DESIGN AND DEVELOPMENT OF AN AUTONOMOUS QUAD-COPTER

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ABSTRACT

Quad-copters are used for military activities, transportation of light to mid weighed goods and aerial photography. This paper presents about a new concept in controlling the quad-copter with reducing the oscillations of the quad-copter while hovering and movements. This monitors speed of all four rotors individually and manages accurately as required and the mechanical structure gives more stability to the quad-copter while making propellers safer. It is an ideal solution for food delivery and light weight items delivery systems. It can be fully automated using GPS assisted navigation, and GSM data feed.

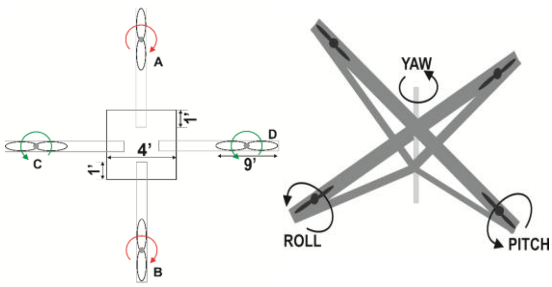
***Key words*: **Quad copter, Multi copter, Arial Vehicle, Speed control. Position control

1. INTRODUCTION

In the developed world the military attacks will be unmanned, the transportation will be on the hands of robots, the robots will reach the places where it is high risky for the humans to reach. The next question what kind of robot will be able to fulfill those tasks, its more advantageous if the relevant task can be done more efficiently, with less power consumption and less time consumption.

An aerial vehicle with the support of four rotors has many advantages than other ways of transportation. A quad-copter uses four rotors with propellers connected to it, propellers pushes the air down and creates thrust to bring lift to the quad-copter. A quad-copter weights less than 1kg and it is small in size, the thrust needed for it to hover is less, so less power consumption. Quad-copter has less limitations, even more it has power to lift objects.

The quad-rotors movements are manipulated by changing the speeds of four rotors individually so there should be four independent motor speed controller units centralized to a main control unit. The load acting on each motor is not the same and is not constant. All the four rotors consume a high current so the battery drains fast, fixing a high capacity battery increases weigh, to increase the quad-copters flight time the quad-copter should hover at a lower power consumption that means the thrust needed to hover the quad-copter should be reached at about 1/3 of total rotor speed.



(a) (b)

Figure 1: (a) Rotational Directions at hovering state (b) Control Parameters to maintain stability

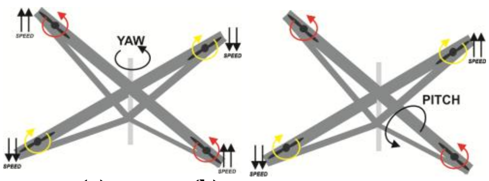
In order to maintain a quad-copter in hovering position it should maintain equal speeds in all four motors and two motors rotate clockwise while the other two rotates anti-clockwise as illustrated in Figure 1. Quad-copters are equipped with position and orientation sensing devices such as accelerometer and gyroscope. With those devices system detects quad-copters orientation error and corrects it with a controller algorithm. In the proposed design of the quad-copter, initially error percentage is reduced by maintaining required speed in each rotor accurately by continuously monitoring speed. There are four sensors connected to the main controller unit, that senses the motor speed and PID algorithms keeps the motor running in the desired speed. Accelerometer Gyroscope combination is also included to the system for further maneuvering of the quad copter. The mechanical was designed to help its manipulation over error correction. Most quad-copters tend to damage its propellers when landing and the propeller protecting mechanisms add more weight. The core structure is developed using L shaped aluminum bars to minimize weight

2. BACKGROUND

The quad-copter should be capable of moving forward, backward, left and right. For taking those movements there are three parameters which should be adjusted precisely. The position or orientation of the quad-copter is determined by YAW, PITCH and ROLL. Those three parameters are maintained by adjusting the speeds of four motors. Each motor produces thrust and torque about its axis of rotation. That torque also should be taken into account when changing any of those parameters.

Setting the YAW to zero makes the quad-rotor steady about its own axis and setting a YAW value positive or negative give a clockwise or a anti-clockwise rotation. The YAW is measured in by the gyroscope connected to the main controller unit. YAW depends on aerodynamic torque in all four motors leading to the direction of rotation. YAW is adjusted by changing speed of the rotors which rotates in one direction; the speed gain in these should be deducted from other pair of motors to maintain a constant total trust, which ensures the quad-rotor stays in same altitude while changing its YAW.

The quad copter makes its forward motion by tilting forward; the forward tilt is the PITCH value measured by the accelerometer. When the quad copter tilts forward, a component of the motor thrust makes the quad-copter move forward. The same theory applies for the reverse motion. A quad rotor adjusts its PITCH and ROLL by applying more thrust to one rotor and less thrust to its diametrically opposite rotor. The left and right motion is initiated by adjusting ROLL values. With ROLL value, which means quad copter is inclined to left or right in certain degrees, the quad-copter starts motion to the relevant direction making left or right movement according to the ROLL measurement. The ROLL is also measured through the accelerometer in degrees.



(a) (b)

Figure 2: (a) YAW control (b) PITCH Control

3. DESIGN

Table 1.0 : Quad-copter weight

Component	**Weight**
Motors X 4 (19g each)	76 g
ESC X 4 (13g each)	52 g
Structure	300 g
Controller board	50 g
Battery	200 g
Total	**678 g**

Table 1.1 : Thrust Calculations

Thrust by each Rotor	700 g
Total Thrust	**2800 g**
Weight/Thrust	**24.21429 %**

Table 1.2 : Power Calculations

Power required for hovering	**Current**
Peak power	40 A
Percentage for hovering	10 A

An estimate of weight was used in selecting motors, the estimated weight lied between 600~700 grams. The quad-copter should be able to hover at about 30% of its full throttle for a stable flight and the current consumption of the motors should lie within 10~15A so it is having a good flight time. The above tables show the actual figures of weight and thrust after selecting components. When motors are at its highest speed, the current consumption is at its max 10A. According to calculations the quad-copter hovers around 24% of its full thrust, and the complete system consumes about 10A in hovering.

$$\mathbf{H(t) = C \div (Cr \times 60)} \quad \textbf{(1)}$$

Table 1.3 :Flight time

Motor load (Cr)	10 A
Battery Capacity (C)	2.5 Ah
Flight Time(mininutes) H(t)	**15**

H(t) is the Hovering time, C is the battery capacity and Cr is the consumption rate. According to equation Eg.1.0 the quad-copter is able to hover for about 15mininutes. In the calculations the current consumed for control systems are not separately added as the power for all four sensors and main controller is supplied by the ESCs.

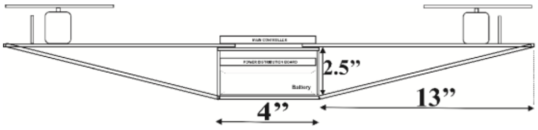


Figure 3.0 : Main Structure

The quad copter main frame is designed to provide protection for motors and propellers by using a special shape for arms. Four motors are fitted to the main frame through a mechanism which reduces transmission of vibration from motors to main frame. The controller unit is fixed at the centre and four sensors to detect speed are coupled with motors. The battery is fixed in the bottom centre.

The propellers and motors are well secured from any impact as the four arms used to mount motors extend towards the end of the propellers. The quad rotor can land at any angle without damaging its propellers. The components in the quad are stacked, battery at the bottom so its centre of gravity is more concentrated toward the bottom center. Its most stable equilibrium state is upright position, so there much less risk in falling it upside down, if its control is lost. Its position of center of gravity gives it a more stable hovering and landing creating pendulum effect on the quad in case of loss of control and while motor speed corrections.

Motor to motor distance has been added to the quad rotor making it more precious in forward and backward motions as well as motor speed controlling. The material used for building the main frame is ultra light Aluminum. Typical box bar used to build quad rotors are replaced by L shaped bars, to reduce its weight by 60%. **L** shape of the aluminum strips gives more rigidity to withstand vibrations.

For each arm of the quad rotor a separate bar has been bent and mounted to the centre at two points having a gap of 2.5 inch, adding more structural rigidity. All the speed sensors and internal circuits are made of SMD components making less space consumption for components and circuits. The system includes a removable LCD display which displays individual motor speeds, battery voltage and PID parameters for easy trouble shooting.

4. IMPLEMENTATION

The Control program is divided into few sections as;

1) Motor driving with PWM
2) Timer/Counter for speed calculation
3) ADC input for GYRO
4) I2C configuring for Compass
5) PID control for motor speed management
6) Hovering the quad with specific thrust

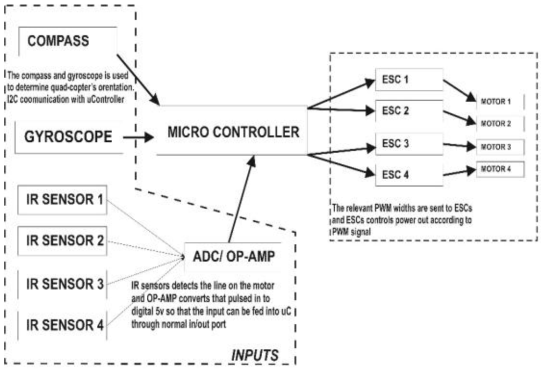


Figure 4.0 : System Architecture

ESC s used for motor driving requires 50Hz PWM, and Motor speed sensor requires a **minimum** timer frequency of **20 MHz with a 8 bit pre-scalars or 5Mhz with a 16 bit pre-scalars.**A PWM with 50Hz frequency has a total length of **20ms.**The Pulse widths relevant to minimum and maximum speeds of motor are 1ms and 2 ms.If the PWM modules is a 8 bit PWM module, the PWM duty range is **0 to 255.**Within that range **1ms to 2ms** lies between **13 and 25** (12.75 to 25.5).That means motor control is limited to a resolution of 12 which reduces accuracy of motor speeds. Therefore to control the speed accurately, it need 16 bit PWM modules. Further microcontroller has to keep counting for four sensors, and most micro controllers only have 4 timer counters, two of them should be used on PWM outputs and only two are left for speed counting. The micro controller has to switch between function and interrupts rapidly. So the system requires high instruction cycles per second rate to switch between tasks efficiently and to complete its functions fast without making any effect on quad copter's performance. As per the requirements a micro controller ATMEGA 128A is selected with

- 4 timer counters
- 4 16 bit PWM outputs
- Dual operating frequency or 16 bit pre scaling
- High instruction cycles per second rate

Table 2.0 The possible TOP values and the relevant PWM resolution.

Clock Speed	**1000000 Hz**	**5000000 Hz**
Output Freq.	50 Hz	50 Hz
Max. width	2.2 ms	2.2 ms
Min. width	1 ms	1 ms
TOP value	10000	50000
Value of maximum Pulse width	8900	44500
Value of minimum Pulse width	9500	47500
Resolution	**600**	**3000**

A maximum resolution of 3000 is attained with 5 MHz clock speed. So the 5 MHz external clock source is used. Four IR sensors are used for detecting rotation of the motors. A black line marked on the surface of the motor triggers the IR sensor output and it is detected by the micro controller. An 8 bit timer is initiated and is set to zero when the sensor detects the black and the timer value is copied in the next detection of the black line within the same execution cycle. For each instruction cycle the system counts the time for one rotation of the motor and speed is calculated with that data.Micro controller supports 16bit pre scaling, giving variety of speed resolutions and clock speed of the micro controller applies a limit on the maximum and minimum speeds that can be measured. Following tables shows the maximum and minimum time periods that can be measured according to selected pre scales, and required times of measurements assuming maximum and minimum rotation speeds.

Table 2.1: Micro controller clock frequancy

CPU clock	5000000	Hz
one tick	0.0000002	s
	0.0002	ms

Table 2.2: Maximum and minimum period per pre-scalar

If prescalar	MIN time(ms)	MAX time (ms)
256	0.0512	14
128	0.0256	8

For optimum accuracy the pre-scalar value is 1024 which make the timer increases by 0.204ms. 256 is also a good pre-scalar in terms of sensitivity but being too sensitive with milliseconds can lead to unwanted fluctuations of readings. A change in the period of 0.2 ms does a change 461 in RPM at the max and 81 RPM at the minimum speed. Speed calculating module uses an 8 bit timer. The microcontroller starts counting up with the detection of the black line marked on the motor surface, and takes its reading in the next detection of the black line. The reading indicates the time taken for one rotation of the motor in milliseconds. With that reading the RPM is calculated using the following equation. The reading from the timer registry should be multiplied with a factor of 0.2 according to pre-scalar.

ω is the rotational speed in RPM and T is the time for one revolution.

$$\omega = (1/T) \times 60000 \quad (2)$$

The most important part of this product is the motor speed controlling, which reduces the oscillating effect in quad-copters. The target is to make the motor run in exact speeds, accurately while the factors around changes. As discussed earlier the changing load on motors make the motor speeds unstable. So an algorithm has to be implemented in a way it could manage a target speed itself. In this section the quad-copters program can be separated in to two parts, one part of the program does it calculation regarding orientation and required speeds of motors and the other keeps handling motor speeds. The speed of the motor is calculated through sensors and it is already in the system, and now the system has a target speed and we are dealing with the difference between the target speed and the current speed which can be called as the speed error. For the system to succeed the speed error should be minimized as possible. Again what is in the system is a target speed and the current speed. For the system to start its job, the motors had to be turned on at its minimum speed. At the start the speed error is high and its getting low when the motors rev up. Proportional and integral method brings the relationship between the PWM duty values and the error.

Following equation show how the Integral error (Ie) is calculated.

$$Ie = Ie + (Ki \times Se) \quad (3)$$

Ki is the Integral error constant and Se is the Speed error. The above equation shows that the system keeps the summing up every cycle. At the start the speed error is higher and it is multiplied by a factor and added to the Integral error. The multiplying factor Ki is determined by trial and error. The Ki factor is actually the multiplying factor which relates the PWM duty value and the error. At its first run the PWM out should be given at least to reach the target speed roughly, and then the speed error is less which further accumulations of error are done for gradually reducing the speed gap.

Pe = Kp x speed error **(4)**

Kp is the proportional error constant and Pe is the proportional error. The above equation shows how the proportional error is calculated, it is just the speed error multiplied by a certain factor. Proportional error correction helps the motor reach its target speed fast when the speed error is high. As the motor gets close to its target speed, the proportional error gets close to zero while the Integral error does further correction.

The final pulse width is gained by adding the both Integral error and proportional error.

Pulse Width = Ie + Pe **(5)**

Finally regardless of the errors the pulse with input for PWM module should lie between 2500 and 5500 so , the pulse with is again filtered in a way which makes all the values higher than 5500 equal to 5500 and all the values lower than 2500 equal to 2500.

5. CONCLUSION

Maximum efforts were taken to reduce speed fluctuations and controlling errors, while keeping power consumption at a low level. The PI algorithm for speed controlling was very successful under changing thrust conditions. The accelerometer and gyroscope was not much stable as its measures fluctuate due to vibration. A kind of special vibration reduction is a must to make the quad-rotor run smooth. Vibration absorbing motor mounts can be used to reduce vibration. Structure wise the lowered centre of gravity made the quad well balanced.

6. REFERENCES

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