial \dot{q_\iota}}\right) - \frac{\partial L(q,\dot{q})}{\partial q_i} \quad (6)$$

Where F_ξ is the translational force applied to the hexacopter, and τ_η are the moments of roll, pitch and yaw. For the translational dynamic of the vehicle, the Euler-Lagrange equation is:

$$F_\xi = \frac{d}{dt}\left(\frac{\partial L(\xi,\dot{\xi})}{\partial \dot{\xi}}\right) - \frac{\partial L(\xi,\dot{\xi})}{\partial \xi} \quad (7)$$

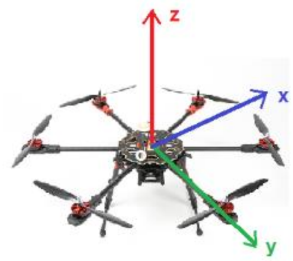


Fig. 5. The hexacopter scheme

Developing:

Where $E_z = [0 \quad 0 \quad 1]^T$, from Fig. 6 with the reference in (O), the system is $\hat{F} = [0,0, U_1]$. U_1 signal is the total thrust of the rotors. If $F_\xi = R(\emptyset, \theta, \psi)\, \hat{F}$, and replacing $\hat{F}$:

$$F_\xi = m\ddot{x} + m\ddot{y} + m\ddot{z} - mg = m\ddot{\xi} - mgE_z \quad (8)$$

$$F_\xi = \begin{bmatrix} \cos(\psi)\, sen(\theta)\cos(\phi) + sen(\psi) sen(\phi) \\ \text{sen}(\psi)\, sen(\theta)\cos(\phi) - sen(\phi)\cos(\psi) \\ \cos(\theta)\cos(\phi) \end{bmatrix} \quad (9)$$

From where is gets the translational dynamic model, that is observed in the equations (16), (17) y (18).

For the rotational dynamic, the equation is:

$$\tau_\eta = \frac{d}{dt}\left(\frac{\partial LRot}{\partial \dot{\eta}}\right) - \frac{\partial LRot}{\partial \eta} \quad (10)$$

Through the vector of angular speed and the matrix of inertia, is developed the equation and is derived each one of the terms, posing as the point of operation around the point of balance to $\phi = 0$, $\theta = 0$ and $\psi = 0$, i.e. $cos\phi \cong 1$, $cos\theta \cong 1$ and $cos\psi \cong 1$ and $sen\phi \cong 0$, $sen\theta \cong 0$ and $sen\psi \cong 0$, where is the stabilization of the system.

Therefore, the generalized moments can be expressed roll, pitch, and yaw with τ_ϕ, τ_θ and τ_ψ, respectively:

$$\tau_\phi = I_x(\ddot{\phi}) - \dot{\psi}\dot{\theta}(I_y - I_z) \quad (11)$$
$$\tau_\theta = I_y(\ddot{\theta}) - \dot{\psi}\dot{\phi}(I_z - I_x) \quad (12)$$
$$\tau_\psi = I_z(\ddot{\psi}) - \dot{\theta}\dot{\phi}(I_x - I_y) \quad (13)$$

Where I_x, I_y and I_z is the inertia of the hexacopter in X, Y and Z, respectively.

For roll, pitch, and yaw of the hexacopter movements, each rotor changes its direction of rotation and speed, such movements should be carried out with the main force constant. The rotation of the propellers produces a gyroscope effect [15]:

$$\tau_{gyroscope} = \begin{bmatrix} -J_r\dot{\theta}\omega \\ -J_r\dot{\phi}\omega \\ 0 \end{bmatrix} \quad (14)$$

Where J_r is the rotational inertia of the propellers and ω is the speed total of the propellers [16]:

$$\omega = -\omega_1 + \omega_2 - \omega_3 + \omega_4 - \omega_5 + \omega_6 \quad (15)$$

Where $\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6$ are the angular velocities of each rotor.

Adding this effect, the rotational dynamic model is obtained [16] and shown in equations (19), (20) y (21). Finally, the complete dynamic model of the hexacopter is [16]:

$$\ddot{x} = (\cos\emptyset \sin\theta \cos\psi + \sin\emptyset \sin\psi)\frac{1}{m}U_1 \quad (16)$$
$$\ddot{y} = (\cos\emptyset \sin\theta \sin\psi - \sin\emptyset \cos\psi)\frac{1}{m}U_1 \quad (17)$$
$$\ddot{z} = -g + (\cos\emptyset \cos\theta)\frac{1}{m}U_1 \quad (18)$$
$$\ddot{\emptyset} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_z}{I_x}\right) - \frac{J_r}{I_X}\dot{\theta}\omega + \frac{l}{I_x}U_2 \quad (19)$$
$$\ddot{\theta} = \dot{\emptyset}\dot{\psi}\left(\frac{I_z - I_x}{I_y}\right) - \frac{J_r}{I_y}\dot{\emptyset}\omega + \frac{l}{I_y}U_3 \quad (20)$$
$$\ddot{\psi} = \dot{\emptyset}\dot{\theta}\left(\frac{I_x - I_y}{I_z}\right) + \frac{l}{I_z}U_4 \quad (21)$$

Where b is the drag factor and l is the distance between the rotor and the center of the hexacopter.

The parameters of the dynamic model developed for the implementation of the model of the hexacopters, according to [16], are presented in Table 1.

The engine for the development of the model is Tarot 4006; according to specifications and features, they are specifically designed for aircraft with multiple rotors.

IV. RESULTS

For the development of environments and 3D models of the Simulator, we have used programs such as Sweet Home 3D, SketchUp, and Blender 3D. Likewise, to integrate them and implement the Flight Simulator, we have used the Unity 3D game engine, and through Visual Studio software implemented the dynamic model of aircraft, and also the feedback of force, which is made possible through the use of the package of Force Feedback Controller. The simulation is possible through a Force Feedback Joystick, or directly from the computer keyboard.

For the calculation of the force that appears in the joystick as opposed to the movement exerted by the user, when the aircraft is near an obstacle, taking into account the distance between the two objects, the method chosen is the creation of fictitious forces around the hexacopter, creating a zone of repulsion to the obstacles that are at the distance set in the programming, according to the dimensions of the aircraft.

Directions that take the fictitious forces that the user perceives through the controller are established through the integration of eight spokes around the hexacopter, of which four are located in the positive and negative X and Y axis and the other four correspond to the velocity, as shown in Fig. 6a. It is important to understand how is related to the strength of feedback the distance between the hexacopter and the obstacle; if the hexacopter is closer to a static object, i.e., whenever the distance is less, this force will increase.

With this preamble, it can be concluded that the strength of feedback must be inversely proportional to the distance. So it has been established a correspondence between both parameters.

$$F = 87 * \frac{1}{2+\log\left(\frac{d}{3}\right)} \qquad (22)$$

Where F is the force feedback that appears on the joystick and d is the distance between the hexacopter and the obstacle.
The algorithm implements the technique of fictitious forces raised previously, and is executed by the Flight Simulator, which is responsible for measuring the distance between the hexacopter and the obstacle found, and performs the calculation of the force on each iteration, fulfilling this way the purpose of increasing the value of the force as it decreases the distance. The magnitude of the force calculated is limited to the range [57.1, 35.1], a value dependent on the distance that lies in the interval [1, 9], considering that were designed hexacopters with a measure of 3 units.

The proposed algorithm is developed taking into account the force allowed in the haptic device, values ranging from 0 to 100, and that the user should perceive a force that advises the nearness of objects, but that doesn't force to change the address. To have an idea of the dimensions of the hexacopters, and distances in the environment generated by the simulator of flight, is important to understand the units of these dimensions. This value is multiplied by 10, and thus, an equivalent value in centimeters, such that the Simulator has hexacopters of 30 cm in diameter and a zone of evasion of the obstacle of 90 cm in diameter.

The address that is assigned to the force that is applied to the driver, when an obstacle is detected near the hexacopter, is distinguished in Fig. 6b. The simulator applies one force at the same time, to optimize the step of the aircraft by places narrow as doors or corridors.

To assess the proper functioning of the application, the elements of the Simulator and the behavior of the hexacopters during its flight are validated, with obtaining feedback from users about the management of the application, through a survey that complements the assessments conducted.

Table 1. Model parameters [16]

Name	Description	Value	Unit
$\boldsymbol{m}$	Mass	1.83	kg
$\boldsymbol{b}$	Drag factor	2.98e-6	Ns^2
$\boldsymbol{l}$	Length of center of mass to the rotor	0.30	m
$\boldsymbol{g}$	Gravity	9.8	m/s^2
$\boldsymbol{J_r}$	Rotational inertia	3.357e-5	kgm^2
$\boldsymbol{I_x, I_y}$	x, y inertia	0.0216	kgm^2
$\boldsymbol{I_z}$	Z inertia	0.0432	kgm^2

To obtain feedback from the user regarding the operation of the Flight Simulator, we have conducted a survey that complements the evaluations, and checks the fulfillment of objectives:

- Assess the degree of difficulty presenting the teleoperation learning of hexacopters.
- Determine which driver gives the user more comfort during flight maneuvers.
- Assess the simplicity and consistency of the interface, and check if its interactivity has an impact on the user.
- Check if the assigned tasks are reached by users.
- Consider whether the force feedback system implemented helps to warn of possible collisions.
- Estimate the viewer that provides every type of camera, and establish what is more beneficial to the user.

The sample size was 20 users, and 100% of the force feedback Joystick helped it to avoid possible collisions, as well as provided an effect of reality, showing the importance of the presence of this feature in Flight Simulator.

CONCLUSIONS

The Flight Simulator, which has three rooms with different levels of difficulty, semi-structured, was able to simulate the (remote) teleoperation of two models of hexacopters, with the force feedback feature. Additionally, the analysis of the dynamic model of the hexacopters allows the study and understanding of their behavior.

The development and implementation were possible due to the control algorithm for the calculation of the force that appears in the joystick, which is opposed to the movement exerted by the user when the aircraft is near an obstacle. Establishing this force should be inversely proportional to the distance of the hexacopter with the static obstacle.

The range of feedback that is perceived in the Force Feedback Joystick, was selected in such a way that notes the proximity of a static obstacle, without forcing the change of direction, allowing this action to be an exclusive decision of the user.

The simulator gives the user a sense of presence, through the use of a haptic device, offering an application that warns about possible collisions of the hexacopters with static obstacles.

The development of a simple, intuitive, and friendly interface to the users, allowed offer a simulator of flight that allows navigation by the application without difficulty, that offers the information, and helps timely.

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