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HEXAROTOR DESIGN PROJECT: MODELING AND ENERGY MANAGEMENT FOR OUTDOOR AERIAL ROBOT

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Abstract. *Hexarotor helicopter or simply hexarotor is rotorcraft that has six lift-generating propellers in three co-axial configurations. Three of the propellers spin clock wise and the other three counter-clockwise. Control of the machine can be achieved by varying relative speed of the propellers. Hexarotor is an under- actuated and dynamically instable system, no new concept; however the modern hexarotors are mostly unmanned. Flying has an advantage when compared to ground based locomotion, as it simplifies the task of overcoming obstacles and allows for rapid coverage of an area. One of the key challenges that has prevented engineers from coming up with convincing aerial solutions for indoor and outdoor explorations is the energetic cost of flying. Advancement in MEMS IMU-aided GPS technology, availability of high speed brushless motors and high power to weight ratio Li-Polymer battery technology, hexarotor can now be relatively successfully designed and fabricated. The purpose of this paper is to illustrate the effects of hexarotor inertia and geometry on dynamic performance for the energy problem regarding aerial exploration within indoor and outdoor environments. A design approach for the construction of a hexarotor aerial vehicle will be presented. Given a specified size and variable payload, selection of various components such as motor-rotor pairs, battery source, and structural material is a crucial design problem and as a means of preserving energy while maintaining a regard task, especially, in the context of MAVs. The design steps that led to the selection of the chosen set of the above components will be given in detail. Once the structure is fabricated, the hexarotor can be tested for thrust generation, payload capability. Thus a study into the materials and manufacturing processes available would be necessary in order to achieve this goal.*

Keywords: *unmanned aerial vehicle; hexarotor; mechanical design; energy management; payload*

1. INTRODUCTION

The unmanned aerial vehicles (**UAV's**) are expected to become a major part of the aviation industry over the next years, primarily enabled by developments in computer science, automatic control, robotics, communications and sensor technologies (Bouabdallah *et al.*, 2007). **UAV's** are important when they come to performing a desired task in a dangerous and/or unaccessible environment (Pastor *et al.*, 2007).

More recently, a growing interest in unmanned aerial vehicles has been shown among the research community. One type of aerial vehicle with a strong potential is the rotorcraft and the especial class of six-rotor aerial vehicle, also called hexarotor. The hexarotor configuration is more propitious to be used and not requires complex mechanical control linkages for rotor actuation and their high payload-to-power ratio makes it a good candidate for inspection and other tasks. For example, the possible application in the aerial supervision of oil and gas plants and detection having the potential to significantly reduce cost and risk to human life. However, all systems of micro aerial vehicle with strict limitation of weight and size must accomplish the mission in the conditions of low noise, long-range flight, and fast response. The requirement for accuracy is pretty restricted (Lin, 1999). This study explores the combination fulfilling the requirement, and utilizes selected electric propulsion system, embedded system, payload and Li-Polymer batteries to carry out optimal combination to be used as power supply system of the hexarotor.

If **UAV** utilizes internal combustion engines as propulsion system, the heat energy efficiency is lower, but the high power density could supply sufficient propulsion power for **UAV**. However, such engines have the disadvantage of generating a high level of acoustic emissions, so it is not proper to the **UAV**; and this type of engine would be affected by the climate more easily. Therefore, most existing developed autonomous miniature flying robots are equipped with combination of motor-propeller and rechargeable battery for power supply. Features of battery such as electricity storage capacity, energy density, power density, discharge rate, voltage, weight, price, auto-discharge rate, sand the circular life for recharge and discharge are all under considerations. All kinds of rechargeable batteries indicate Cadmium-Nickel battery has higher power density; it can release the maximum energy in unit time. Actually, since the inner resistivity is low, when large current is supplied, the voltage has little change during discharging. It seems that the batteries are more appropriate for power supply of **UAV**. However, the voltage of **Ni-Cd** battery is small (about 1.2V), for common receiver and server which require voltage from 4.8V to 6V, 4 to 5 batteries would be required. The additional weight of battery would increase the weight of **UAV** during taking off.

Another disadvantage of **Ni-Cd** battery is that the capacity is small, and energy density is low. If it supplies the energy for motor, the time of usage would be extremely short due to large current discharging, and it could not complete the **UAV**'s mission. In addition, the increase of discharge rate would further decrease the battery power and shorten the life span of battery. As to **UAV**, if chosen existing **NiMH** battery, the weight would be still the major issue. Voltage of Lithium battery is about triple of **Ni-Cd** battery, the advantage is low energy density, light weight, small volume, and large capacity (Lin, 1999; Li, 1997), which would be more appropriate for fulfilling requirement of **UAV**. The restrictions are high internal resistance, when discharge large current, the voltage of battery would drop dramatically, output power would be decreased and affect the driving force of the motor.

Recently the Lithium polymer (**Li-Poly**) are being widely used in hobby and **UAV** applications (Draganfly Innovation Inc, 2010). They work well because they can hold a large amount of current and are lighter than **Ni-Cd** and **NiMH** batteries. But with this increase in battery life come potential hazards. The voltage of a **Li-poly** cell varies from about 2.7 V (discharged) to about 4.23 V (fully charged), and the cells have to be protected from overcharge by limiting the applied voltage to no more than 4.235 V per cell used in a series combination. Overcharging a **Li-poly** battery will likely result in explosion and/or fire. During discharge on load, the load has to be removed as soon as the voltage drops below approximately 3.0 V per cell (used in a series combination), or else the battery will subsequently no longer accept a full charge and may experience problems holding voltage under load.

Various rechargeable batteries have various disadvantage and advantage when applied in **UAV**, the optimal battery product for application in **UAV** is still absent. For now, there is not one kind of battery that can be applied broadly to all sizes of **UAV**. Electrical transmission would provide different current to produce different driving force in accordance with signal. There is an upper limit of current to elevate the upper limit would definitely increase the weight. If the weight is too large, the loading would be increased and affect the sensitivity and success of the vehicle as well. This study would consider factors mentioned above to carry out testing and look for the optimal combination (Sung *et al.*, 2001). The present residual charge should be displayed to the user and issues regarding lack of current should be efficiently to deal with the issue on time.

Based on different studies of battery management, the power management system, payload and autonomy of hexarotor aerial vehicle is developed in this paper. It is mainly composed of embedded control system with battery voltage detection circuit constituted by electric capacity corresponding to working time.

2. HEXAROTOR SYSTEM

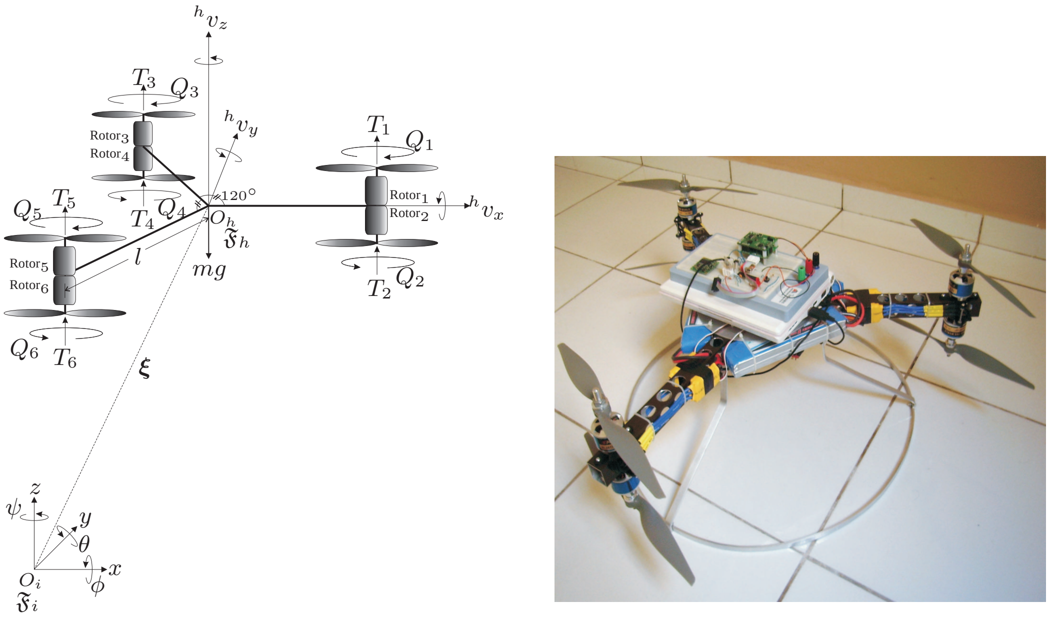
The hexarotor concept has been around for a few years ago with draganflyer X6 helicopter built by Draganfly Innovation Inc (2010). The rotorcraft vehicle, has been chosen by many researchers as a very promising vehicle for indoor/outdoor navigation using multidisciplinary concepts (Madani and Benallegue, 2007). Hexarotor aerial vehicle, under consideration in this paper, consist of a rigid cross frame equipped whit six rotor as shown in figure 1 The six rotors are arranged as three counter-rotating co-axial pairs mounted at the ends of the three arms, with matched sets of counter-rotating rotor blades without gears to wear out. The co-axial layout doubles the thrust without increasing the size of the footprint, and naturally eliminates loss of efficiency due to torque compensation.

The up (down) motion is achieved by increasing (decreasing) the total thrust while maintaining an equally spaced individual co-axial pair thrust. The forward/backward, left/right and the yaw motions are achieved through a differential control strategy of the thrust generated by each co-axial pair. If a yaw motions is desired, the thrust of one set of rotors must be reduced and the thrust of the other must be proportionally increased, while maintaining the same total thrust to avoid an up-down motion. Hence, the yaw motion is then realized in the direction of the induced reactive torque. On the other hand, forward (backward) motion is achieved by pitching in the desired direction. There is no change on direction of the rotors.

2.1 Forces and Torques Acting on Hexarotor

The mechanical structure is based on certain basic assumptions as given below:

- Hexarotor body is rigid;
- Propellers are rigid without gear boxes;
- There is no air friction on hexarotor body;



(a) (b)

Figure 1. Hexarotor helicopter configuration: (a) Modeling, (b) Experimental system.

- Free stream air velocity is zero;
- Drag torque Q is proportional to propeller speed with D as drag constant;
- Design is symmetrical.

The total thrust to the hexarotor may be expressed as a vector in the body fixed frame by (Bramwell *et al.*, 2001; Seddon, 1990; Dzul *et al.*, 2002):

$$\mathbf{T} = \mathbf{G}(a,b)\sum_{i=1}^{6}|T_i|, \tag{1}$$

where,

$$\mathbf{G}(a,b) = \frac{1}{\sqrt{1-\sin^2 a \sin^2 b}}\begin{bmatrix} \sin a \cos b \\ \cos a \sin b \\ \cos a \cos b \end{bmatrix}$$

if $a \approx 0$ and $b \approx 0$ very small. Lifting forces generated by the spinning propeller and the weight, are responsible for all the motion of body, as the external effects such as air friction, wind pressure etc. have been neglected. Then, the total lift of the main rotor T is expressed as (Sanca *et al.*, 2008):

$$\mathbf{T} = \begin{bmatrix} 0 \\ 0 \\ \sum_{i=1}^{6}|T_i| \end{bmatrix}; \tag{2}$$

The torques generated by the thrust vectors, where the gravitational force does not generate a torque since the hexarotor is free to rotate around its center of mass, is given by:

$$\tau_i = [l \times \mathbf{G}(a,b)|T_i|] = l \times T_i \tag{3}$$

The total torque generated by the hexarotor it is given by:

$$\boldsymbol{\tau} = \begin{bmatrix} \frac{\sqrt{3}}{2}l(|T_3|+|T_4|-|T_5|-|T_6|) \\ \frac{l}{2}(|T_3|+|T_4|+|T_5|+|T_6|-2|T_1|+2|T_2|) \\ \sum_{i=1}^{6}(-1)^{i+1}Q_i \end{bmatrix}, \tag{4}$$

where Q_i are the anti-torques. The aerodinamics drags on the rotors generate some pure torques acting through the rotor hubs.

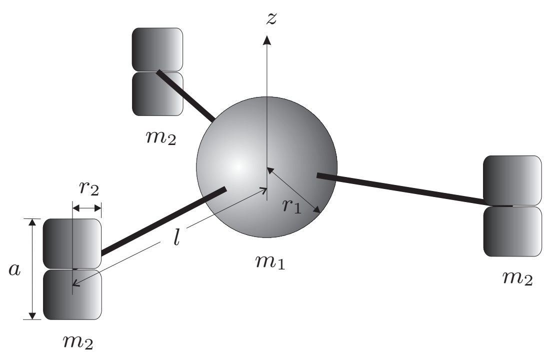


Figure 2. The moment of inertia for the hexarotor.

2.2 Moments of Inertia of Hexarotor Body

Hexarotor mechanical structure, as shown in fig. 2, six rotors are arranged as three counter-rotating co-axial pairs mounted at the ends of the three arms, embedded electronic system and power supply at the intersection. Then, the moment of inertia matrix is essentially symmetric about all the three axes, therefore $J_{xy} = J_{xz} = J_{yz} = 0$ it implies that

$$\mathbf{J} = \begin{bmatrix} J_{xx} & 0 & 0 \\ 0 & J_{yy} & 0 \\ 0 & 0 & J_{zz} \end{bmatrix}. \tag{5}$$

The moment of inertia can be approximated assuming a spherical dense center with mass m_1, that represent the embedded system with radius r_1, and cylindrical masses of mass m_2, that represents the rotor and motor configuration with radius r_2 located at a distance l from the epicenter expressed by:

$$J_{xx} = J_{yy} = \frac{2}{5}m_1 r_1^2 + \frac{3}{4}m_2 r_2^2 + \frac{1}{4}m_2 a^2 + \frac{3}{2}m_2 l^2; \tag{6}$$

$$J_{zz} = \frac{2}{5}m_1 r_1^2 + \frac{3}{2}m_2 r_2^2 + 3m_2 l^2. \tag{7}$$

2.3 Hexarotor Hardware Architecture

Architecture, from the point of view of the aerial robot, was organized into several independent blocks, connected through the local bus that is composed by data, address and control bus (figure 3). A master block manager operates several slave blocks. Blocks associated with the interfaces of sensors and actuators, communication and auxiliary memories were subjected to direct control from the block manager. The advantage of using a common bus was the facility to expand the system. Inside the limitations of resources, it was possible to add new blocks, allowing an adapted configuration of the robot for each task.

2.4 Structure

The custom-build platform is based on a conventional three co-axial rotor design. The idea is to have a tight integration between the structure, electronics and sensors board to reduce weight, minimize wiring, and improve manufacturability. A good material for structure fabrication is the carbon fibre based on printed circuit board (PCB) and another a less expensive alternative is to the use of aluminum profiles. The figure 1 illustrates the hexarotor structure build with aluminum frame. An important aspects for the choice of material is directly related to engine power and the total masse and payload. This simple platform survives small collisions such as walls and ceiling without causing damage to either the platform or the obstacles. The system is designed so that additional control boards and/or sensors can be stacked in its centre with minimal effort. The total weight of the structure, including the embedded electronics, without the battery, is 1.37kg. The table 1 illustrates the principal parameters and characteristics of the experimental aerial vehicle.

2.4.1 Propulsion

The propulsion system consists of six emax BL$2815/09$ (920rpm/v) outrunner brushless motors, each fitted with APC 12×6 E/EP (thin electric/thin electric pusher) composite propellers, which are powered by a $4-$cell 4450 mAh Lithium Polymer (LiPo) battery (weighing 464 g). This configuration provides 5.886 N (600 g) of thrust, at the maximum battery voltage for each motor, giving a total thrust of 15.2055 N (1550 g).

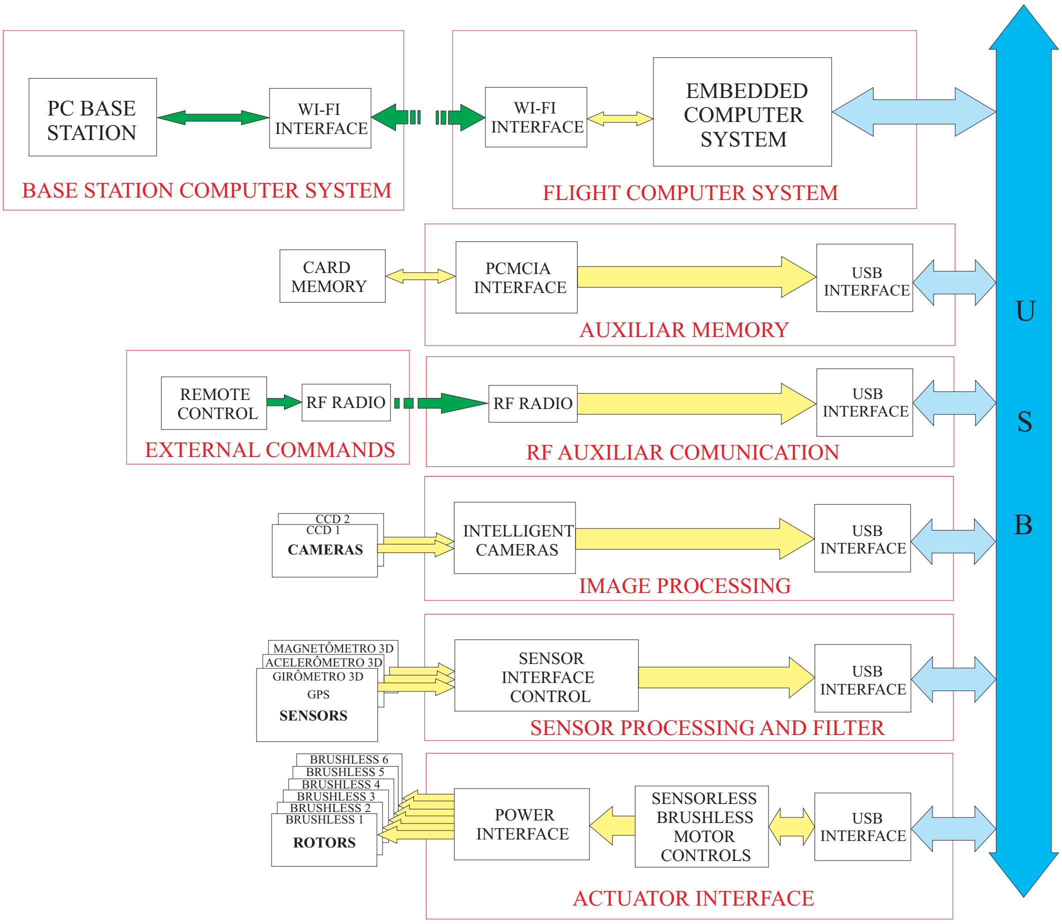


Figure 3. Hardware architecture block diagram of the proposed system.

Table 1. Some characteristics of hexarotor aerial vehicle.

Component	Weight	Quantity	Total Weight
E-Max Brushless Motor BL2815/09 No load current: 10V/1.7A Current Capacity 38A/60s Dimensions: 30/15mm	112g	6	672g
E-Max 50A Brushless Electric Speed Control Output Current 50A Burst Current 65A Size 58×27×10mm	36g	6	216g
Thunder Power RC Li-Polymer 4450mAh 14.8V 22C cont/ 40C Burst 98A/178A TP4450-45HP	464g	3	1392g
APC 12×6 Thin Electric Propeller APC 12×6 Thin Pusher Electric Propeller Diameter: 12" Pitch: 6" Hub inner diameter: 0.25"	25g	6	150g
Hexarotor aluminium's Structure	1145g	1	1145g
Netbook Computer	933g	1	933g
Extra Payload	700g	1	700g
TOTAL			5208g

Table 2. Some sensors implemented on hexarotor.

Component	**Weight**
Inertial Measurement Unit with 6 Degrees of Freedom - Sparkfun SEN-08454 - 3 axes of acceleration data, 3 axes of gyroscopic data, and 3 axes of magnetic data.	28g
Smart GPS Antenna module ME-1000RW Chip	30g
Wireless TRF-2.4G Transceiver	5g
USB Web-cam	130g
TOTAL	**193g**
EXTRA PAYLOAD	**507g**

2.4.2 Sensors

In order to compute the attitude and position of the hexarotor, the information provided by an inertial measurement unit (**IMU**), a global positioning system (**GPS**), and a camera was implemented. The table 2 illustrate some sensors implemented on hexarotor.

2.5 Endurance Estimation Model

In order to calculate the estimated flight endurance we make the assumption that when the platform is flying the thrust is equal to its own weight. It is also assumed that the fluctuations in the control response average to a constant value and are equal to the static test case. First the motor and propeller setup is characterized to determine the systems relationship between power consumption and thrust. Then, based on this characterization, an estimation model is used to deduce the estimated flight endurance using the total take-off weight and the battery capacity. The estimation model can also deal with variations in payload mass, payload power consumption and idle state power consumption. With this method the performance of future battery technologies can also be estimated based on the specific energy density of the technology. This estimation model is then used to find the best battery for hexarotor system by performing an optimal search from a list of available batteries.

The estimated flight endurance can be calculated as follows:

$$t_E = \frac{c_B}{p_M + p_I}, \tag{8}$$

where, c_B is the battery capacity, expressed by $c_B = e_D m_B$, being e_D the specific energy density (W.h/kg) and m_B relative mass; p_M is the motor power taken from the thrust at the point where the thrust is equal to the total take-off weight m_T of the platform and p_I is the total idle-state power consumption. The total idle-state power consumption is a summation of the avionics p_A and payload power p_P consumptions. In order to calculate the estimated flight endurance we need to define the total take-off weight m_T that is obtained by summing the individual component masses of the structure $m_S = m_1 + 3 \cdot m_2$, battery m_B and payload m_P:

$$m_T = m_S + m_B + m_P \tag{9}$$

There is one major limitation, with respect to the battery voltage, that needs to be taken into account. As the battery voltage reduces during the flight there is also a relative reduction in the available thrust. Therefore, it is necessary to take a measurement of the motor thrust limit m_L when the battery is at its minimum voltage. This can be done using the motor test (figure 5) by setting the power supply to the minimum battery voltage and recording the thrust. This thrust measurement allows us to calculate the maximum payload mass limit m_{X_P}:

$$m_{X_P} = m_L - m_S - m_B. \tag{10}$$

3. Flight Experiments

The power management system of the hexarotor is mainly composed of microcontroller circuit and battery voltage detection circuit (illustrated in figure 4). The task of interfacing a common personal computer with actuators and sensors of the robot was made by the Microchip's microcontroller 18F2550 that has special functionality of being a **USB** device.

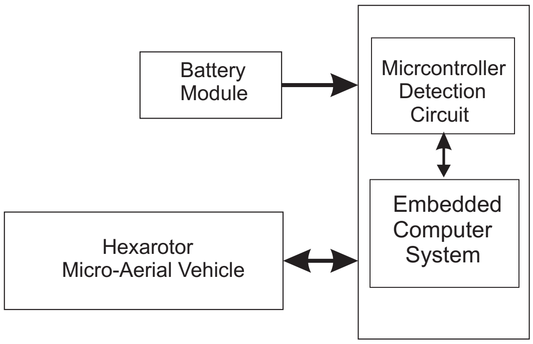


Figure 4. Detector block diagram.

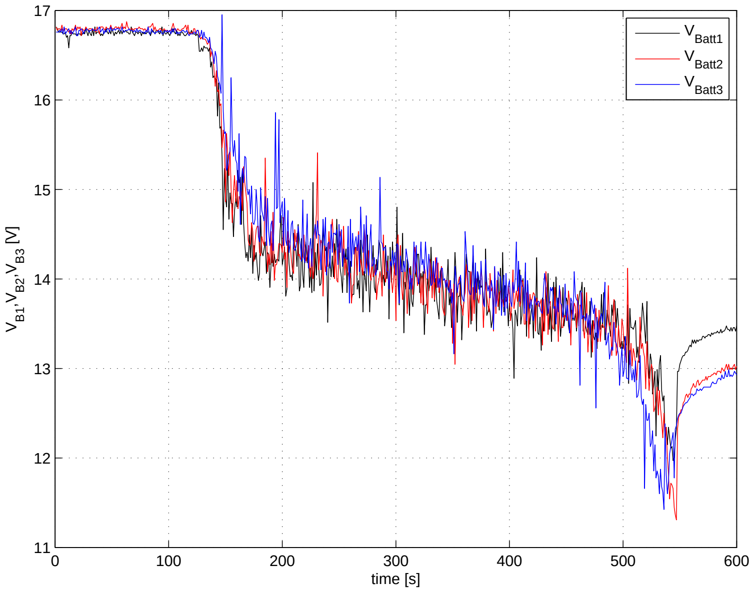


Figure 5. Battery endurance to the Hexarotor aerial vehicle: $m_T = 4.733$Kg;$t_E \approx$ 7min.

Maranhão and Alsina (2009) proposes a simple Master-Slave model as a **Hardware/Software** architecture for **UAV**s. The architecture follows the master-slave model and uses the Standard **USB** as communication interface. The main contribution is a C++ library, which makes possible communicate an embedded **PC** with several microcontrollers. Through this interface, it is possible to build an aerial vehicle using a standard Linux as operational system, and even though, attend to certain time deadlines.

Thus, through the Microchip's **USB** framework and the tools provided, we were be able to create a link that interfaces a computer software, running in a level over the interface class, and actuators and the sensors tools.

To control the speed of the brushless motors used in the hexarotor, for example, we must provide a Pulse-width modulation (**PWM**) signal with period 20ms were by default we have a pulse of 1ms. If we increase the bandwidth, we will obtain a bigger speed. 2ms of pulse is were we have the top speed, just like in servomotors for radio-controlled models. That signals are connected into the electronic speed controls (**ESC's**) which are responsible to drive motors, power interface, and determines the speed of the rotors. A graphical interface was developed with all the options necessary to control manually the take-off and the landing process to the hexarotor. This software generate a package containing the six integer values that corresponds with the motors speed. This is sending for the microcontroller over the **USB**.

Another firmware was developed to check over the analog digital converter **ADC** channel inputs of the microcontroller. The voltage of the three batteries that composes the embedded system is 14.8V, and the maximum voltage is 16.8V (figure 5). Because upon the channel **ADC**, the input voltage must be in the range between $0\text{V}\sim 5\text{V}$, the network is calculated as the following.

$$V_{sense} = V_{battery}\frac{R_1}{R_1 + R_2} \leq 5V \tag{11}$$

Resistances of voltage division are respectively $R_1 = 10\text{k}$, $R_2 = 25\text{k}$ to endurance test. In each second, the microcontroller collect the batteries voltage and send to the computer over the **USB** interface. A software that runs in parallel with

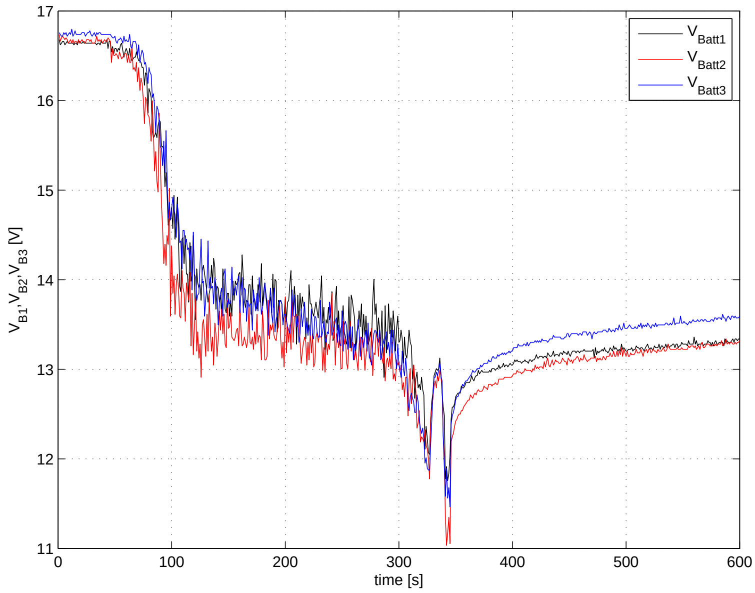


Figure 6. Battery endurance with $m_T = 5.433$kg and the endurance estimation is $t_E \approx 4$min.

the motor/rotor speed controls is responsible for archive this information in a text file that can be analyzed after the end of the experiment.

The goal of these experiments is to test the flight endurance estimation model with variations payload mass, payload power consumption and time spent attached to the ceiling. A first experiment, illustrate in figure 5, the platform was flown under manual control and stop watch was used to time the flight endurance. In this experiment was made to create some log files that include the voltage history of the batteries pack. We had change some parameters like the total weight, batteries charging time in the tests. The total weight to the hexarotor aerial vehicle without the extra payload is $m_T = 4733$Kg we had a lost in the time fly of $t_E \approx 7$min.

The graphics generated (figure 5), the values obtained on the tests shows that when we turn the six motors on and the hexarotor take-off (around $t = 100$s), the batteries voltage declines very fast and then stabilizes in a level that the declines become more soft (around $t = 150$s).

Again, another abrupt decline marks the moment that the vehicle has to initiate the landing process ($t = 550$s) because if it continue to fly, we can have some damage on the batteries that must remain with some voltage on their cells to prevent any kind of deteriorate.

In such a way, the acknowledge of the voltage decline behaviour of the batteries is very important to detect and prevent any power or mechanical anomalies that can appear on a hexarotor in fly routine. This detection can be made by an operator in the land or base station that can monitoring online, also an intelligent routine can be implemented on computer to analyze the voltage and performance on a mission.

The second experiment is illustrated in figure 6, where the time endurance $t_E \approx 4$min, when the total weight is increased in $m_T = 5433g$.

4. CONCLUSIONS

In this work, the project and design of an experimental hexarotor aerial vehicle was presented. The system integrates the evaluation of battery management that could provide more efficient control to evaluation of power system, and elevate accomplish rate of mission, moreover, to avoid lose caused by aerial vehicle collapse and resulted form error in current capacity control. Except for to avoid failure of flight mission, by calculation and accurate control of current, hexarotor can be provided with control with longer flight range, sufficient usage of battery and appropriate feedback of system operation status. Operator can be provided with more clear status and all kinds of information. The future works will develop a behavioral study of autonomous robust tracking control to the hexarotor, serving an aerial surveillance mission.

5. ACKNOWLEDGMENTS

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