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CONTROL OF AN UNMANNED AERIAL HYBRID AIRSHIP-QUADROTOR VEHICLE

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Abstract. *Combining key characteristics of devices that already exist could introduce an innovative product that would be applicable to many fields of study and create a whole new type of technology. Rotatory-wing aircrafts like helicopters and drones have recently received a lot of attention from researchers and many papers have been published about control models and improvements for those vehicles. They can be used in applications such as surveillance, remote hovering tasks and when high maneuvering ability is required. Lighter-than-air vehicles can also be used for similar applications, despite the differences between them. While drones and helicopters are known for high speed and maneuverability, the main characteristics of airships are flight stability and low power requirements. The purpose of this article is to study how those two vehicles can be combined into a hybrid aircraft that is light, easily maneuverable and controlled and also have flight stability at low speed saving energy when hovering. Simulation tests were performed in order to compare the behavior of the aircraft with and without the balloons, which will introduce the airship characteristics. The results of these simulations are presented and analyzed to validate the benefits of the new model proposed here. Guidance for further studies in this area is also given by the end of the paper.*

Keywords: *airship, quadrotor, hybrid, control, UAV.*

1. INTRODUCTION

The need of aerial vehicles which offers safety and autonomy is increasing nowadays, as it is indicated in literature. Helicopters are an expensive solution and its application is limited. Quadrotors are an alternative solution; it can be applied in many different situations, indoor and outdoor, and have a significant autonomy. Despite being one of the best option to some applications, it shows some minor problems that interfere in the process; e.g., if it is applied to record a sports competition, the noise of the quadrotor can interfere in the athlete performance or in the TV transmission.

Another solution is using an airship, because it has a great autonomy. It can be applied in uncountable areas and has a graceful degradation. However, airships have a low altitude and low speed problem, which has a small contribution in non-manned aerial vehicles.

Considering that both UAV (Unmanned Aerial Vehicles) show some limitation, the idea of combining the best characteristics of a quadrotor and a lighter-than-the-air vehicle can be a solution to many appliances.

The purpose of this article is to study how a vehicle that combines both, quadrotor and airship, would behave considering mainly energy consumption and stability.

Bringing the safety, aerostatic forces and the low mass of a blimp together with the maneuverability, high altitude and the high speed of a quadrotor, it is expected that the set became more stable, safer and widely applicable.

The set, quadrotor and a blimp, is constitute of four rotors, each with a set of pitch blades, and four or eight balloons, one or two in each arm of the set. System`s design is shown in Fig. 1.

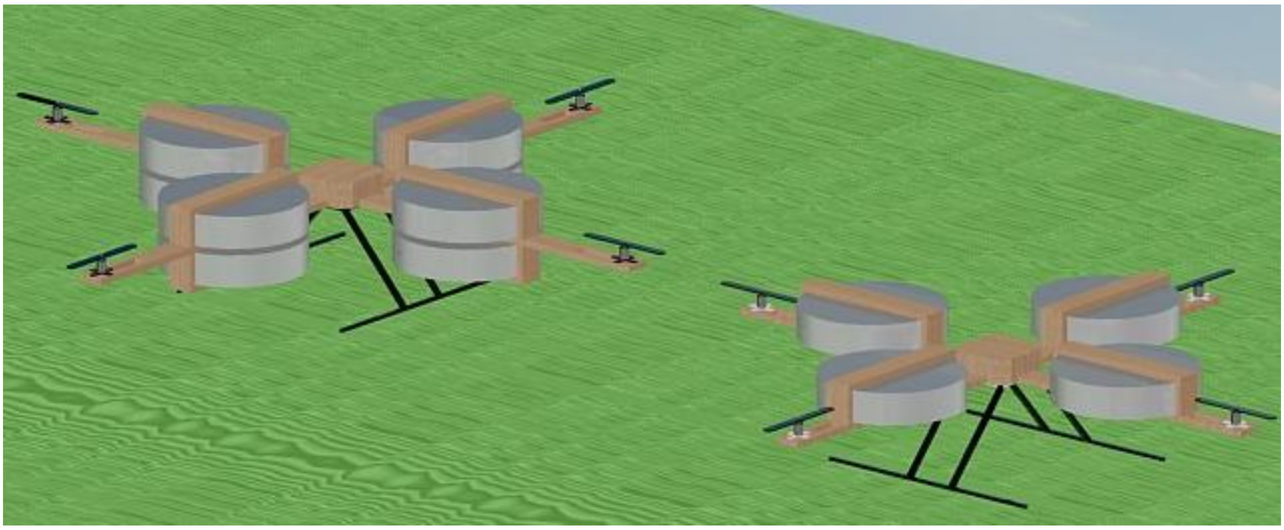


Figure 1. Design of the system

The analysis of the mathematical model of the quadrotor system is based on Samir Bouabdallah's dissertation "Design and Control of Quadrotors with Application to Autonomous Flying". The model does not consider the disturbances caused by the wind, since in principle the vehicle is being developed for flights indoors. First, some simulations were performed only with the quadrotor. Second, it was added the influence of four and eight balloons. For the analysis of the complete system behavior, it was calculated the thrust exerted by the balloons with 45 cm of diameter and 20 cm of height. These values are based on commercialized cylindrical helium balloons.

The challenge of creating this new aerial vehicle is given by the nonlinearity of the system, since this is the main difficulty in the mathematical modeling and control of both systems, quadrotor and airship.

The following section is the literature review, which presents what has been published about quadrotors, airships and others subjects related to this article. After that, the system model was stated as well as how the balloons were added to the quadrotor model. And then the simulations and the analysis of the results are presented in the next section. Lastly, the conclusion, where the reader will understand not only what was achieved in this article but also will be aware the following steps on the development of this new vehicle proposed.

2. LITERATURE REVIEW

2.1 Quadrotor

Unmanned aerial vehicle (UAV) platform concept is the basis for the development of quadrotor helicopters. Its structure consists of four rotors, two counter-rotating pairs and fixed pitch blades that are positioned at the corners of the aircraft (Hoffmann *et al*, 2013).

The design, modeling and control of a quadrotor, has to consider some important characteristics. One of them is the height of the rotor, which influences directly on the stability of the system. Based on simulations, the rotor should be slightly away from the centre of gravity (Pounds et al, 2010 B).

Another property to be analyzed is the mass of the structure, wich is directly connected to the control and dynamics of the system. A large drone needs a bigger rotor, in this way the inertia increases and becomes harder to control, because the dynamics of the motor will be different. For stabilization, the quadrotor must have a fast thrust dynamics (Pounds *et al*, 2010 A).

According to Pounds *et al* (2010 B) the dominant dynamics of a helicopter, or a quadrotor, is associated with the longitudinal dynamics of the vehicle and its symmetry. This means that the attitude dynamics can be described by a single equation. Attitude dynamics is described in attitude estimation.

A great challenge is the control of quadrotors, because it has a nonlinear dynamics leading to a complicated controlling method. It is necessary to linearize the system, and then apply a control technique.

There are some movements that a quadrotor is capable to perform, for instance, hover in Fig. 2, roll in Fig. 3, pitch in Fig. 4, yaw in Fig. 5 and thrust in Fig. 6.

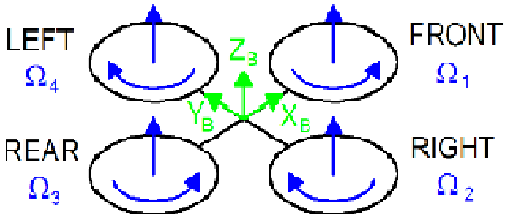


Figure 2. Hover

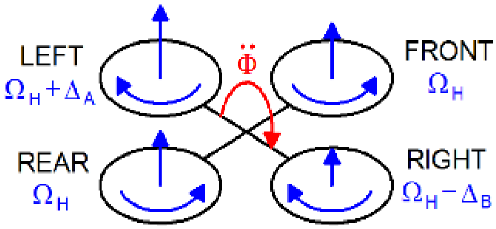


Figure 3. Roll

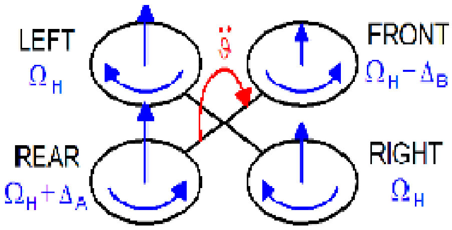


Figure 4. Pitch

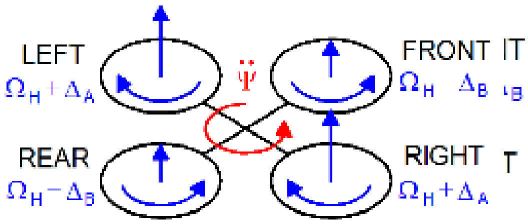


Figure 5. Yaw

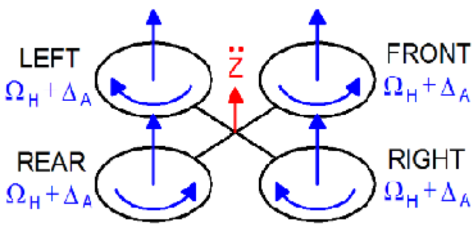


Figure 6. Thrust

2.2 Airship

Nowadays the airships are being rediscovered. The fields of appliance include heavy freight, aerial transport and indoor and outdoor surveillance (Moutinho and Azinheira, 2005).

Lighter-than-the-air (LTA) vehicles (airships) derives most of their lift from aerostatic, not from aerodynamics forces. If there is a failure during the flight, there is a graceful degradation, and also it is safer than helicopters, airplanes and balloons, because it is operated at a low attitude and low speed (de Paiva et all, 2006).

Airships can inspect countless areas, such as mineral and archaeologic prospecting, surveys in urban and rural areas and man-made structures (power transmission lines and others) (Azinheira at all, 2006).

The use of LTA vehicles requires a control which has a set of predefined points in latitude and longitude with a specific speed and altitude which is an important problem for the flight path since the system is nonlinear (Moutinho and Azinheira, 2005).

2.3 The hybrid concept

In the literature review, only one study was found with a similar project to the one proposed in this article. Earon et al (2007) present the design of a hybrid aerial vehicle, combining the characteristics of a quadrotor and a blimp. The goal is that the buoyant force exerted by the balloon ensures low power consumption and give stability to the vehicle to hover, like a blimp, while the four thrusters provide greater maneuverability and agility. The vehicle called Quanser ALTAV Mk II consists of a helium balloon in lenticular shape with four thrusters attached using a system of mounting feet and guy-lines that uses the resultant side-wall pressure of the airship to ensure a solid mount. The thrusters are placed along the centre-line of the balloon. Therefore, there is no need to use higher thrust force to perform the movements of pitch and roll.

Two experiments were conducted on a soccer field. In the first, the vehicle received command to take-off, fly to a predefined point and hover. In the second experiment, the vehicle received command to take-off and fly through a predetermined set of GPS waypoints. The vehicle presented a good response to handle wind and other disturbances, but the control must be upgraded to operate in more extreme weather conditions.

2.4 Attitude estimation

In combination, accelerometers and gyroscopes are used in position, velocity, and attitude computation in many different applications that involve motion and navigation tracking for underwater and land vehicles, aircrafts, and robots (Stančin and Tomažič, 2011). Wang and Yang (2012) state that the attitude can be observed by the numerical integration of angular velocity from microelectromechanical systems (MEMS) gyroscopes or by three-axis MEMS accelerometer. Many works on quadrotors, like the one presented by Suh (2006), propose attitude estimation using accelerometers and gyroscopes.

The structure of an accelerometer consists of a very tiny mass connected to the sensor's structure by a spring. A damping component is also considered in this model. When the device is accelerated on the sensing axis the mass tends to resist to this movement due to its inertia and it causes a displacement that is proportional to the applied force. The transducer responds with a voltage variation (Oliveira, 2014).

An accelerometer is capable of measuring inertial and gravitational accelerations. From Newton's equation of force we get

$$F = m\,(f + g) \tag{1}$$

where f represents inertial accelerations and g the gravitational ones. Analyzing the Eq. (1), one can understand the difficulty of measuring attitude angles only using accelerometers (Titterton e Weston, 2005). Therefore, Oliveira (2014) proposes a fusion of other inertial sensors, such as the gyroscope to obtain better results when estimating an object's attitude.

The principle of operation of a gyroscope is based on the Coriolis (Henriques, 2011). A small mass is kept vibrating along one axis imposing a linear velocity v to the mass. When an angular velocity along a perpendicular axis is applied to the system, an alternating force is developed along the third axis (perpendicular to the other two axis) due to Coriolis force as written in Eq.2 (Henriques, 2011).

$$a_{gyro} = 2\omega * \vartheta \tag{2}$$

Where a_{gyro} is the acceleration due to the Coriolis effect, ω is the angular velocity applied to the system and ϑ the linear velocity imposed to the mass.

3. SYSTEM MODELING

The model used on the simulation was developed based on Bouabdallah's (2006) system modeling of a quadrotor described on his dissertation "Design and Control of Quadrotors with Application to Autonomous Flying". And as in his thesis, the model developed assumes that: 1. The structure is supposed to be rigid; 2. The structure is supposed to be symmetrical; 3. The Center of Gravity and the body fixed frame origin are assumed to coincide; 4. The propellers are assumed to be rigid; 5.Thrust and drag are proportional to the square of propeller's speed (Bouabdallah, 2006).

In his dissertation, Bouabdallah describes not only the system modeling but also the system control. Focusing only on the system modeling the following equations of motion were obtained. For a better comprehension of the equations below, some symbols are recalled: m=mass, Ω=rotation, b=thrust coefficient, d=drag coefficient, g=gravity, l=distance from the propeller to the centre of gravity, I_{XX}=moment of inertia in x-axis, I_{YY}= moment of inertia in y-axis, I_{ZZ}= moment of inertia in z-axis, J_r=rotor inertia, x=displacement in x-axis, y=displacement in y-axis, z=displacement in z-axis, ϕ= roll angle, θ= pitch angle and ψ=yaw angle, B=balloons acceleration, N=number of balloons, V=balloon's volume, h= balloon's height, r= balloon's ray, D_{air}=Air's density, D_{He}=helium's density, F=balloon's force.

$$m\ddot{x}=(\sin\phi\sin\psi+\cos\psi\sin\theta\cos\phi)[b(\Omega_1^2+\Omega_2^2+\Omega_3^2+\Omega_4^2)] \quad (3)$$

$$m\ddot{y}=(-\cos\psi\sin\phi+\sin\psi\sin\theta\cos\varphi)[b(\Omega_1^2+\Omega_2^2+\Omega_3^2+\Omega_4^2)] \quad (4)$$

$$m\ddot{z}=\{(\cos\psi\cos\phi)[b(\Omega_1^2+\Omega_2^2+\Omega_3^2+\Omega_4^2)]\}-mg \quad (5)$$

$$I_{XX}\ddot{\phi}=\dot{\theta}\dot{\psi}(I_{ZZ}-I_{YY})-[J_r\dot{\theta}(\Omega_2+\Omega_4-\Omega_1-\Omega_3)]+[lb(\Omega_4^2-\Omega_2^2)] \quad (6)$$

$$I_{YY}\ddot{\theta}=\dot{\phi}\dot{\psi}(I_{ZZ}-I_{XX})-[J_r\dot{\phi}(\Omega_2+\Omega_4-\Omega_1-\Omega_3)]+[lb(\Omega_3^2-\Omega_1^2)] \quad (7)$$

$$I_{ZZ}\ddot{\psi}=\dot{\theta}\dot{\phi}(I_{XX}-I_{YY})+[ld(\Omega_2^2+\Omega_4^2-\Omega_1^2-\Omega_3^2)] \quad (8)$$

To analyze the attitude of the quadrotor, $\ddot{x}, \ddot{y}, \ddot{z}, \ddot{\phi}, \ddot{\theta}$ and $\ddot{\psi}$ were integrated twice, obtaining the displacements x, y, z and the angles ϕ, θ, ψ.

To add the balloons Eq. (5) was modified, resulting in Eq. (9).

$$m\ddot{z}=\{(\cos\psi\cos\phi)[b(\Omega_1^2+\Omega_2^2+\Omega_3^2+\Omega_4^2)]\}-(mg-mB) \quad (9)$$

To calculate the acceleration obtained adding the balloons the following equations were used:

$$V=h\pi r^2 \quad (10)$$

$$F=Ng(VD_{air}-VD_{He}) \quad (11)$$

$$B=\frac{F}{m} \quad (12)$$

The forces produced by the balloons were considered in the model as one force acting on the center of mass of the device. This is possible because each pair of opposite balloons was symmetrically positioned and the moment force of each balloon is considered to be nullified when summed to the moment force of the opposite balloons. The force of each balloon was distributed over the braces of the quadrotor and then centralized. The forces of the balloons are proportional to the number of balloons N.

An important consideration is that the model ignores disturbances generated by wind. In a first moment this study intends to control the vehicle in flights indoors, where this disturbances are supposed to be null.

The results obtained in the simulations as well as the analysis are described in the section 4.

4. RESULTS

To analyze the effect of the balloons addition, the simulations were performed on Simulink using two different models. Firstly, the model of a common quadrotor. Varying the rotors' supply voltages was possible to observe the behavior of the open-loop system and simulate some basic movements such as hover, thrust, roll, pitch and yaw. Secondly, the model of the quadrotor with four and eight balloons to compare the system behavior and the advantages obtained.

The first test consists of trying to make the vehicle hover, i.e., finding a supply voltage that makes it uphold approximately the same altitude. For the vehicle without balloons, it was required a supply voltage of 25.5 V. With four balloons, the supply voltage needed was 21.8 V, about 14.5% lower than the first test. With eight balloons, it was needed a supply voltage of 17.4 V, about 32% lower than the first test. It proves that the balloons can perform a significant contribution to the lift of the vehicle and reduce the power consumption.

To test the thrust movement, the rotors of vehicle were supplied with 50 V for the three cases. Figures 7, 8 and 9 show the X, Y and Z motion of the vehicle without balloons, with four balloons and with eight balloons respectively. With four balloons, the upward velocity was 8.6% higher than without the balloons, and with eight balloons, it increases to 21% higher.

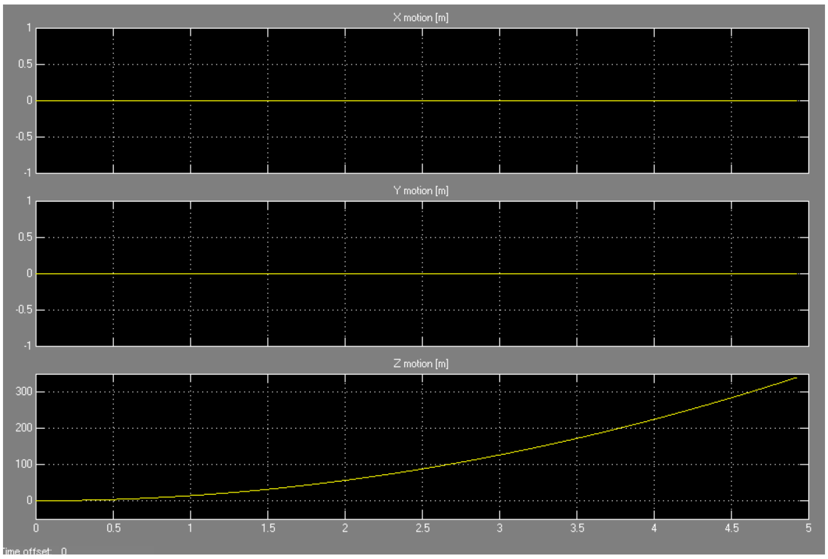


Figure 7. X, Y and Z motion for thrust without balloons

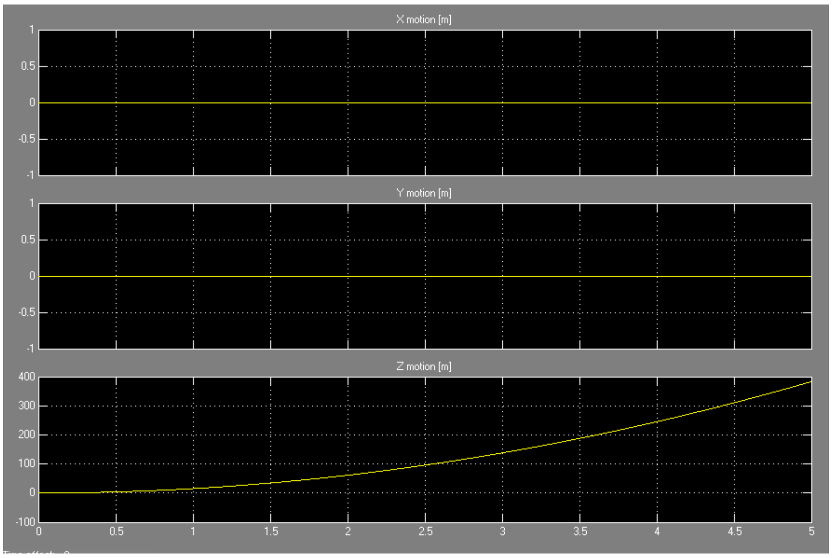


Figure 8. X, Y and Z motion for thrust with four balloons

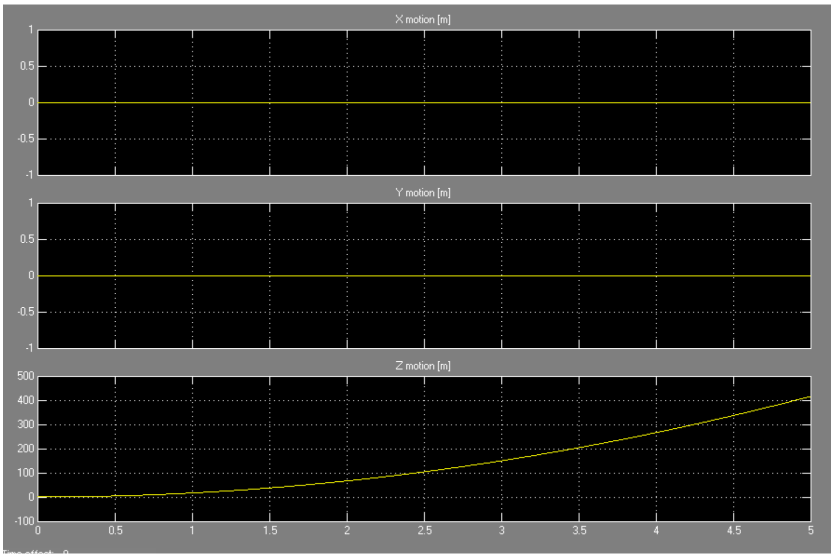
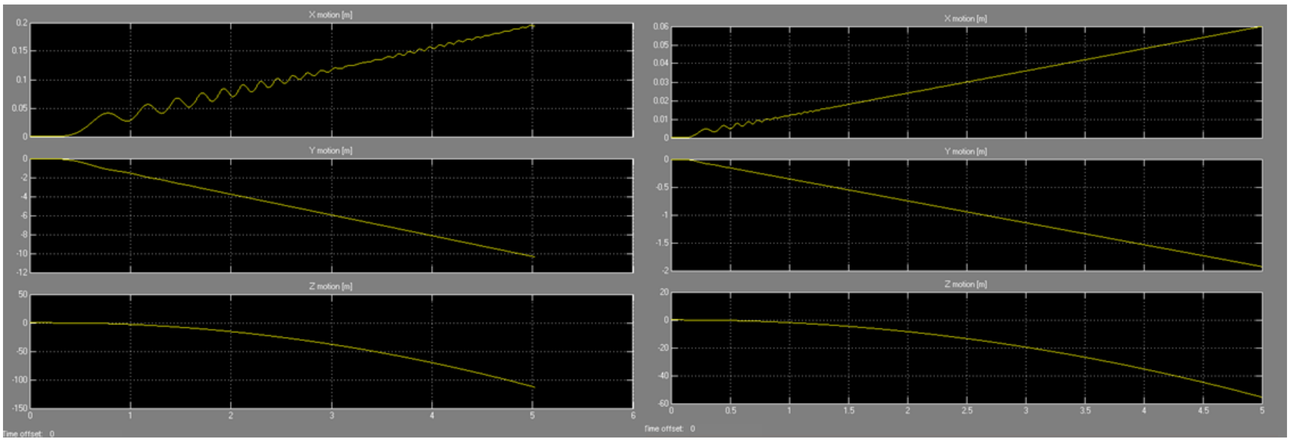


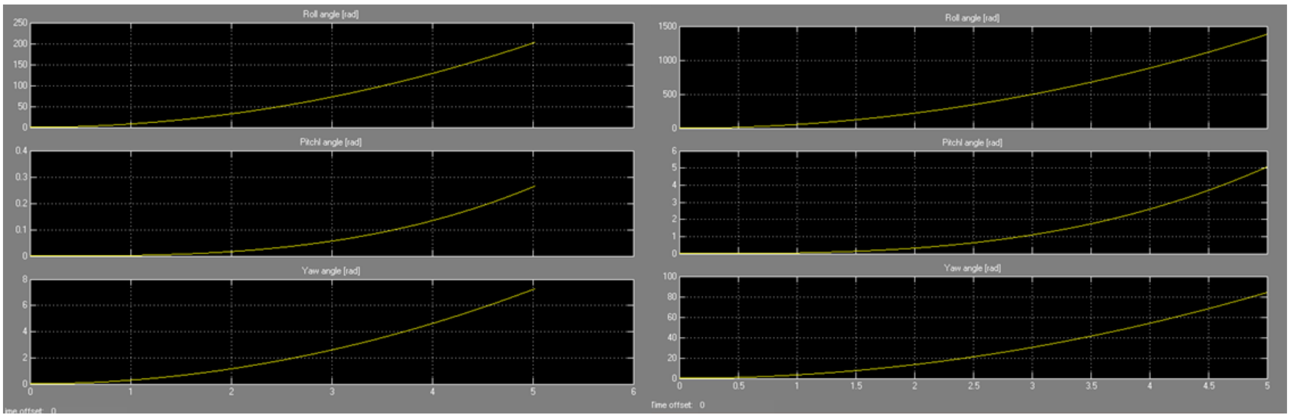
Figure 9. X, Y and Z motion for thrust with eight balloons

Roll, pitch and yaw simulations were also performed. As these tests were made in open-loop, the vehicle presented instability. However, the addition of the balloons improved the vehicle performance, reducing instability. Figure 10 below shows the instability in the linear motion and the improvement generated by adding the balloons in the roll tests. Figure 11 shows the roll, pitch and yaw angles to the same case.



(a) (b)

Figure 10. (a) X, Y and Z motion for roll without balloons (b) X, Y and Z motion for roll with eight balloons



(a) (b)

Figure 11. (a) Roll, pitch and yaw angles for roll without balloons (b) Roll, pitch and yaw angles for roll with eight balloons

5. CONCLUSION

This article presented a new model of unmanned aerial vehicle that combines the best characteristics of a quadrotor and an airship. As it can be observed from the plots presented in section 4, the results of the tests performed considering the forces of the balloons prove to be more efficient than the ones without them. The minimum voltage required for hovering drops from 25.5 V (classical quadrotor structure) to 17.4 V (structure with eight balloons), which means 32% less energy for hovering tasks, as shown on the hovering test. Upward velocity is also enhanced 21% when the balloons are coupled to the aircraft's structure. The tests described in this paper, which were performed in open-loop, prove that the mathematical model used is valid and represents the behavior of a quadrotor. Comparing the behavior of the system with and without the balloons it is possible to affirm that the addition of these items prove to be more stable, faster and consuming less energy as proposed in the beginning. Despite the good results obtained, the model still presents some limitations to be enhanced in a near future. As future work, the model has to be improved by considering the balloons being ellipsoids instead of cylinders and adding the disturbances caused by wind. The position of the balloons should be taken into account as well, once the sum of the forces exerted by them was considered in the simulations as a single force acting on the center of mass. For further studies the force of each balloon will be modelled separately considering its moment acting on the axis of the quadrotor. The next goal is to turn this vehicle fully autonomous. Therefore, it is proposed here the development of a controller for this new aircraft structure that should take into account the redundancy of the balloons and the compensation of the rotors in case one or more balloons burst. The positive results obtained in this development towards an autonomous hybrid aircraft reinforce the conviction that the construction of such device is clearly feasible. As an ultimate result of this work, a prototype of the vehicle presented on this article will be built and the experimental results will be compared to the simulations.

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7. RESPONSIBILITY NOTICE

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