Quadcopter Design for Medicine Transportation in the Peruvian Amazon Rainforest

Juan A. Paredes, Juan Acevedo, Hector Mogrovejo, Jorge Villalta, Roberto Furukawa

Perú IEEE EMBS – Pontificia Universidad Católica del Perú, Lima, Perú

juanaugusto25@gmail.com

***Abstract*— Medicine transportation in the Peruvian Amazon Rainforest is difficult due to environmental hazards and lack of proper land transportation roads, which leads to insufficient and improper health services in this area. In order to overcome the terrestrial impediment[1]s mentioned above and remedy this situation, a quadcopter UAV system is proposed to be used for aerial transportation of medicine. This paper will explain the mechanical, electrical and control design considerations taken into account for the implementation of the proposed system.**

***Keywords*— Aerospace Technology, Aerospace Control Systems, Unmanned Aerial Vehicle, FEM Analysis, Sensor Fusion.**

I. Motivation

THE UAV industry has seen increased technological developments in recent years, thus creating more accessible flying autonomous vehicles. With it, companies around the world identified commercial applications for said technology, namely as low-cost transportation of low-weight cargo vehicles. Companies such as Google, Amazon and DHL have developed their own prototypes with the goal of creating commercial networks based around UAV transportation. Other companies have focused on more humanitarian applications. For example, Matternet, in association with Doctors Without Borders, experimented with delivery drones in Papua New Guinea [1] with the purpose of delivering blood samples across this region for faster tuberculosis analysis.

In light of this situation, it is proposed that a UAV would alleviate the current medicine transportation situation in the Peruvian Amazon Rainforest. In this area, there exist geographical barriers that consist of “the difficulty that entails getting access to health services, due to distance, transportation and seasonal geographical isolation”, as stated in the “Informe Defensorial Nº 134” [2]. Muddy roads and the great distances between town make it difficult to establish an efficient terrestrial medicine distribution network. Moreover, according to the results of the Second Census of Native Communities in the Amazon Region conducted in 2007 [3], in an interval of 12 months, approximately 20,679 patients were diagnosed with parasites, 11,232 with diarrhea, 8,026 with lack of nutrition and anemia, and 7,202 with malaria which demonstrates the need of a better transportation system.

This paper proposes a design for a UAV of the quadcopter type for medicine transportation in the before-mentioned area. Due to its intrinsic ability to overcome terrestrial obstacles, its speed and its simplicity in design, a quadcopter would be most suitable for this kind of task. The design takes into account the transportation of low-weight cargo and a structure impermeable to water (in case rain suddenly starts pouring).

II. System Overview

The proposed system is a quadcopter suitable for long-range transportation of medicine. Figure 1 displays the basic components of said system. The flight controller regulates the rotation speed of the rotors via Electronic Speed Controllers (ESC) in order to control the thrust and torque that these exert on the system and, consequently, its mobility. The desired attitude and position is determined by instructions send by a user via wireless communications or preprogrammed before take-off.

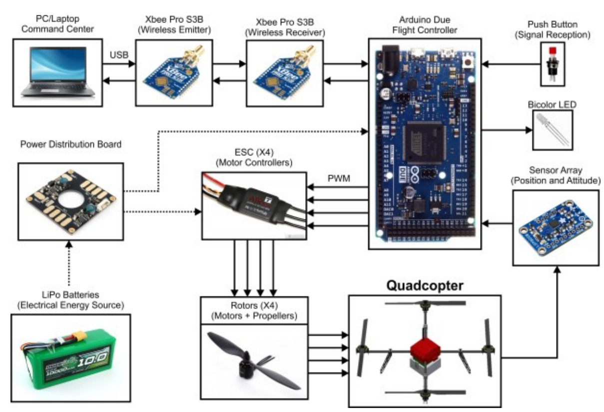

Fig. 1. An overview of the UAV proposed system. The communications, energy distribution and control feedback systems are displayed and will be explained in the next sections of the document.

The quadcopter system is also composed by an array of sensors which allow the flight controller to receive information regarding the state of the system. Also, a couple of simple electrical components are included, such as a bicolor LED to signal the state of the flight and low battery condition, and a push button that may be pressed to let the system know that the medicine has been retrieved. The LiPo batteries supply the entire system with electrical energy. A power distribution board is employed to help with this task.

978-1-5090-1341-8/16/$31.00 ©2016 IEEE

A couple of requirements are needed for the system to perform optimally in the given conditions. First of all, weight distribution along the structure of the quadcopter should be symmetrical so that stabilization procedures may be simplified. In addition, the system should be impermeable to water so that it can sustain itself in case rain starts pouring in. It should be noted that the objective here is not to fly in rainy conditions but to persevere through them in case they happen spontaneously. Other requirements will be reviewed as they become relevant through this document.

III. Throttle Calculation

The main three components of the quadcopter propulsion system are the ESCs, the brushless motors and the propellers. A combination of these three elements will determine the payload the quadcopter will be able to lift and the amount of time it may be capable of hovering above the ground. The battery capacity is also an important factor to take into account in these calculations.

Taking into account a battery with capacity E in mAh and an energy safety factor of SF, the real battery capacity E_R may be calculated in the following fashion:

$$E_R = E \times SF. \tag{1}$$

Normally, companies that sell aeronautic components provide tables that display the resulting thrust (T) of applying a certain quantity of amperage (I) to a specific motor and propeller combination. Such thrust is normally displayed in terms of grams (g). In order to lower battery consumption, a low thrust should be used in these calculations. A safety factor should also be applied to this thrust value as well, which will be assumed to be the same as the energy one. This way, real thrust (T_R) can be calculated like this:

$$T_R = T \times SF. \tag{2}$$

In order to calculate remaining lift (L), one must subtract the weight of the batteries (m_B), the rotor weight (m_r) and the payload weight (m_P) from the total thrust. In the case of a quadcopter, the formula would look like this:

$$L = 4T_R - m_B - m_r - m_P. \tag{3}$$

The remaining lift represents the maximum amount of weight in grams that the frame may weight, which, in this case, will be addressed in the mechanical design section.
In order to estimate the total hover time (t_h), one must get the motor current (I_m) correspondent to the thrust used before and the current consumed by the rest of electronic components (I_r) (in preliminary calculations, this last value must be assumed). The calculation to be performed is the following:

$$t_h = \frac{E_R}{4I_m + I_r}, \tag{4}$$

in which the time is given in hours.

Considering a payload of about 2 kg for the medicine, the selected devices were the U8 Pro Motor - KV170 (which present an additional benefit by being waterproof), 26” x 8.5” carbon fiber propellers and the AIR 40 ESC, all products of T-MOTOR.

For the remaining lift and hover time calculations, a battery with 20 Ah capacity and 2.378 kg mass was considered, as well as a safety factor of 0.85, a throttle of 65% and an I_r of 1 A. The corresponding current consumption and thrust were obtained from the tables provided by T-Motor [4]; a portion of said tables is displayed in Table 1. Using this parameters, a hover time of 31.29 minutes was calculated as well as a remaining lift of 1.836 kg. This last constraint will be addressed in the mechanical design section.

TABLE I
Thrust data table provided by T-Motor

Throttle	Current (A)	Thrust (g)
50%	4.4	1420
65%	7.9	2220
75%	10.6	2780

IV. Mechanical Design

The proposed mechanical design aims to be as light as possible in order to meet the mass constraint set in the throttle calculation, be symmetrical in order to simplify the control requirements and rigid enough to prevent either material failure or (in the case of the arms) bending. Said quadcopter is presented in figure 2.

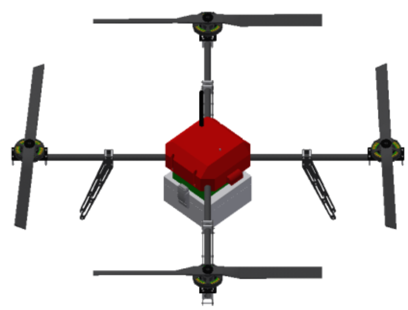

Fig. 2. Proposed frame design for the Quadcopter.

A. Main Hub

The main hub is composed by two carbon fiber plates with a thickness of 3 mm assembled by four boom clamps; these clamps will also keep the carbon fiber tubes assembled to the main hub through a tight grip. Allen bolts are used to perform this assembly. The clamps and booms can be bought, but the plates will have to be machined, preferably with a CNC mill and carbide or PCD milling drills. Figure 3 displays this structure.

The frame is designed to contain the electronic components needed to control the drone, such as sensors and controllers. For that purpose, a top protection structure made of ABS (Acrylonitrile Butadiene Styrene) with a thickness of 1 mm will protect the sensors from rain, dust and wind forces. This component could be manufactured by a 3D printer, although further procedure will have to be performed to the printed structure in order to guarantee impermeability, such as painting to coat the surface of the structure.

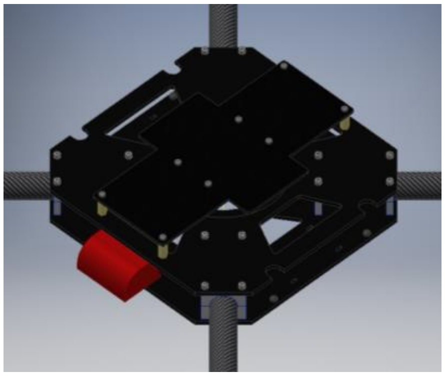

Fig. 3. Central hub without upper case. Its purpose is to assemble all the rotors through its clamps and to house sensible electronics, such as the flight controller and the sensors.

B. Arms

Each of the four arms consists of a carbon fiber tube with 20 mm diameter, 2mm of wall thickness and 500 mm of length, enough to prevent the propellers from hitting the main hub. These are assembled to the main hub through boom clamps and are used to mount the landing gear and the rotors.

In theory, the arms will sustain a maximum force of 38.06 N due to the thrust of the chosen rotor combination. Through an FEM simulation of these forces, it was determined that, under the effect of that force, the arms will have a safety factor of 7.42, meaning the arms won't suffer from material failure in these conditions.

C. Landing Gear

Landing legs are mounted to each arm, each one having two clamps, two carbon fiber plates and three aluminum standoffs as part of their structure. Landing plates are 2 mm wide and have certain parts removed to lower the weight of the structure and maintain the necessary rigidity for landing operations.

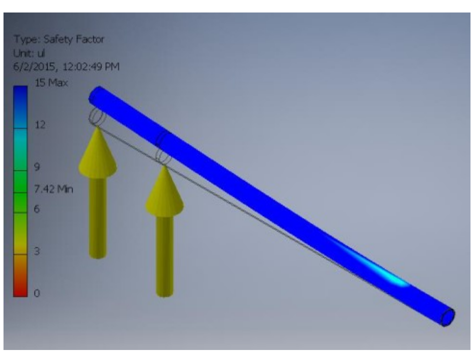

Fig 4. Safety factor of frame arms after performing FEM simulation. The side of the tube under the clamps is under the most pressure during a flight.

D. Motor Mounts

The mounting is composed by 3 mm carbon fiber plates assembled to each arm by two boom clamps. Each plate should be designed to fit the U8 Motor's mounting holes. It is encouraged to drill a circular hole in the middle to allow the U8 rotor to freely rotate and to remove as much material as possible to reduce the overall weight.

E. Medicine Package

The bottom part of the drone is an ABS plastic box with a 2 mm thickness held together by two toggle latches. The box is used to carry medicine and two Li-Po 10 Ah batteries on its top. It is assembled to the main hub by aluminum spacers. In order to get its contents, the latches have to be opened so that the lower part of the box becomes unfastened while the top part remains attached.

F. Total Mass and Symmetry

A 3D model of the proposed quadcopter was created in Autodesk Inventor to determine the mass and inertia moments of the frame. The estimated frame mass is 1.6 kg, less than the established limit. Also, since the resulting products of inertia are low compared to the principal moments of inertia, it can be concluded that the frame is symmetrical enough not to complicate the design of a control algorithm. These inertia moments are shown in Table 2.

TABLE II

QUADCOPTER FRAME INERTIA MOMENTS (IN KG.M^2)

I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
5.3832×10^{-2}	5.3831×10^{-2}	9.4120×10^{-2}	-1.1832×10^{-3}	-1.1363×10^{-5}	1.1860×10^{-5}

G. FEM Analysis

In order to verify that the proposed mechanical designed won't break during a flight, FEM analyses were performed on the 3D model of the frame under critical conditions (maximum rotor thrust) for testing, considering the carbon fiber as a brittle material. The FoS along one of the arms is shown in figure 4. The Factor of Safety will determine whether or not the structure will be resistant enough. The results from the analyses are displayed in Table 2. Due to the FoS having a value greater than 3 on all the components, it can be concluded that the quadcopter will resist the greatest thrust the rotors are capable of.

TABLE III

FACTOR OF SAFETY UNDER CRITICAL CONDITIONS

Component	Material	FoS
Arm	Carbon Fiber	3.93
Top central plate	Carbon Fiber	4.45
Lower central plate	Carbon Fiber	3.16
Standoff connector	Aluminum 6061	10.44
Top box package	Plastic ABS	4.01

V. Electrical System

In this section, the main electrical components will be mentioned as well as the way in which they are all connected and how they contribute to the functioning of the quadcopter system. The block diagram displayed in Figure 5 may be used as a reference for the rest of this section since it summarizes its contents.

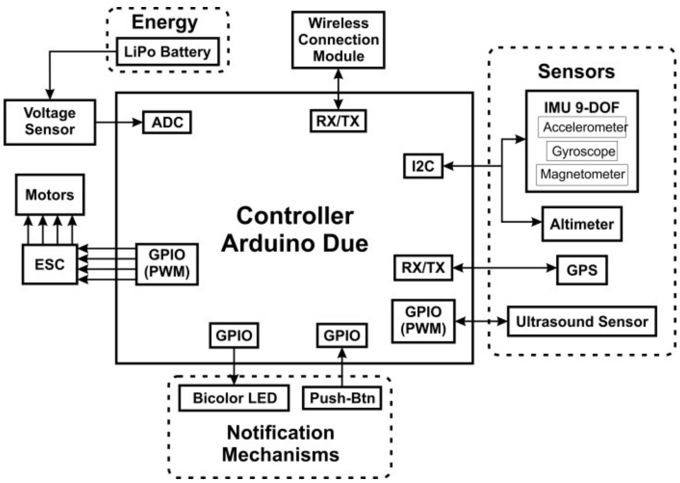

Fig. 5. Block Diagram of Quadcopter Electrical System. The main electrical connections are shown here in a simplified manner

The most important part of the electrical system would be the flight controller, which is in charge of recollecting environmental information, sending control signals, handling communications among other tasks. Due to its flexibility, amount of input and output connection options and processing power, an Arduino Due was chosen for this assignment.

Several sensors will be needed by the controller for it to be capable of establishing a reliable feedback loop. Four main sensors are needed for this task, which are the following:

- **IMU:** This sensor includes an accelerometer, a gyroscope and a magnetometer and it allows the controller to get information about the attitude and heading of the quadcopter. Most IMUs are connected through an I2C bus.

- **Altimeter:** This sensor determines the current altitude over sea level of the quadcopter from absolute pressure readings. It would be advisable to use one capable of I2C communication.

- **GPS Module:** This device will allow the quadcopter to get its geographical location and heading in the world, granted that it doesn't get obstructed by walls and receives signals from at least four satellites. Serial communication is commonly used to communicate with these devices.

- **Ultrasound sensor:** This sensor uses ultrasonic waves in order to measure the distance to the closest solid object. The quadcopter will use this sensor in order to measure its distance to the floor and perform landing operations more precisely. Most of these systems send information through PWM signals.

In order to control the quadcopter and use the information obtained by the sensors, the controller must send signals to control the generated lift. For that purpose, PWM signals will be sent to ESCs, which in turn will regulate DC voltage to control brushless motors.

In order to maintain communications with a ground station, a wireless module must be installed in the quadcopter, which will establish serial communication with the controller to send telemetry messages. Signal strength will be determined by the chosen signal frequency, module signal gain and antenna gain.

Another important system is the voltage sensor, which is connected to the quadcopter and can measure how much energy is left in it. If a LiPo battery is discharged too much it may become permanently damaged, so this system is used to prevent this and look for a recharge station when the battery level becomes low enough. The controller reads this value through an analog input.

The notification mechanisms are used for notifying and getting information from the operators as stated in the system overview section. They send signals to the controller through its GPIO.

The Arduino Due will power most of these components, while it and motors will be directly energized by the batteries through a Power Distribution Board. This board should be designed so that it can handle the required amount of current that all the electrical components will require.

VI. Control System

In order to study the dynamic model, it's important to have a simple representation of the quadcopter. Therefore, the system shall be represented by a central spherical body coupled to four cylindrical arms; at the end of each of these, the rotor will be attached, which will allow the actuation of the system. This is illustrated in figure 6.

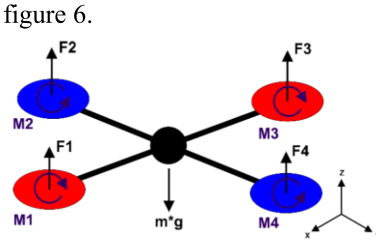

Fig. 6. Quadcopter Free Body Diagram

Four control variables will be defined to control pitch (ϕ), roll (θ) and yaw (ψ), which will be T, τ_ϕ, τ_θ and τ_ψ respectively.

$$T = F1 + F2 + F3 + F4 \tag{5}$$

$$\tau_\phi = L\,(-F2 + F4) \tag{6}$$

$$\tau_\theta = L\,(-F1 + F3) \tag{7}$$

$$\tau_\psi = -M1 + M2 - M3 + M4 \tag{8}$$

Considering the thrust and moments to be proportional to the squared rotational velocity, the following can be established:

$$F = b \times \omega^2 \quad (9)$$
$$M = q \times \omega^2 \quad (10)$$

With these equations, a transformation matrix that relates the previous variables with the squared rotational velocities can be obtained, which will be used by the flight controller to send the correct PWM signals to the ESCs and control the rotation of the motors.

$$\begin{bmatrix} T \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & -b\,L_i & 0 & b\,L_i \\ -b\,L_i & 0 & b\,L_i & 0 \\ -q & q & -q & q \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix}. \quad (11)$$

The Euler equations will be used to outline the dynamic equations of the quadcopter. The documents [5], [6], [7] and [8] were used as reference for this section. The equations are the following:

$$\begin{bmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} s\,\phi * s\,\psi + c\,\phi * s\,\theta * c\,\psi \\ -s\,\phi * c\,\psi + c\,\phi * s\,\theta * s\,\psi \\ c\,\phi * c\,\theta \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\ \tan\theta & \cos\phi\ \tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{bmatrix} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix} = \begin{bmatrix} \frac{(I_{yy}-I_{zz})}{I_{xx}}\ \dot{Q}\ \dot{R} \\ \frac{(I_{zz}-I_{xx})}{I_{yy}}\ \dot{P}\ \dot{R} \\ \frac{(I_{xx}-I_{yy})}{I_{zz}}\ \dot{P}\ \dot{Q} \end{bmatrix} + \begin{bmatrix} \frac{\tau_\phi}{I_{xx}} \\ \frac{\tau_\theta}{I_{yy}} \\ \frac{\tau_\psi}{I_{zz}} \end{bmatrix}. \quad (14)$$

In these equations, X, Y and Z represent the 3D location of the quadcopter and PQR represent its angular velocity along the body coordinate system.

A PID controller will be proposed to control this dynamic system. Since this controller requires a linearized plant to be tunes, the dynamic equations stated before will be linearized around the hover operation point, in which $\phi = 0°, \theta = 0°$, $\psi = \psi_o$ and $T = m * g$.

$$\ddot{X} = g\,\theta \quad (15) \qquad \ddot{\phi} = \frac{\tau_\phi}{I_{xx}} \quad (18)$$
$$\ddot{Y} = -g\,\phi \quad (16) \qquad \ddot{\theta} = \frac{\tau_\theta}{I_{yy}} \quad (19)$$
$$\ddot{Z} = \frac{T}{m} \quad (17) \qquad \ddot{\psi} = \frac{\tau_\psi}{I_{zz}} \quad (20)$$

For this system, the feedback loop would require the sensors to get the process variables, which would go through a state estimation phase to estimate and filter the required variables and compare these with the reference values to get the error. This error would be used as input for the controller, whose outputs would have to be decoupled into rotor angular velocities in order to affect the system. This is represented by the diagram in Figure 7.

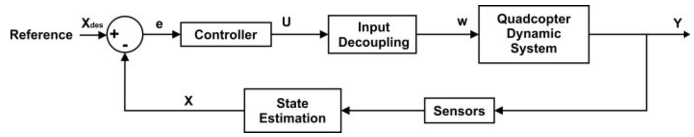

Fig. 7. Proposed Control Feedback Loop

Controlling the altitude and the yaw required a single feedback loop, although an offset must be included in the altitude controller for it to keep countering the quadcopter weight. Horizontal position control requires two control loops; the outer loop determines the required pitch/roll according to the position error and the inner loop determined the required torque according to the pitch/roll error. This is illustrated in Figure 8.

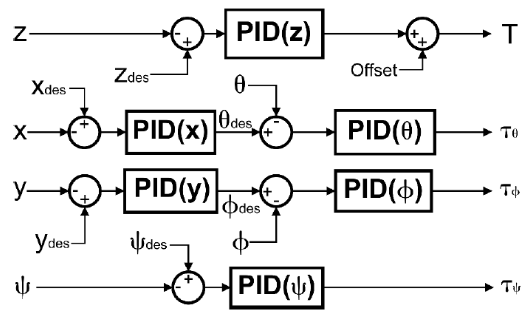

Fig. 8. Proposed Control System

The values for the simulation were taken from the information gained from the 3D model of the structure and documentation from the rotor. The model's values are m = 5.978 kg, L = 0.5 m, I_{xx} = 0.0746 kg.m^2, I_{yy} = 0.0746 kg.m^2, I_{zz} = 0.111929 kg.m^2, b = 5.1248*10^{-6} N/RPM^2 and q = 2.8750*10^{-6} N.m/RPM^2.

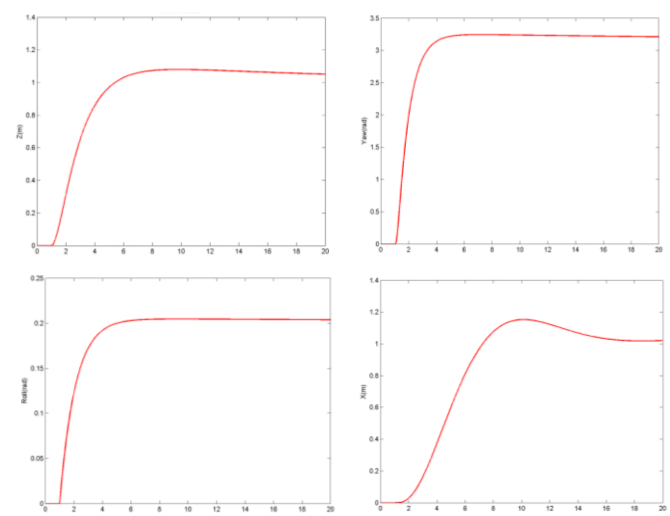

Fig. 9. Step response of dynamic system with PID controller implemented. [Up-Left] Altitude control (Z). [Up-Right] Yaw control. [Down-Left] Pitch/Roll control. [Down-Right] Horizontal Position Control (X/Y).

The simulation results are displayed in Figure 9. Most systems converge to their set points in an acceptable amount of time. The horizontal position control shows an underdamped behavior and takes longer to converge to the set point due to the nature of the controller with two loops. Through these simulations, it has been demonstrated that the proposed design can be controlled through a simple control algorithm like the PID controller.

VII. Observations

The present paper aims to present a design for a medicine transport system. However, in order for the transportation service to work other devices will be required. For example, a monitoring center may be required to overview the condition of all the quadcopter in flight, as well as a communications antennae distributed throughout the area of operation in order to coordinate activities in a more efficient manner. More importantly, to guarantee an efficient deployment, automatic recharge centers will have to be deployed in strategic locations for the quadcopters to recharge when their battery is low on power. This could prove to be challenging due to the difficulty of performing precision landings and the requirement of the station to be protected against rain. These problems will be assessed in future studies.

Regarding the proposed dynamic model, many factors weren't considered which would influence the system under realistic conditions. For example, drag forces weren't modeled since these depend on the body geometry and current airspeed, which would prove to be complicated; also, the gyroscopic forces occasioned by the motors weren't considered since their modelling required the knowledge of the motor inertia. Future research will aim to construct more realistic models.

VIII. Conclusions

A quadcopter design for medicine transportation in the Peruvian Amazon Rainforest was proposed in this paper. The reasons behind its design were explained through the entire document and the following conclusions were established:

- The proposed thrust system is capable of attaining a hover time of 31.29 minutes with a frame with 1.836 kg of mass with an 85% Factor of Safety.

- The proposed frame structure is capable of keeping a stabilized flight while lifting 2 kg of cargo and housing the entirety of the electrical components needed for the quadcopter to fly autonomously. Also, a top protections was designed to protect the electrical components from rain, dust and other hazards.

- The proposed electrical system, that included a sensor array, brushless motor speed controllers and other peripherals, will allow the creation of a feedback loop to control the quadcopter through the system controller.

- The proposed PID controller is capable of controlling the designed quadcopter in ideal conditions, although better results may be attained through further tuning.

Acknowledgments

The team would like to thank professor Carlos Saito from Pontificia Universidad Católica del Perú for his advice on UAV design and component selection.

References

[1] J. Leber, «Doctors Without Borders Is Experimenting With Delivery Drones To Battle An Epidemic,» 16 Octubre 2014. [Online]. Available: http://www.fastcoexist.com/3037013/doctors-without-borders-is-experimenting-with-delivery-drones-to-battle-an-epidemic.

[2] Programa de Comunidades Nativas, «"La Salud de las Comunidades Nativas: Un reto para el Estado - Informe Defensorial N° 134",» Defensoría del Pueblo, Lima - Perú, 2008.

[3] Dirección Nacional de Censos y Encuestas, «II Censo de Comunidades Indígenas de la Amazonía Peruana 2007 – Tomo 1,» Instituto Nacional de Estadística e Informática (INEI), Lima-Perú, 2008.

[4] T-Motor, «U8 - Pro - Efficiency Type,» [Online]. Available: http://www.rctigermotor.com/html/2013/Efficiency-Type_1219/176.html.

[5] C. Powers, D. Mellinger and V. Kumar, «Quadrotor Kinematics and Dynamics» in Handbook of Unmanned Aerial Vehicles, New York, Springer Reference, 2015, pp. 307 - 328

[6] T. Bresciani, «Modelling, Identification and Control of a Quadrotor Helicopter» Department of Automatic Control, Lund University, Lund, 2008.

[7] P. Pounds, R. Mahony and J. Gresham, «Towards Dynamically-Favourable Quad-Rotor Aerial Robots» Australian National University, Canberra.

[8] D. Hartman, K. Landis, M. Mehrer, S. Moreno, J. Kim «Quad-Sim: Mathematical Model Documentation» [Online]. Available: http://www.mathworks.com/matlabcentral/fileexchange/48053-quad-sim