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Service quadrotor drone for object manipulation

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ABSTRACT

In recent years there has been an accelerated development of unmanned vehicles for different service applications and it is expected for this devices to grow rapidly in the years ahead. However, there are minimal applications of this vehicles for object manipulation in an interior environment. The aim of this research is to develop a stable quadrotor capable of manipulating small objects and navigate remotely trough an indoor space for service purposes, hence it presents the design and construction of a quadrotor drone for interior conditions which includes a pneumatic system as the principle mechanism for object manipulation located at the bottom of an air filled sphere, with the intention of carrying objects of small dimensions. This sphere helps the stabilization of the vehicle while carrying objects by a geometrical distribution of the mass of the whole system. The design of the structure and the pneumatics suction system includes multiple mechanical studies like fluids dynamics, both static and dynamic structural analysis among others in order to select the appropriate materials and architecture of the unmanned vehicle. The control and stabilization are made with feedback control algorithms over a Raspberry Pi and a Navio+ shield and it is commanded with wi-fi communication from a mobile device.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have become a new vast subject of study for researchers and enterprises due to the several amount of applications they can have. Starting from surveillance, search and rescue, civil monitoring to agriculture and multi-vehicle human collaboration with haptic interfaces (Yuksel, October 2016). Now, the increasing use of this vehicles not only responds to the demand of unmanned devices that enables humans become apart from dangerous situations, but also, they fulfill some other advantages, like a cost and time reduction of these tasks.

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Despite the fact that the common UAVs are only equipped with a camera and sensors to develop their chores, they are able to accomplish a great quantity of challenges. Thus, if a manipulator is added to these vehicles, the number of new possibilities of usage increases dramatically (Ramon Soria, 2016). Hence, in the last years, there has been a combination of manipulator and UAVs control researches to develop a stable vehicle capable of grasping carrying objects through some distances. Consequently, the main approach to this new challenge, is to add a manipulator robotic arm to the UAV. However, this coupling involves new control and modeling problems due to the fact that both of the systems have their own kinematics performance and they are dependent of each other in order to stabilize the entire arrangement.

Although there have been numerous researches on this arm approach, most of them focus on the use of multiple robotics arms or in the combination of multiple UAVs to accomplish some difficult tasks, such as the project ARCAS (Aerial Robotics Cooperative Assembly System), where an utilization of multiple UAVs with 6-DOF robotic arms in a coordinated way is achieved (Trujillo, 2016). Even so, this methods tend to complicate the control models and it is no longer viable for easy chores, like the ones performed in an interior situation, where a UAV does not require to carry big and heavy objects, nor to have a fast performance compared to some other activities, like rescue.

Alternatively, during this research, a new approach for object manipulation is proposed seeing that the main objective is to create an UAV capable of manipulating small objects in an interior room. The entire drone is designed with a sphere shape filled with air, which will include at the bottom a pneumatic system as the principle mechanism for object manipulation. The purpose of this design, is to help the stabilization of the drone with the manipulator mechanism instead of adding a control problem with it, plus the fact that it can be a low-cost solution for indoor approaches compared to the robotic arm methods.

2. DESIGN OF THE DRONE

The UAV conceived during this research must be capable of carrying a 600 ml. bottle of water through a distance of 500 m with the aid of a suction cup system fueled by a sphere shape tank. The UAV will follow the quadrotor approach because of the advantages that it has, such as a better stability and an easier control method, plus it is the more viable option seen that it can maneuver in closed spaces and it is able to perform a VOTL (Vertical Take-Off Landing).

2.1 Structure and materials

To decide the main structure dimensions and shape it is needed to choose the elements for the entire functionality of the system. First of all, the entire drone will have to carry an object of 600 mg, then the structure weight must be between 1 and 1.5 kg, and the electronics and the pneumatic system must not exceed 1 kg. As a result, the drone will have to carry a weight of approximately 3 kg.

Seeing that a quadrotor is sufficient to fulfill the necessities of this project, because it enables the control of four degrees of freedom, it is required to choose the motors that adequate to the main objectives. This is accomplished with 2 poles brushless motors at 700 kV and a consumption of 0.5 Ah, given this type of motors are used to carry 1 kg or more, plus it offers stability when there are not abrupt changes of direction and low velocities are needed. The propellers elected are made of carbon fiber and they have two blades which measure between 22 and 25 cm.

Secondly, the dimensions are selected in accordance of the sphere, which will be the main tank that fuels the entire pneumatic system. Considering a commercial water-bottle of 600 ml with a height of 25 cm, a spherical tank with a diameter of 600 mm is enough to fulfill the task. The material used for this sphere is a synthetic rubber called styrene-butadiene rubber (SBR) which used for surgical gloves or mold products such as toys, wheels, rollers or window seals. Subsequently, the structure that will support this container can be visualized. It will be made of three rings that share the same rotation axis and that are connected with strands as it is represented in Fig.1.

Fig. 1 Computational design of the support structure

This support structure is the final proposal after several changes made due to the result of numerous analysis. It presents high stability because its gravity center is located on the axis of rotation and the intermediate ring (Fig. 2). Besides, the strands serve as connectors and shock absorbers, taking into account that it is possible to have some incidents where the drone can hit the floor or a wall. The difference of the diameters between the rings is obtained with the length of the propellers given that they measure 24 cm, and the distance calculated between both rings over the X-axis is 14.60 cm, in order to provide the sphere an extra security space. The total height between the superior and the intermediate ring is 5 cm so that the drone maintains the stability and the weight distributed. This structure is intended to be of carbon fiber because of its low-density, its high mechanic resistance and its facility of fabrication and molding.

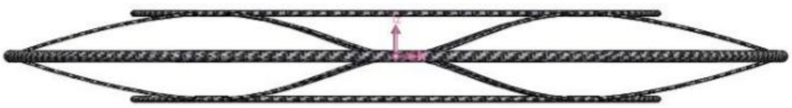

Fig. 2 Gravity center location in the support structure

2.2 Analysis and simulations of the structure

Once defined the entire structure of the drone and taking into account that it is going to be immersed in an air environment, it is fundamental to create a fluid analysis through a CAD software to determine the behavior of the design and its viability. There are three stages that are needed to have an overall view, the velocity of the air that transits over the drone structure, the existent turbulence on important regions and the pressure applied over the sphere tank. For this analysis, a 10 m/s velocity of air entrance was taken.

2.2.1 Velocity of the air that transits over the drone structure

During this analysis, the first important result is the fact that the spherical shape of the tank facilitate the air flux. As seen in Fig. 3 low air velocities are present at the entrance of the control volume (between 8 and 11 m/s), this shows that configuration of the study is correct and that there are no elements that accelerates the mass flow rate. It is important to mention that the acceleration of the air generated by the rotation of the propellers are not being studied, the object of this study is the behavior of the general structure of the vehicle.

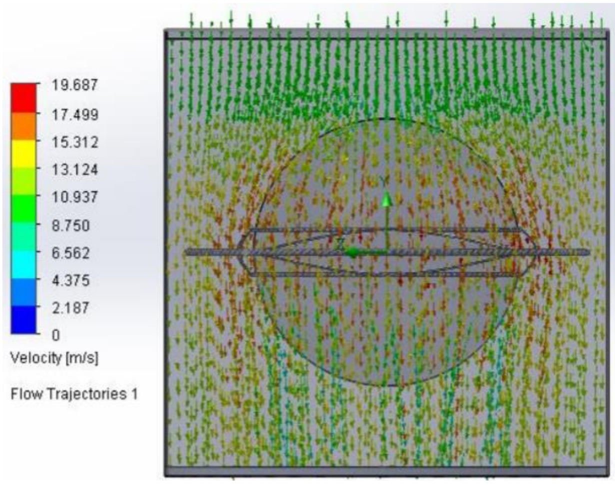

Fig. 3 Results of the velocity of air study

In Fig. 3, the intermediate zone of the control volume, where the drone main structure is located, presents high velocities in the correct flow direction. The viability of the geometry proposed is reinforced because the velocities of 20 m/s are located in this zone. What is more, even if there are not propellers acting over the air, it accelerates itself, generating low pressure zones in the bottom of the sphere and causing the raising of the entire vehicle. Thanks to this performance, when the propellers are added, they are going to receive an accelerated air flow, which will make easier their work and will enable a greater impulse so that the drone can upraise.

The flow of the air throughout the sphere can be observed in Fig. 4, there is a uniform distribution and it facilitates the movement control of the device, owing to the fact that the propellers must shove aside the same air quantity so the drone can be in an equilibrium and stable state. In Fig. 5, where the number 1 is marked, the air corresponding to that point because of the entrance column over itself concentrates adding a quantity of air that comes from the superior part of the sphere, generating a massive air column which will be helpful for moving the drone, situation that is a result of the spherical shape proposed.

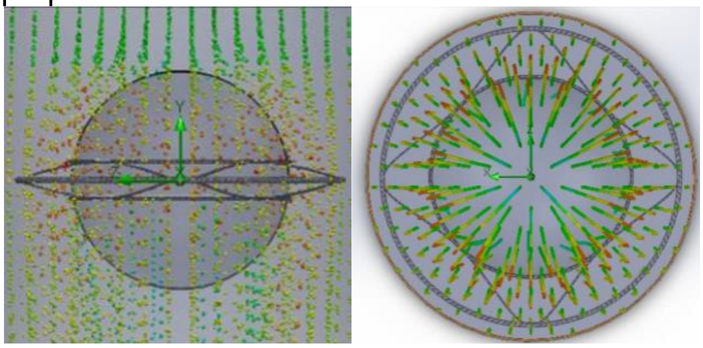

Fig. 4 Flow of the air throughout the sphere

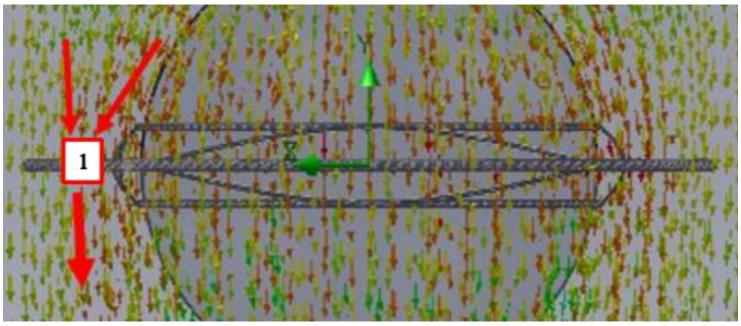

Fig. 5 Behavior of air flow in the spherical structure

2.2.2 Existent turbulence on important regions

Turbulence is defined as a flow regimen characterized by a low momentum diffusion, high convection and high speed space-time changes of pressure and velocity. Hence, it is an undesirable concept in aerial vehicles, seeing that it can destabilize them. In Fig. 6 the results of the turbulence study are shown, the zones marked with the red arrow are the ones which are prone to the generation of vortexes, however, this is not a dangerous zone because this behavior was expected and is easily controlled with the variations of the propellers velocity. Now, the zones with more turbulence taking into account the entire structure are shown in Fig. 7 and they are as expected. Finally, in Fig. 8 an overall view of the turbulence can be seen, one of the most important results is that there are no zones with high turbulences concentrated at the bottom of the vehicle. Nevertheless, there are zones with medium turbulence (between 75 and 145 s^{-1}) around the structure just under the propellers location, so this zones can be easily controlled.

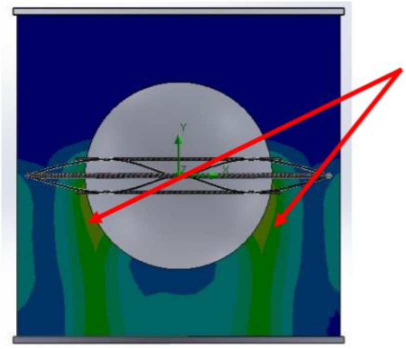

Fig. 6 Zones prone to vortexes generation

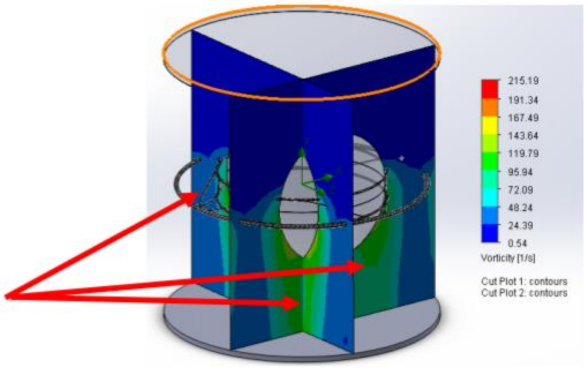

Fig. 7 Zones of greater turbulence

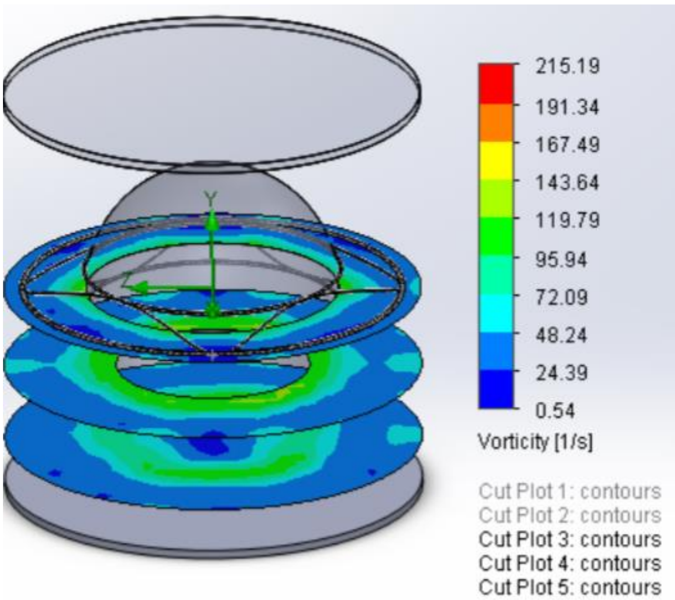

Fig. 8 Overall view of turbulence zones

2.2.3 Pressure applied over the sphere tank

This study is important because if the pressure applied over the sphere is high or concentrated in certain points, it can lose stability and make more difficult its control. Bearing in mind that this shape helps the navigation of the drone, as seen in section 2.2.1, the fact that it can change this form due to abrupt pressure changes can cause a displacement to one side or another. Nonetheless, it is expected that the pressure is not uniform in all the sphere, because at the time it opposes to the air movement the pressure applied to the superior area must be greater than the one applied on the middle and the inferior part.

In Fig. 9 the results of this study are shown, the pressures presented in the sphere are not high compared to the atmospheric pressure of 101 325 Pa, therefore, there are not abrupt pressure changes that can modify the geometry of the air tank. An important outcome is that the difference between the pressures of the superior and inferior part of the sphere is 400 Pa, a minimal quantity that represents no risks to the geometry of the drone. Additionally, the difference between the atmospheric pressure and the one of the superior part or the inferior part is about 1.5 kPa and 1.1 kPa respectively, a minimum quantity that is not dangerous. Another conclusion obtained is that the air will travel close to the sphere so that it will be always in contact with it, effect that will help the acceleration of the vehicle at the time of its raising.

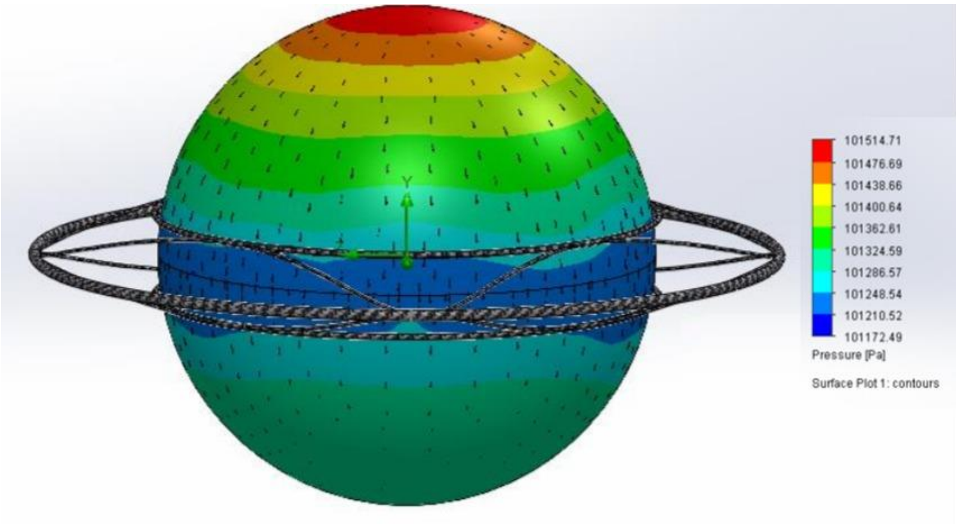

Fig. 9 Results of the pressure applied to the sphere tank

2.3 Final design proposal

After the simulation stage and due to the favorable results of the proposed design, it is needed to generate some changes to the structure so that it can be manufactured in an easy way and that it also takes into account some details such as the security against incidents in the propellers. First of all, the initial design includes a single piece frame, however, this makes the fabrication difficult because of the complex form that it has to take, plus in the case of an incident that provokes a rupture in the material the entire structure has to be rebuild. Thus, the new design involves creating a frame with different pieces, including supports that are capable of buffer the effects of a failure.

The new model is shown in Fig. 10, there the frame is divided in three rings and four bases that gather together the entire structure. The weight of the bigger ring is of 350 gr, the little rings are 100 gr considering carbon fiber as their material. The bases are also made of this material and because of their shape it can be used to buffer some undesirable effects, it is also proven that it will support the weight of the vehicle (Fig. 11), because if a study is created where an extreme of the base is fixed and the other receives a vertical force of 100 N, the maximum strain created is of 386 MPa, a low value compared to the maximum strain that a carbon fiber can handle which is 825 MPa. Each of these bases will weight 50 gr.

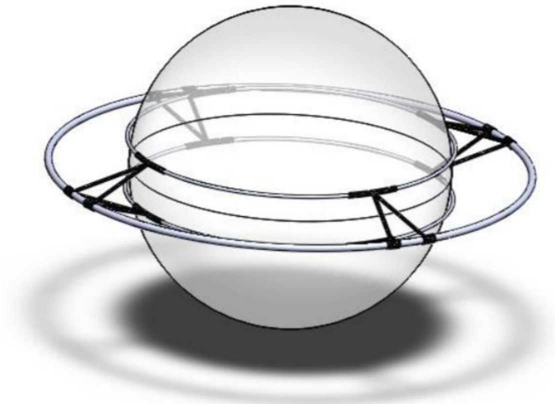

Fig. 10 Second design proposal

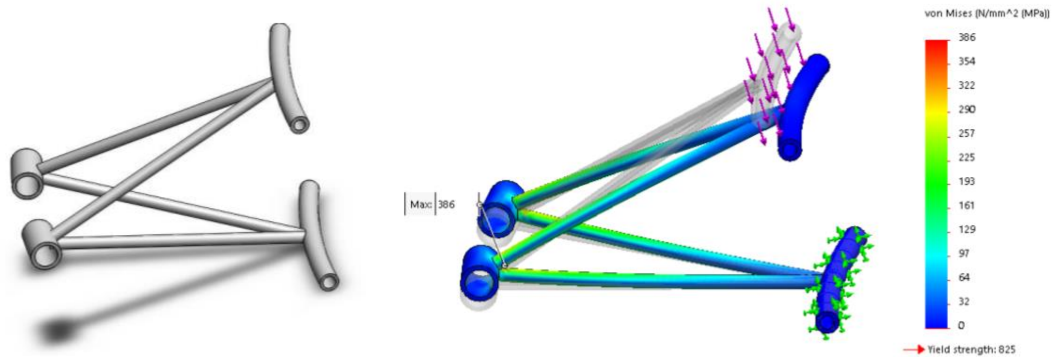

Fig. 11 Base design and results of its linear statical analysis

Finally, a support for the brushless motors is required, in Fig. 12, the intended design is presented. It is easy to assemble and let the motors to be secured to the structure, it also has the possibility to be interchangeable. Besides, the security factor is still needed and it is addede to the propellers in this part of the desing, a frame that protects the user against any failure that can cause an accident or an injury. The addition of these security frames and the entire assembly of the motors and propellers are shown in Fig. 13. The final design is displayed in Fig. 14 and it has a total weight of

1200 gr, including the sphere, the rings, the ring bases, the motor bases and the security frames.

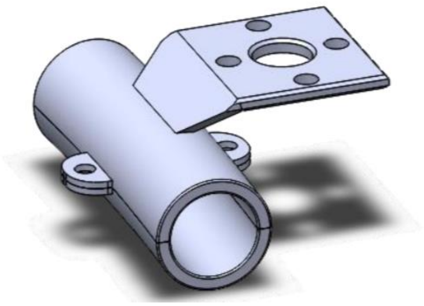

Fig. 12 Base for brushless motors

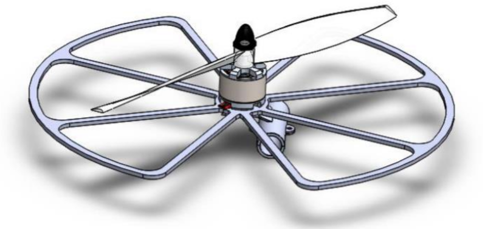

Fig. 13 Assembly of motors and propellers with security frames

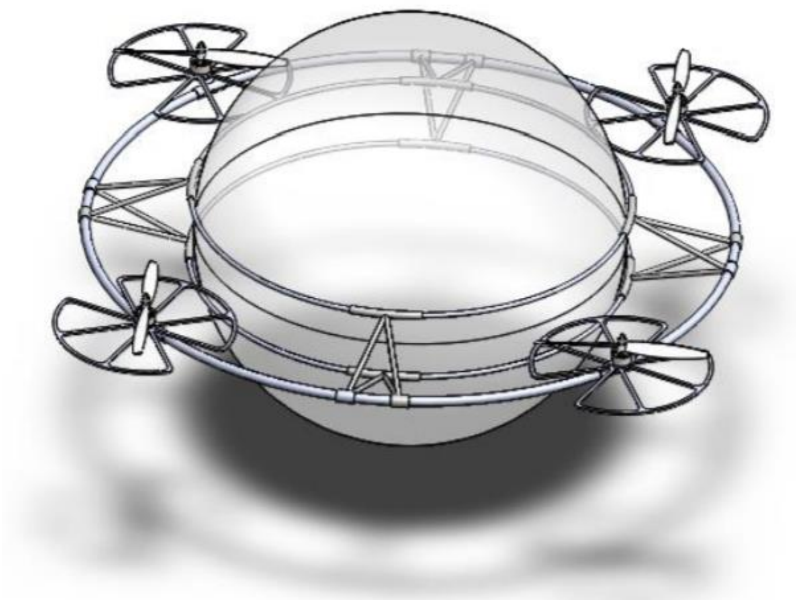

Fig. 14 Final design proposal

3. PNEUMATIC MANIPULATION SYSTEM

As mentioned before, another subject introduced in this research is the manipulation system which is going to be done by a pneumatic mechanism. A suction cup is the main element that will take the bottle and carry it through its destination. Taking into account that the sphere is going to be the tank, the other components required are not going to be heavy nor numerous. This system is formed by suction cups, vacuum ejectors, control valves and a muffler.

Now, it is important to mention that the bottle will be taken when it is in a vertical position, owing to the fact that it is more likely to find a bottle in this manner and it helps the stability while the bottle is in an awaiting stage. The diameter of the water bottle cap is 28 mm and the contact area is not a completely flat surface, it has a minimum curvature. For this reason, a deep suction cup is chosen with a commercial diameter of 20 mm and the proposal for the material is a nitrile rubber (NBR) due to its friction factor of 0.75 with the plastic cap.

After that stage, a pneumatic vacuum generator with a laval nozzle of 0.45 mm and a standard vacuum ejector, its generator is in T shape, it has a connection fitting in 4 mm in its compressed air and vacuum connections, it also includes a muffler at the exit. To determine the force needed of the fastener system it is needed to set that the suction cup is going to be in a horizontal position and the movement will be made in a vertical direction which is the optimal case. In this case, and for the suction cup selected, the suction force is given at a 70% (0.7 of a bar) and it is projected a pressure at the 80% of vacuum, so the final force is of 19.42 N. With this information, the acceleration that the product must have for an efficient performance is given by the Eq. (1):

$$a = \mu * (\frac{F}{m*s} - g) \tag{1}$$

Where, a is acceleration of the equipment, μ is the friction coefficient (0.75 for NBR), F is the theoretical suction force (19.42 N), m is the mass (1 kg) and s is the security factor (1.5 for lineal movements). Substituting all the values, the acceleration of the equipment is 2.35 m/s^2. This result is close to reality thus the election of the ejector and the suction cup are correct.

Once this is done, the pneumatic circuit must be generated. The pneumatic ejectors are based on the Venturi principle for its function. In the first position, the air is injected, it passes through the laval nozzle and it goes to the exit. Because of this, in the middle position a suction is created, so the suction cup must be placed in this position. In order to regulate the suction system a 3/2 control valve. In the first position of this valve, there is not air flowing, so there is no suction generated. When the valve is activated the air of the compressor comes through the laval and it generates the suction mechanism. Furthermore, the circuit can be complemented with switches and security elements, all this is important because in order to fulfil the main objective of the drone, it needs to avoid the risk of a suction system failure.

In Fig. 15 the electro pneumatic circuit is presented. The system starts with a 3/2 valve with a self-lock button returned by spring which commutes a 5/2 valve. This valve must let the air pass through the vacuum ejector to begin the suction and to maintain the non-return valve in a stage where it also lets the air pass through. The non-return valve ensures the function of the manipulator even if there is a failure in the power system, because if the pressure falls down to 0, it will send a signal in order to maintain the suction system working. It is important to mention that the valve 1.2 2/2 is in the circuit to simulate any failure in the system, it will not be present in the real circuit.

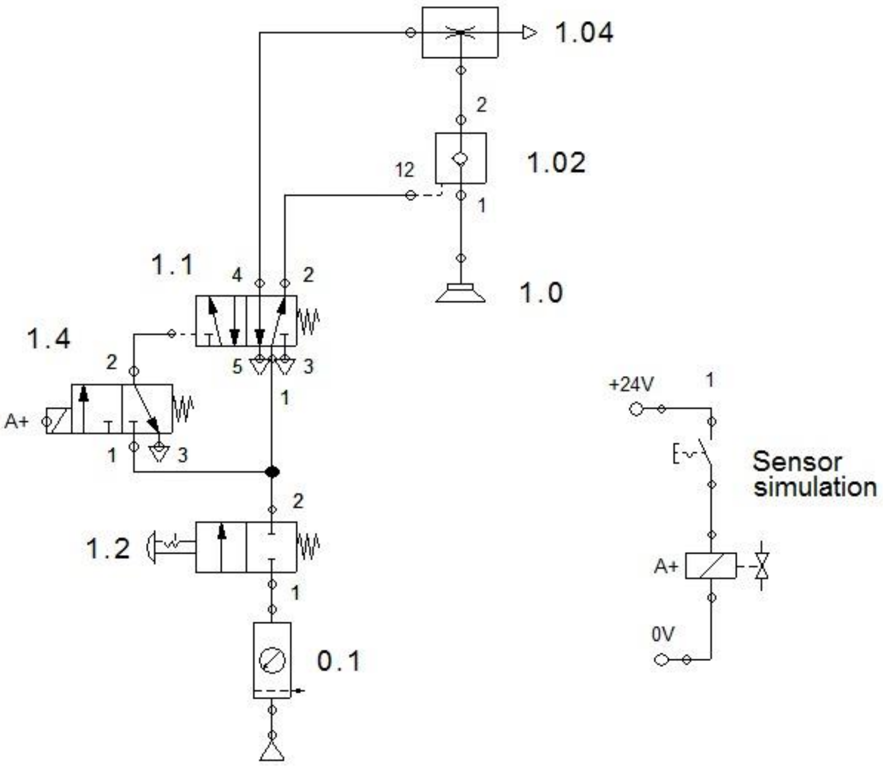

Fig. 15 Final electro pneumatic circuit

Finally, in Fig.16 four different cases of the circuit function are shown. The first one represents the circuit in its original state, the 3/2 valve has not commutated and there is no failure in the 1.2 valve, the 1.1 valve lets the air pass through it. Secondly, the figure shows that the 1.2 valve is activated and it is waiting for the sensor signal. In the third figure the 3/2 and 5/2 valves commutate, the 1.1 valve keeps the air flowing through the ejector, the suction starts. The fourth image represents the case of a power system failure in the 2/2 valve, in this case the non-return valve closes and does not let the air flow from the suction cup to the ejector, this maintain the object suctioned in its place. There must be taken into account that the entire system will be controlled by the drone computer, thus, the activation of the 3/2 valve will be done with an electrical signal and the entire system has to be monitored with sensors to send the interrupt signals when needed.

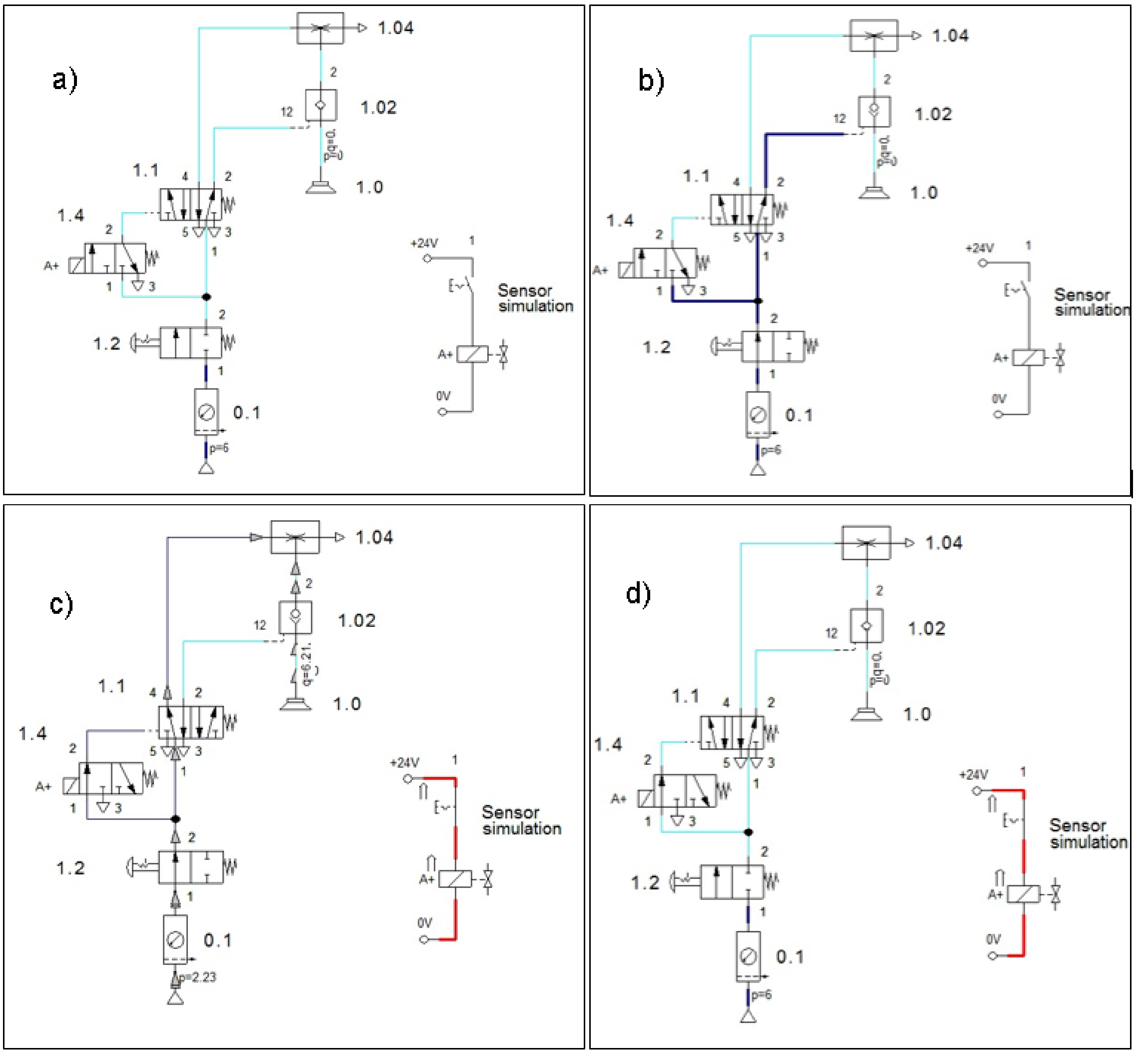

Fig. 16 Function of the circuit: a) Original state, b) 1.2 Valve self-locked, c) Suction activated, d) Failure in the system

4. DRONE CONTROL

In order to maintain a low cost approach for this project, a small single board computer called Raspberry Pi 3 and a complement board called Navio+ were chosen to control the drone, as it is not going to be autonomous, it needs to communicate with a mobile device where an operator must be present sending the signals to follow a path. The communication is intended to be via Wi-Fi because of the long distances it can reach, the speed and the security of the data that it offers. In the mobile device, a program is created in order to obtain the signals directly from the keyboard to control the drone. The rising and descent are handled by the up and down arrow keys. The movements in the X-axis including forward, back, left right are commanded by the “w”, “s”,” a” and “d” keys respectively. The activation and deactivation of the suction system is controlled by the “j” and the “l” keys. Finally an emergency button is activated with the “enter” key.

With regard to the control of the drone there are two main parts worthy to discuss. First of all there has to be a control algorithm based on the drone dynamics and kinematics. Knowing that there are four main variables that define the motion of a drone, the altitude and three different spatial rotations, the pitch, the roll and the yaw. Each one of the rotations defined with respect to one particular axis and represented in the Fig. 17 with the Greek letters Theta, Phi and Psi.

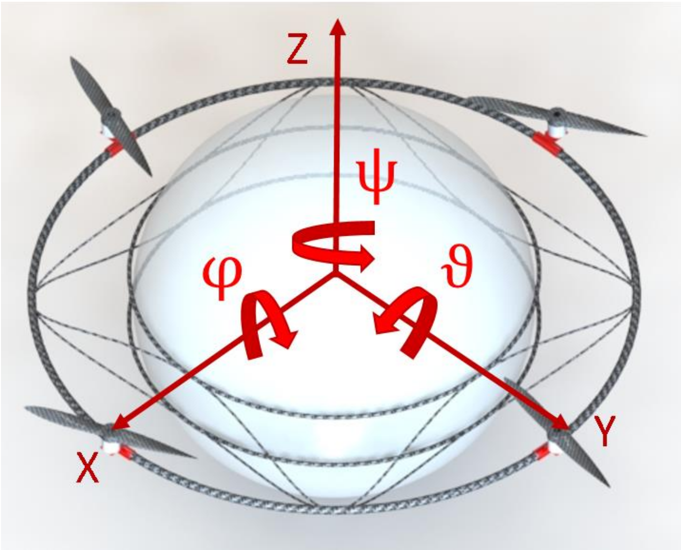

Fig. 17 Three rotations of the quadcopter

Once defined the principal variables involved in the motion of the drone, the dynamic model can be summarized by Eq. (2), Eq. (3) and Eq. (4).

$$\mathbb{J} = \begin{bmatrix} I_{xx} & (I_{yy} - I_{xx})\psi & (I_{xx} - I_{zz})\varphi \\ (I_{yy} - I_{xx})\psi & I_{yy} & (I_{zz} - I_{yy})\vartheta \\ (I_{xx} - I_{zz})\varphi & (I_{zz} - I_{yy})\vartheta & I_{zz} \end{bmatrix} \quad (2)$$

$$\ddot{q} = \begin{bmatrix} \ddot{\vartheta} \\ \ddot{\varphi} \\ \ddot{\psi} \end{bmatrix} \quad (3)$$

$$\tau = \begin{bmatrix} M_{\vartheta} \\ M_{\varphi} \\ M_{\psi} \end{bmatrix} = \begin{bmatrix} (T_3 - T_1)d \\ (T_4 - T_2)d \\ -K(T_1 + T_2 + T_3 + T_4) \end{bmatrix} \quad (4)$$

Where $\mathbb{J}$ represents the relation between the inertia matrix of the quadrotor and the rotation angles, $\ddot{q}$ represents the angular acceleration vector of the three rotations of the quadrotor and τ the momentum of every rotation of the quadrotor, equal to a vector that results of the four thrusts of evert propeller, the distance from the propellers to the center of mass and the constant K, that is the coefficient between the torsion and the thrust constant for a single motor. These equations determine the necessary thrust in each motor in order to rotate the quadrotor a certain angle moving with a certain acceleration. Also the equations are needed to module the quadrotor in a virtual environment to simulate its movement.

The simulations of the drone can be done using the mathematical software MATLAB from Mathworks, along with Simulink and Simmechanics to implement the mathematical model that defines the drone motion and translate the different variables into a virtual simulation. The simulation presented in this paper can be explained with the help of the flow diagram in the Fig. 18.

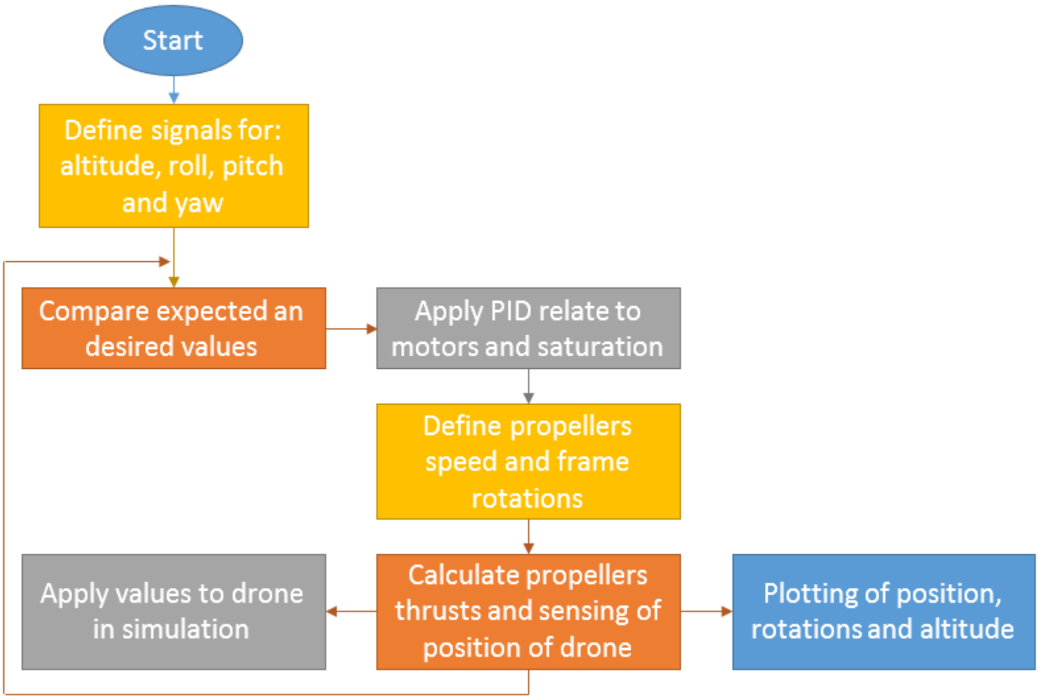

Fig. 18 Flow diagram of the simulation

The program takes four different signals corresponding to the desired altitude, roll, yaw and pitch of the quadrotor and then calculates the speed of the propellers to achieve the necessary thrust in each one of them according to the weight of the whole structure and the inertia momentums along each axis. After this the simulation applies these values into the virtual propellers and pushes the virtual drone trough the trajectory result of the initial signals. The signals are different for each value as it can be seen in the Fig. 19. The figure represents the input values necessary to follow the trajectory shown in the Fig. 20 across a rectangular surface of 7 per 10 meters, considering the variations of the position throughout the time. The trajectory shown represents the final path of the quadrotor in the simulation ran for 55 seconds.

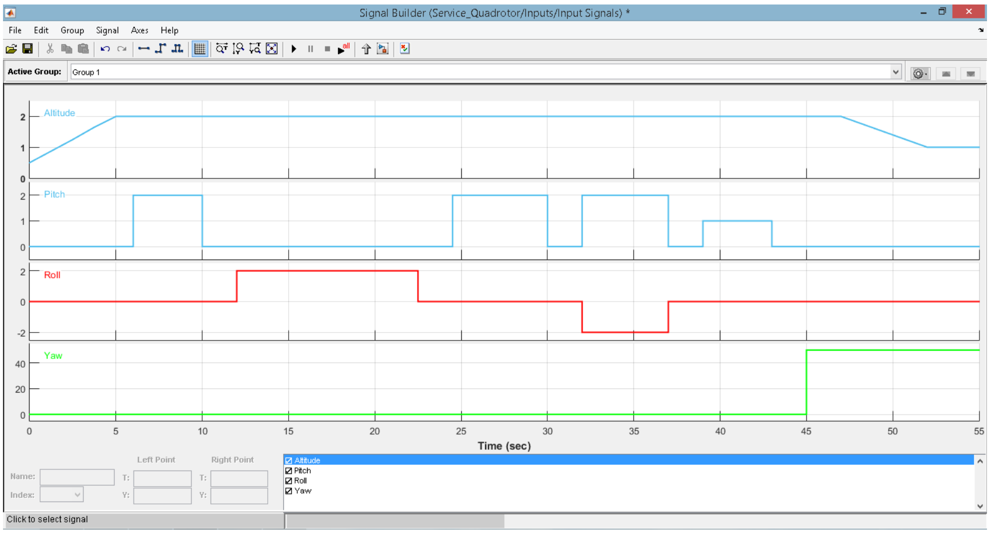

Fig. 19 Initial signals for each variable

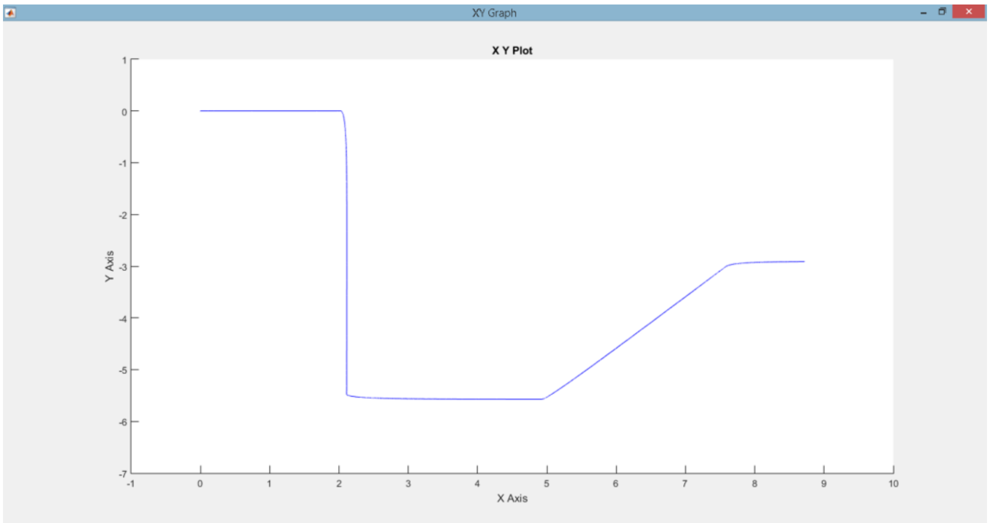

Fig. 20 Trajectory followed by the quadrotor in the simulation

Also the output plots of the variables are shown in the Fig. 21 and Fig. 22. It can be seen that there is still a little error during the changes in every rotation or significant movement of the drone. This is an effect mainly of the inertia that the model has to break in order to change its position and direction. Nevertheless this errors are minimum considering the manual control of the quadrotor and can be rectified slowing down the quadrotor response to changes. Besides that, the model shows a very stable movement and once it reaches the desired value it stays very close to it.

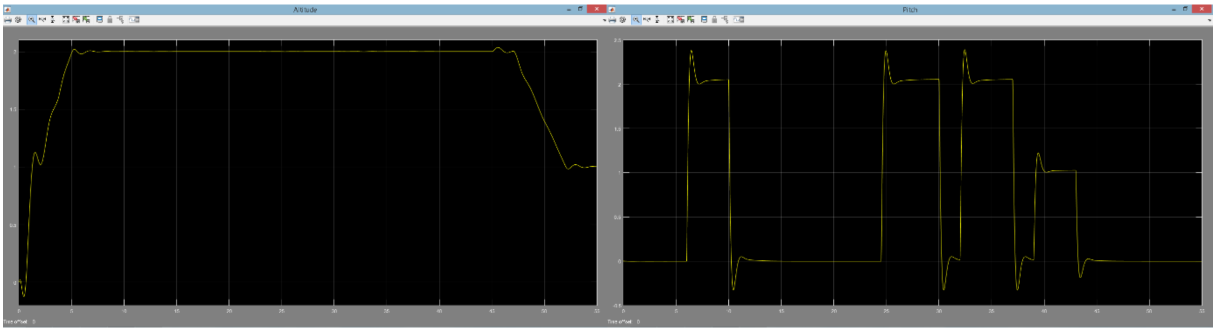

Fig. 21 Simulation graphics: a) Altitude, b) Pitch

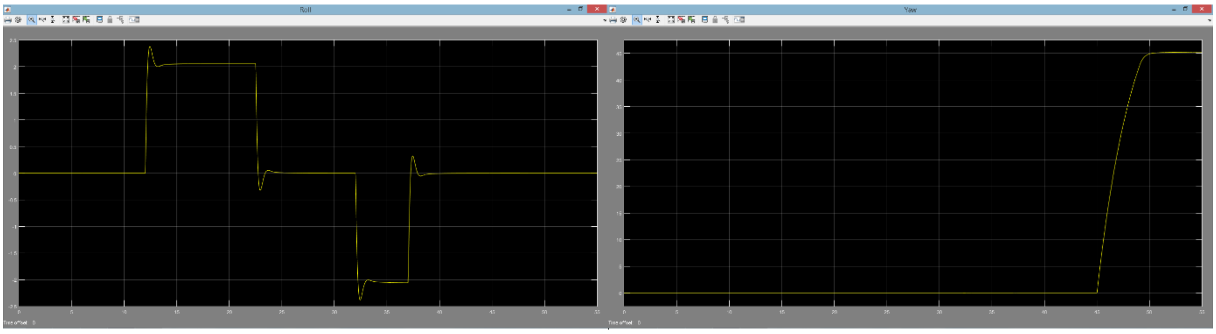

Fig. 22 Simulation graphics: a) Roll, b) Yaw

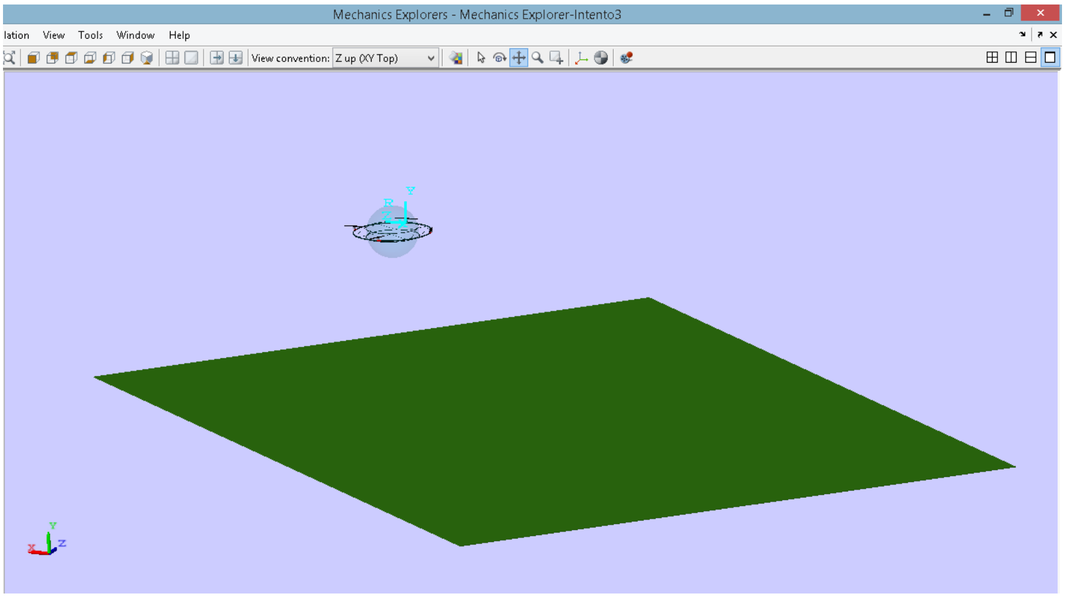

Fig. 23 Simulation running

5. CONCLUSIONS

By the end of this research, the fact that indoor unmanned vehicles can be used for service purposes is proven and this idea is completely viable. The design proposed is a functional option for a new development field as a more stable and cheaper option than using other manipulation systems, such as robotics arms. It is important to remember the fact that the use of a spherical drone makes easier its control and its movement throughout the air and it includes the manipulation system in it, so it does not need to be taken as different kinematics models.

In addition, the pneumatic system seems to work efficiently in accordance to the weight that it has to carry. In this research the water bottle was proposed for a quantitative approach, however, it can be changed by objects of similar dimensions or it can be improved in future works to carry another type of shape objects or to carry more weight. In the case of the control, as all the algorithms were created by the authors in accordance to the kinematics and dynamics equations, they can have a better performance if more error control is added to it and if the feedback become more useful to the main control algorithm, however, because of the drone structure and the stability that it has, there are no significant problems in this area.

As the simulations showed the control can be obtained knowing that the simulated model worked according to the mathematical model and that can be used to achieve a real control of a quadcopter. Clearly this transition requires the consideration of different factor like the air currents, the variation of the weight of the quadrotor due to the lifting of an object and the variation of the voltage provided by the batteries throughout the time. However this variations can be addressed using other simulation methods like the air flow simulation and the dynamic change in the weight of the quadrotor.

Finally, further research is required for this type of drones on account of the fact that this entire design works excellently in an indoor environment, where there is no need of performing complex tasks and a basic manipulator that can carry one thing at a time can be helpful for the users. What is more, the election of a small computer such as a Raspberry Pi, gives the opportunity of adding a vision system with a camera that can expand the applications of this drone, starting on making it autonomous or to use it as a monitor or search device.

REFERENCES

Ariyanto, M. M. (2013, June 4-5). Validation of a quadrotor helicopter Matlab/Simulink and solidworks models. *IET Conference on Control and Automation 2013: Uniting Problems and Solutions.* Birminghan, UK. doi:10.1049/cp.2013.0012

Bathe, K. (2014). *Finite Element Procedures.* Massachussetts, USA: Pearson Education.

Cataldi, E. M. (October 2016). Impedance Control of an aerial-manipulator: Preliminary results. *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2016).* Daejeon, Sotuh Korea.

Ebel, F. P. (2004). *Electropneumatics Basic Level.* Denkendorf, Germany: FESTO.

Festo Didactic. (2008). *PLC Applications Electro-Pneumatics.* Québec: Canada.

Jha, A. R. (2016, November 2). *Theory, design, and applications of unmanned aerial vehicles.* Florida, United States of America: CRC Press.

Mellinger, D. L. (2011). Design, modeling, estimation and control for aerial grasping and manipulation. *2011 IEEE/ RSJ International Conference on Intelligent Robots and Systems (IROS).* San Francisco, CA, USA: IEEE.

Moaveni, S. (2015). *Finite Element Analysis: Theory and Application with ANSYS.* Minnesota, USA: Pearson Education.

Ramon Soria, P. B. (2016). Extracting Objects for Aerial Manipulation on UAVs Using Low Cost Stereo Sensors. *Sensors, 16*(5), 700. Retrieved from http://doi.org/10.3390/s16050700

Trujillo, M. V. (2016). Sistema aéreo no tripulado con capacidad avanzada de manipulación. *DESEI+D 2016 del Ministerio de Defensa España*. Retrieved from https://aeroarms-project.eu/wp-content/uploads/2017/01/DESEID_2016_paper_95.pdf

Yuksel, B. S. (October 2016). Aerial Robots with Rigid/Elastic-joint Arms: Single-joint Controllability Study and Preliminary Experiments. *2016 IEEE/RSJ Int. Conf. on Intelligent Robots and System.* Daejeon, South Korea.

Yuksel, B. S. (October 2016). Differential Flatness and Control of Protocentric Aerial Manipulators with Any Number of Arms and Mixed Rigid-/Elastic-Joints. *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2016).* Daejeon, South Korea.