A SELF-BALANCING QUADCOPTER DESIGN WITH AUTONOMOUS CONTROL

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ABSTRACT

The unmanned aerial vehicles became popular in most research works related to flight controls, control systems, aerodynamic designing and robotics, a quadcopter is considered as a modern application of the above listed fields of interests. This research presents the design of a quadcopter with the motor, propeller selections and balancing mechanical structure and the implementation of the control system. The control design of the quadcopter is decided to be different from the common design, giving two propeller power at a given single motion. The control system is powered by a *dsPIC* microcontroller, the onboard range detectors, gyroscopes and accelerometers provide the look ahead features, making it possible to achieve an autonomous control of the quadcopter.

Key words: Quadcopter, UAV, Complementary filter, Position control, Motor control, Motor drive

1. INTRODUCTION

An aerial vehicle (AV) is considered as a transport medium through the air which is made in different scale factors. The scale is determined according to the application it is used. The AVs which are manufactured in small scales also known as unmanned aerial vehicles (UAVs), often engage in applications such as military and law enforcement operations, aerial imagery and filming, first responders in unethical environments for search and rescue [3], and research platforms for various fields. Most of these applications require UAVs which are capable of hovering in the air, therefore mini scale airplanes do not fall under this category. Therefore multi-copters become more practical in this situation, a multi-copter become advantageous than a standard helicopter, when it is maneuvering the whole unit in the air, being easily controllable due to the available multiple degrees of freedom with multiple independent motors. There are several types of multi copters, *Tri-copters, Quadcopters, Hexa-Copters and Octa-copters.* A Quadcopter differs from the other types, being simple in aerodynamic design, a simplest symmetric design of the multi-copters, because the design of the other copters require several experiments and proven results of predicted structure symmetry for the optimum flight control.

The quadcopter is an aerial vehicle driven by four high speed propeller blades rotated by four high torque motors, [1] known as Brushless DC motors. The well balanced mechanical structure will be responsible for an easy balancing mechanism, and avoided failures due to minimized intensive mechanical vibrations. The most common quadcopter design keeps a single motor per one direction movement while leaving the two sided motors idling, thus reducing the response time in action. Instead of the common practice, in this project it was managed to keep two motors active, giving a high responsiveness per a single direction movement, at any moment required. Most UAVs are controlled by a remote controller by a pilot or a computer, on the ground. The others are controlled autonomously. The autonomous control is known as guiding a given object, to a target location or point while minimizing the deviation from the given path [2]. In this scenario, the quadcopter should be controlled keeping its balance according to the reference level momentarily. This autonomous control is done by the control unit onboard the UAV by estimating movements using the look ahead systems connected. The main sensor feedback system will provide the sufficient data input for this operation on the quadcopter [1]. Using the data input, the quadcopter can be controlled autonomously. The rest of the paper will give a background knowledge on the autonomous control of the quadcopter in section 2, and it will continue to section 3 where the design of the quadcopter is described. In last section, section 4 will be dedicated to the results of the parametric analysis.

2. BACKGROUND

The quacopter is controlled by changing the torques of the each motor independently, thus changing the vector of the applied force [1]. Therefore the quadcopter can be lifted, hovered and landed. Additionally pitch, roll and yaw are achieved with different combinations of the applied force vector [5]. Lifting, hovering, or lowering of the quadcopter is done by applying respectively a higher, equal or lower force than its self-weight. In this process the four rotating motors supply this force, So two motors, the right front motor (RF) and left rear motor (LR) are rotating clockwise as in Figure 1, while left front motor (LF) and right rear motor (RR) are rotating

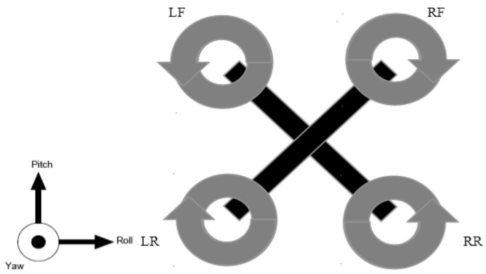


Figure 1: Motor rotation directions of the Quadcopter; Motors: left front (LF), right front (RF), left rear (LR), right rear (RR).

at counter- clockwise direction as in Figure 1, eliminating the torque created by the first two (RF and LR). The three different stages of the maneuvering of the quadcopter, namely *Take- off, Hover, Landing;* are obtained by changing the applied thrust force (F_{th}) with regard to the exerted weight force (F_w) of the quadcopter which is about 1 kg~ 9.8 N. The F_{th} is directly proportional to the rotating speeds of the motors. Therefore the applied F_{th} can be changed by the motor speed controlling. The following conditions listed in Table: 1, can be defined according to the considered force combinations, the state of the applied acceleration (a) can be found in the means of the reactive force (F_{th} - F_w) using the Newton's relation.

Table 1: Force and Acceleration conditions at three scenarios.

Scenarios	State of F_{th}	Acceleration (a),
Take off	F_{th}>9.8 N	$a = F_{th}$ - 9.8 m/s^2>0
Hovering	F_{th}=9.8 N	$a = F_{th}$ - 9.8m/s^2=0
Landing	F_{th}<9.8 N	$a = F_{th}$ - 9.8 m/s^2<0

The movements pitch, roll and yaw are obtained by increasing and decreasing the motor speeds partially. Pitch is used to move the quadcopter in forward or reverse directions [6]. The pitch forward is attained by rotating the motors, LR and RR in higher speeds than other two. The reverse pitch is obtained by the other way. The right roll is achieved by increasing motor speed on LF and LR while left rolled increasing the motor speeds of RF and RR than other two. The quadcopter is left yawed by increasing motor speeds of LR and RF and right yawed by the other way [6]. Taking these background data into consideration the various interconnected systems were introduced, simplify the design process, which will be discussed in the next section.

3. DESIGN AND IMPLEMENTATION

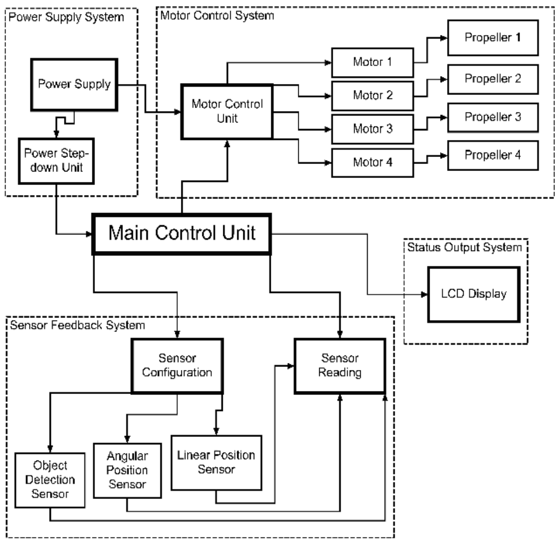


Figure 2: System Architecture

The design of the quadcopter was simplified using divided sub-systems, which are interconnected with each other and connected to the main controller unit, as in Figure 2. The power supply system will power for the main controller and the other systems, the sensor feedback system will provide inputs according to the configurations, the motor control system actuates the motors, the status output system, will provide information regarding the each change on the system itself. The key component for the thrust generated, is the best motor and propeller combination for the quadcopter. The brushless out-runner DC motors (BLDCs) were selected over the brushed motors due to the capability of giving out higher rpm consuming less power and it is more energy efficient. A BLDC operates on DC three phase power signals, therefore the special motor controllers known as electronic speed controllers (ESCs) are the key components of the motor control system. The selection of the required BLDC mostly depends on the thrust required for the whole unit of the quadcopter. The total unit weighs approximately 1kg, and the quadcopter consists of four motors which altogether provide the upward thrust required. Therefore each motor should lift minimum of the one fourth of the total weight, approximately 250g.With this considerations the available options of motors were limited to 840 rpm/V motors which were *2830/12 840KV by DYS Ltd.*, which provided lower rpm but higher thrust with larger propeller blades. To acquire the calculated thrust, 10 inch propellers were recommended by the motor specifications, and it further recommends, 20A current limiting ESCs, *SKY III 20A by Favourite Ltd.* were chosen. Taking the limiting currents as the burst discharges, the four motors may require about 80A current discharge, therefore a power source of Li-Po (Lithium-Polymer) battery was picked considering a continuous discharge rate of 80A per 10 minutes of interval, the power was selected as *X 2200mAh 3S 40C Li-Po by Vortex Ltd*. The key to a steady and controlled flight of the quadcopter revolves around stability, where the stability is achieved through a well-designed frame [4]. The frame plays a crucial role since it is the structure that holds all the components together and is dependent on a number of factors where the

Figure 3: One cantilever Arm of the Quadcopter, fixed at center, free end holds the motor

material selection and proper dimensioning is vital. Choosing the right material relies mostly on strength, weight, machinability and vibration resistivity. Aluminum was chosen as a better option due to its inherent strength, rigidity, light weight, easy machinability, and availability. This combination of the properties of Aluminum makes it a suitable material for an aerial vehicle. The quadcopter design involves a symmetric X configuration. Considering the dimensioning, the lengths of the two bars which forms the X was determined based on the propeller blade length and its cross section was determined through a stress calculation. The length of a propeller is about 28 cm; therefore the motor-to-motor length should be about 53cm, which was determined according to the Pythagorean. One arm of the quadcopter (from center to motor end) acts as a loaded cantilever beam, fixed at center as it is shown in Figure 3. With a static equilibrium calculation using the conditions of stability, along with the parameters defined in the Table 2, it was possible to define a relation of distance from O, *x* vs. bending moment, *M*. (01)

Table 2: Parameters in Stress Analysis

	Parameter	Value
	Diameter (m)	To be selected
	Length (m)	0.265
	Self-Weight (N)	1383.014 d^2
	Reactive Force exerted by Motor (N)	2.94
	Vertical Reaction at O (N)	W-F
	Horizontal Reaction at O (N)	0
	Bending Moment at O (Nm)	0.132W-0.265F

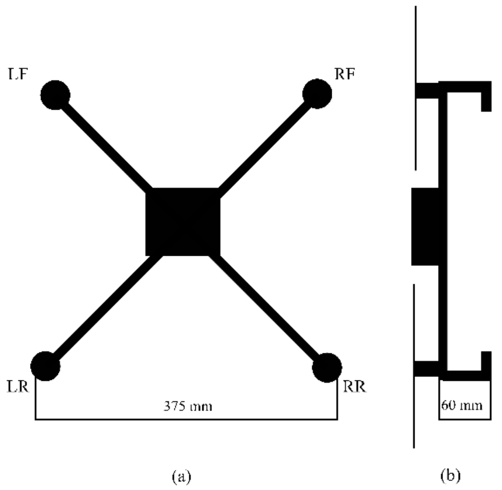


Figure 4: The rendered image of the Structure with dimensions. (a) Top View showing all four motors, (b) Right Side View, showing the motors in right side, RF and RR.

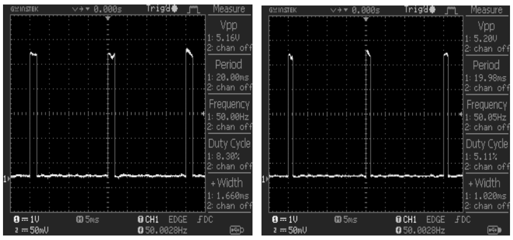
$$M = -Rx + M_o \quad \textbf{(01)}$$

The above relation (01) gave the maximum bending moment to be at O, using this value with Jourawski's Formula a shear stress of 13.6 MPa was determined, which was in the mid-way in elastic range of stress- strain curve of Aluminum, by using 0.5" x 0.5" hollow square, cross section of aluminum. Therefore the final structure was decided to make from 0.5" Aluminum square bars. The final structure along with the dimensions of 530 mm motor-to-motor length was rendered using a CAD package as in Figure 4. The top view is illustrated in Figure 4 (a) where the width is 375 mm; the Figure 4 (b) is the front view, which denotes the height of the landing gear, 60 mm. The electronic control components, sensor systems and the power source are mounted on the base plate, which is centered on the body on top view. Design of the base plate require considerations on minimizing the vibrations and insulating the electronics from the body structure, while keeping the balance.

The quick responsiveness of the sensor feedback system and the glitch less command output on the motor actuator system governs the stable control [5]. The main control unit is selected, as it should be capable of sensor communication, individual motor control with separate speed control with pulse width modulation (PWM), and data input and output (I/O) ports. As the microprocessor, a 16-bit digital signal processor with advanced RISC architecture, *dsPIC30F4011* chip from Microchip Ltd. was selected. The power source of the quadcopter is much higher, thus the voltage supply for *dsPIC30F4011* is step-down to be 5V using 7805T IC. Considering these requirements, the main control board is created, making I/O pins accessible using male headers. The ESCs should be placed on the structure, as the heat generated on them is spread away rapidly. Since the motors drain a much higher current, it is vital for a battery-meter is implemented using the *ADC* channels on the *dsPIC30F4011*. The control of the *BLDCs*, using *SKY III* is done with the output compare pins available on the *dsPIC30F4011*. The angular position sensor (*Gyroscope sensor*) and the linear position sensor (*Accelerometer sensor*) come together in one sensor module, *MPU-6050* by Invensense. The communication between the *MPU-6050* and the *dsPIC30F4011*, is made using I^2C protocol. The direct values from the accelerometer and the gyroscope were not very accurate with the actual measurements, the accelerometer values are interrupted by the motor thrusts, making it unstable over short time periods and gyroscope values never returns to zero, when the actual position is at the zero level.

Therefore the *Complementary Filter* is used for this purpose [5]. This filter can be presented as (02), with the parameters listed in Table 3. The pitch and roll angles are calculated using individual filters for each axis.

$$\propto = k_G(\propto + G.dt) + k_A.A \qquad (02)$$



(a) (b)

Figure 5: Change of Pulse Stream applied when configuring the ESC, (a) Maximum Speed, (b) Minimum Speed

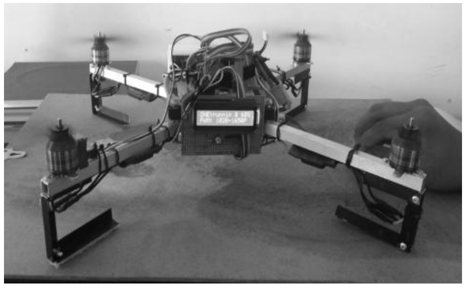


Figure 6: Getting Ready for Take-Off

Table 3: Parameters in Complementary filter (02)

	Parameter	**Value**
$\propto$	Angle (□)	-
k_G	Gyroscope Constant	0.97
k_A	Accelerometer Constant	0.03
G	Gyroscope Data	-
A	Accelerometer Data	-
dt	Time Step (ms)	0.01

The design steps and predictions, taken in this section will be proved true in the next section using parametric analysis.

4. PARAMETER ANALYSIS AND EXPECTED RESULTS

To control the motors using the ESC, *SKY III*, it is configured by storing the speed limits, using the required pulse stream as in Figure 5. The pulse stream output was measured using a digital oscilloscope to make sure the expected values are obtained as shown is Figure 6. After assembling the unit, the thrust force at the full throttle was measured using a digital balance, and it was 1.667th of the self- weight, thus retaining more than 50% of reactive force (F). Figure 6 shows the finished product getting ready for take-off.

5. REFERENCES

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