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Performance Analysis of Medium Altitude Low-Cost Autonomous Quadcopter

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Abstract. In modern engineering, the rapid growth in the development of unmanned aerial vehicles which deserves the major space in the area of intelligence and surveillance operations. Unlike the conventional aircraft, the number of rotors mounted in an autonomous body that determines the propulsive efficiency as well as the maneuvering capabilities of unmanned aerial vehicles. The main objective of this research reveals that the low cost and an autonomous aerial vehicle with four rotors configuration design to achieve the long endurance flight limit. The developed Quadcopter flying model integrated with Arduino autopilot module which effectively controls the various maneuvering actions during the flight. This paper also reveals the entire hardware structure of the designed Quadcopter and its flight dynamic response characteristics. The remotely operated Quadcopter model was subjected to the flight test and the performance parameters have recorded. The flight test was conducted in an open environment in which stability parameters has been observed during onboard. Pitch angle, the Rotational speed of four rotors and the various attitudes of Quadcopter were changed accordingly to maintain the steady level flight. Findings are plotted with respect to the flight endurance. **Keywords: -** Quadcopter, Maneuvering, Attitude, Flight test

1. Introduction

The special abbreviation of "DRONE" that is expressed as Dynamic Remotely Operated Navigation Equipment and which are trending the aviation market in recent times. Many aerial vehicles are booming in the aviation sector with various configurations. In general, the aviation hunters will always stick with the reliability, cost-effectiveness and the performance of Drones. In a Quadcopter Drone, the directed upwards rotors are constructed with square shaped frames with equally in the distance which are a reference to the center of mass of the body.(1) In general, the angular velocities acting in the rotors are mainly used to control the trajectory of the Quadcopter model.(2) As like conventional unmanned Aerial Vehicles, Quadcopter can perform search and rescue, inspections, traffic monitoring, aerial photography, terrain monitoring and several other applications. Recent days Quadcopter has gained more responses from military sectors and research scholars.(3) In the modern aerial vehicle industry, most of the rotor based autonomous vehicles are implemented with Integrated Modular Avionics package and Global Positioning System for the effective control of its flight profile in a 3-Dimensional region. In this research paper, a genuine practical approach is proposed to build and design of a prototype Quadcopter which is low cost and minimum power consuming avionics bay for the efficient endurance.

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1.1 Structure of Quadcopter

The Quadcopter structure is assumed as rigid body configuration with rotors on each frame which produce angular velocities with respect to its clockwise and anticlockwise rotational effects.(4) The angular positions which determine the attitude of Quadcopter in an inertial reference frame. Pitch angle is always expressing the rotation of Quadcopter structure with respect to Y-axis. Rotational moment around the X-axis is explicated with Roll angle and the moment about Z-axis stated based on Yaw angle. (5) In general, Quadcopter has six degrees of freedom as three rotational and three translational motions which are developed from four independent rotors. The coupling effect of translational as well as rotational motion will provide the betterment in achieving six degrees of freedom during the flight test.

2. QUADCOPTER HARDWARE MODULE

The Quadcopter hardware model integration process was performed at the Flight-Sim Lab, at Bannari Amman Institute of Technology, Erode. The overall Quadcopter structure was built around the gross weight of 0.9 kg which can carry the payload capacity of 0.15gram. The designed model aims to operate at the maximum voltage of 12v and that can be sufficient for all four motors which were mounted on the Quad frame. Low cost and lightweight hardware have been utilized to achieve better thrust to weight ratio. (6) The entire Quadcopter structure was designed in consideration with reliability as well as low power consumption criterion to maintain the maximum endurance limit. The total cost of this Quadcopter was estimated at around $246. The total breakdown of the hardware components integrated with Quadcopter is mentioned in the Table. (1)

Table 1. Quadcopter components and Cost Estimation

S.No	Name of the Hardware Components	Price ($)
1	Rotobotix Frame F450 Integrated PCB version	11.16
2	Propeller pairs named REES52 1405	3.66
3	Electronic Speed Controller M30-A	8.66
4	Lithium-Polymer 3000 mAh (milliamp-hour), 12volt	33.86
5	Ardupilot 2.8 mega flight controller	45.28
6	GPS Telemetry	43.86
7	BLDC: 4xMotors(1400volt)/Accessories	38.01
8	Six channel: Transmitter plus Receiver	49.71
9	4xServo MotorSG90	8.77
10	3-Axis: Accelerometer and Gyroscope Module	2.68

2.1 Speed controller and the motor configuration

The small, low cost, four lightweight Brushless Direct Current motors are arranged in the “X” shaped Quadcopter frame. (7)The multicolored identified motor consists of fourteen motor windings with 13 stator arms which can be operated at 1400 Kv. (8)The lower kilovolt DC motors provide very high torque value even at lower rotational speed to push the propeller blades towards maximum thrust. The all four motors together were able to produce 1.5 kg of thrust to lift and create momentum about the Quadcopter model. The four motors are driving the fixed pitch propeller via the Electronic Speed Controller connected with Microcontroller unit. The reinforced carbon-fiber based propeller pairs named REES52 1405 were used to produce maximum rotational speed during the operation. The Electronic Speed Controller M30-A operated at the frequency 50 Hz was integrated and that will transfer the sufficient amount of electric energy to enable all the electronic components mounted in the Quadcopter structure.

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2.2 Energy storage device

The operating level of remotely operated unmanned aerial vehicles is purely depending on the energy storage device. If the efficiency of the battery is not capable of storing and discharging the sufficient power, then the endurance level of an unmanned aerial vehicle will be unsatisfactory. This research paper reveals about the performance of 3 cell-series Lithium-Polymer 3000 mAh (milliamp-hour), 12v with the instantaneous discharge of 55A battery source was implemented in the Quadcopter Model. The major advantages of using Li-Po batteries are always lighter, smaller and lifelong as well as the maximum charging capacity when compared with Ni-Ca, Ni-MH, and Lead acid batteries. The designed Quadcopter model carries the Li-Po based battery with 184 gram of weight.(9)

2.3 Panel of Quadcopter Avionics

Heart of this Quadcopter structure was strongly built enough to control the trajectory with the help of reliable avionics panel. The Integrated Modular Unit consists of Ardupilot 2.8 mega flight controller with Global positioning system (GPS) tracker, 3-axis ADXL-345 series accelerometers, 3- Axis L3G4200D Gyroscopes with 16-bit resolution, receiver, and transmitter. The new version of Ardupilot APM 2.8 is capable of performing autopilot mode of operation in which altitude and coordinated can be controlled. The APM 2.8 mega microcontroller is one of the reliable open source autopilot system adopted with the latest sensor technology. (10)This GPS has an accuracy of 5 meters in position measurement which uses 45 milliamps at 6.5 volts and that is enabled with a Wide Area Augmentation System. The Radio Frequency enabled six channel receivers (433 MHz operating frequency) were integrated into flight control avionics unit.

When the input signal is transmitted from the ground controlled transmitter unit, the receiver reads the signal and sends it to the microcontroller. In this six-channel operation, the first four channels are uses as roll, pitch, and yaw and throttle control. The fifth channel is used to trigger the switch control to initiate the programming sequences of Quadcopter flight. The sixth channel is used for safe control of the ground handling process and finally, that will turn-off the closed loop operation.

Figure. 1. Assembled Low-Cost Quadcopter

2.4 Processing with Arduino Microcontroller

Arduino 2.8 mega microcontroller is basically inexpensive and powerful in nature also simple to perform programming sequences and provides tremendous benefits as compared to other Microcontrollers. (11)Arduino 2.8 mega operates at 16 MHz clock speed and input/output pins that can be used to integrate Electronic Speed Controller, Input Receiver, Global Positioning System, Storage Device Port, slots for connecting personal computer and other peripherals. The input receiver’s signals are mapped with Electronic speed controller output.

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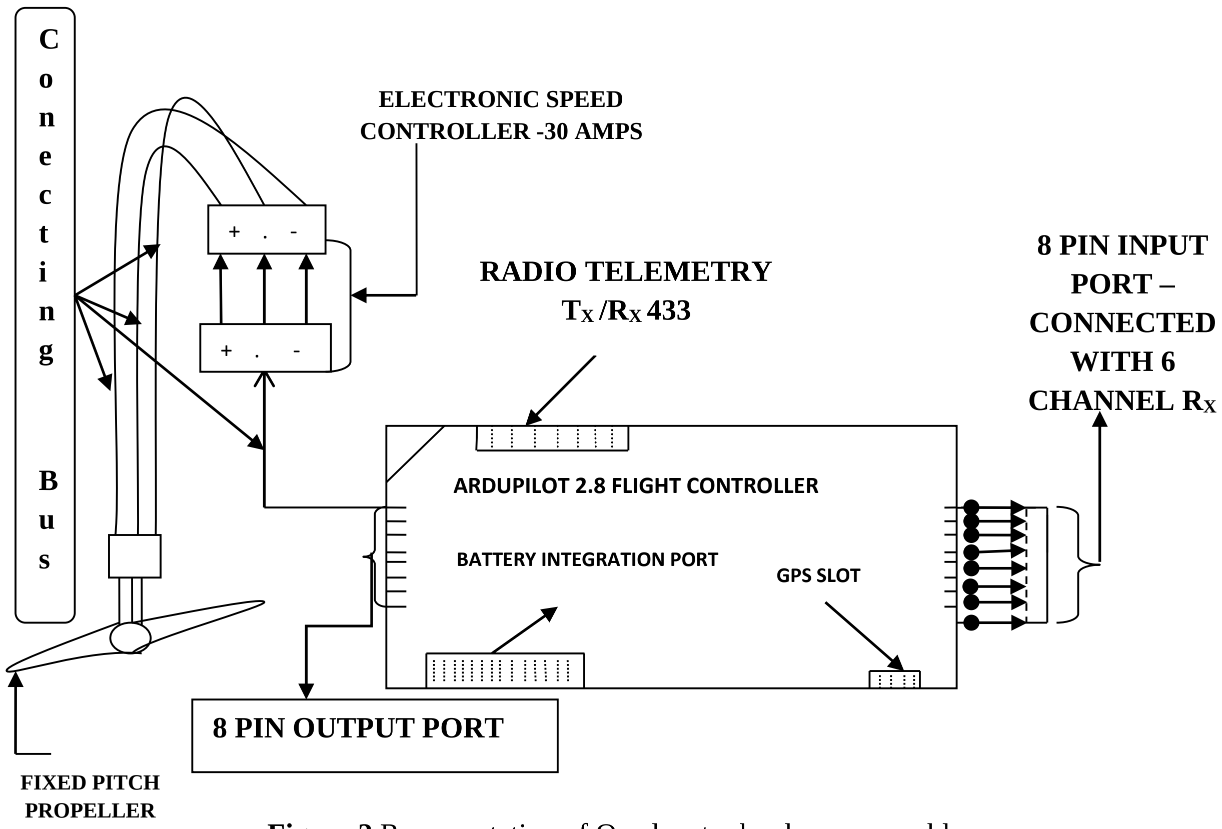

Figure.2.Representation of Quadcopter hardware assembly

Therefore the special output signals are sent from the Arduino board to Electronic Speed Controller which controls the motor speed. Measured data from Global Position System or Photography/Video or attitude information from gyroscope were stored in the Microstorage device mounted in the Arduino 2.8 autopilot module.

3. Dynamics of Quadcopter – "X" Shaped configuration

The four rotors mounted on the Cross symbol ("X") shaped Quadcopter produces angular velocity due to the rotational effect of propellers. (12)According to the Law of Physics, if two propellers are spinning clockwise direction, then the other two adjacent propellers will be spinning in a counterclockwise direction. With this phenomenon, the torque produced on the four rotors can be balanced when all propellers rotate at the same rate. The torque produced in electric motors can be expressed as

$$\tau = K_t(I_i - I_o) \tag{1}$$

Where τ is the motor Torque, I_i - is the input current supplied to all the motors, I_o - is the supplied current when no load on the motors and K_t is the proportional torque constant.

Considering voltage drop V across each motor, Motor resistance R_m, V_∞ is the angular velocity of the motor and also K_v is the proportional constant of electromagnetic force due to the propeller rotational speed.

Power produced from the motor can be represented as

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$$P = IV = \frac{(\tau + K_t I_o) K_v \omega}{K_t} \tag{2}$$

Further simplifying the Quadcopter rotor dynamics model and assuming that $K_t I_o$ is very much less than Torque produced on the motors. The power produced from the model can be defined as

$$P \approx \frac{\tau K_v \omega}{K_t} \tag{3}$$

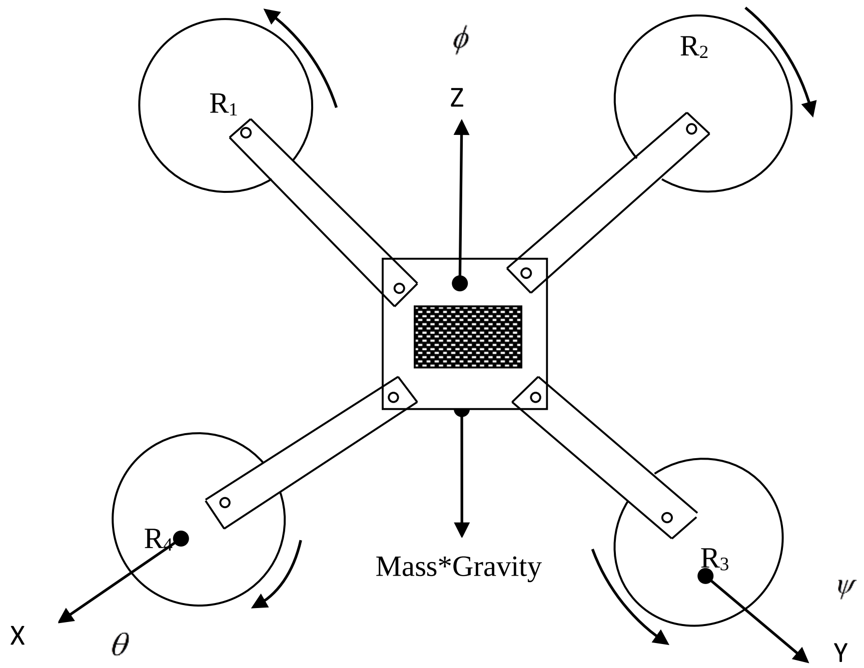

Figure.3. Outline of “X” type Quad-Model

When the Quadcopter model is assumed to be operated at low speed and maintaining constant thrust as well as floating same attitude, this maneuvering is said to “Hovering”. Most of the Quadcopter models are flown at such attitude to obtain the exact aerial photography or terrain monitoring applications in real-time applications.

Considering the free stream velocity V_∞ is zero (air surrounding the Quadcopter is zero), the expression of hovering velocity V_h of designed Quadcopter can be determined.

According to the Momentum theory, the equation of hovering velocity of a Quadcopter model is framed as

$$V_h = \sqrt{\frac{T}{2\rho A}} \tag{4}$$

ρ is the density of the surrounding air and A is the area swept out by the rotor.

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Relating the hovering velocity which influences the power required to maintain a steady attitude and that can be represented as

$$\mathrm{P} \equiv \frac{\tau K_v \omega}{K_t} = \frac{T^{\frac{3}{2}}}{\sqrt{2\rho A}} \tag{5}$$

In general, Torque is a kind of twisting force that used to rotate the propeller and also provides thrust to move the Quadcopter to and fro. Here each rotor creates some amount of torque about the directional axis and that leads to contribute sufficient angular acceleration as well as the phenomenon to overcome frictional drag forces around the Quadcopter model. As per principle of aerodynamics, the frictional drag force component can be written as

$$\mathrm{D} = \frac{1}{2} S v^2 C_d \rho \tag{6}$$

Here D is the Drag force, S is the reference area (Cross-section of Propeller), C_d is the coefficient of Drag. The effect of frictional drag force which creates some amount of opposite torque on the Quadcopter inertial frame during the flight. Due to this frictional drag, the undesirable torque on the Quadcopter model can be indicated as

$$T_D = R\frac{1}{2} S v^2 C_d \rho = R\frac{1}{2} S (R\omega)^2 C_d \rho \tag{7}$$

Where R is the Propeller Radius, from the above equation, it was observed that the torque due to drag component is always proportional to the square of angular velocity.

$$\boldsymbol{T_D \alpha \omega^2}$$

Considering the all four rotors in the Quadcopter model, the total torque on the directional axis (Z-axis) has expressed with respect to the rotational directions of propeller blades. Total torque is the summation of all the torques from the propeller

$$\mathrm{T}_{\text{total}} = c(\omega_1^{\,2} - \omega_2^{\,2} + \omega_3^{\,2} - \omega_4^{\,2}) \tag{8}$$

Where c is the aerodynamic coefficient. If the propeller is spinning in a clockwise direction, it considered as positive and the counterclockwise rotation of propeller is represented as negative. In this research paper, the designed Quadcopter model which consists of two equally distributed uniform rods crossed at the center point of the structure arranged diagonally with four motors. According to the equation of motion, the acceleration of the Quadcopter is mainly due to the thrust, gravity and linear frictional effects.(13)

By considering the position of Quadcopter is "o", g is the acceleration due to gravity, Drag force D, Thrust Component T_c, Then the linear motion is represented in the following form

$$p\dot{a} = D + RT_c + \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} \tag{9}$$

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Therefore the rotational equation of motion of the designed rigid Quadcopter model can be represented from the Euler`s equations of for rigid body dynamics with respect to the X, Y and Z axis.

$$\omega_r = \begin{bmatrix} \tau_\alpha I_{xx}^{-1} \\ \tau_\beta I_{yy}^{-1} \\ \tau_y I_{zz}^{-1} \end{bmatrix} \tag{10}$$

Here ω_r is the rotational motion expresses with respect to maneuvering, α is the roll torque, β is the pitch torque and γ is the yaw torque.

3.1 Quadcopter flight test at open environment

The Quadcopter flight test was conducted in the open environment around the radius of 200 meters. From the flight test, it was observed that the designed Quadcopter was able to carry 0.15gram of weight and continuously flown up-to 30 minutes of endurance. During the flight test, the major manoeuvring parameters such as pitch angle, roll angle, and yaw angle were changed as well as controlled with respect to the trajectory. Also observed the power consumptions of each component to accelerate the Quadcopter in a 3-Dimensional frame.

Figure. 4. Quadcopter Flight Test conducted at Bannari Amman High Ground

The power requirement at every of each stage of flight test and throttle was adjusted from the zero to maximum to pull the Quadcopter with the payload. The discharging level of the attached Li-Po battery was observed in connection with the endurance limit.

4. Result and Discussions

Observation from the flight data, it clearly shows that the influences of vibration on the Quadcopter which severely affects the stability. When the initial throttle was activated from the ground-based transmitter controller, there itself the motors start working and by the way, the four propellers were

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spinning to produce power. Due to this, vibrations were acting on the frame and that will cause a little flutter effect during the flight. Though manned aircraft/Rotor-based fixed-wing unmanned aerial vehicles were able to control during the gliding operation, but form the flight test, it was clearly monitored that the Rotary wing Quadcopter were difficult to control when there is a discontinuity in transmitting power and operating signals.

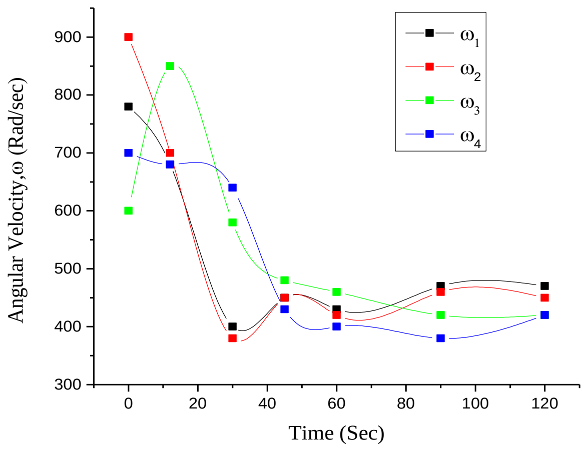

Figure. 5. Quadcopter angular velocities with respect to the reference trajectory

The variation in Roll angle, Pitch angle, and Yaw angle has been observed during the maneuvering process and the dynamic response of the designed Quadcopter model was explicated based on the angular displacement/angular velocity.

Pitch angle θ is initially increased to maximum and maintained around 1.9 degrees (with little oscillation) to achieve the steady level condition during the flight test. Pitch angles have recorded when increasing/decreasing the front and back rotor blades rotation, Roll angles were observed by changing the rotation of left and right rotors and also yaw angles have observed with changing the rotation rate of the counterclockwise set of rotors.

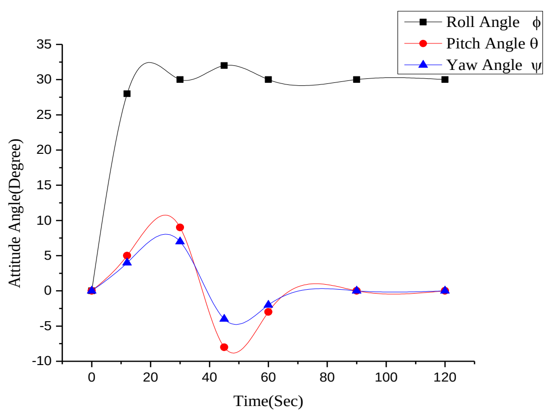

Figure. 6. Measured attitude values from the Quadcopter following a maneuver

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The attitudes values are measured from the onboard 3-axis accelerometers during the flight test. After a few seconds of flight, Quadcopter settled with a balanced attitude and that has been clearly executed in the above graphical presentation.

The mentioned graphical representation in Fig.7.denotes the variations of time versus motors RPM (Rotation per Minute) leads to produce sufficient thrust to take Quadcopter for the further level of attaining range and endurance.

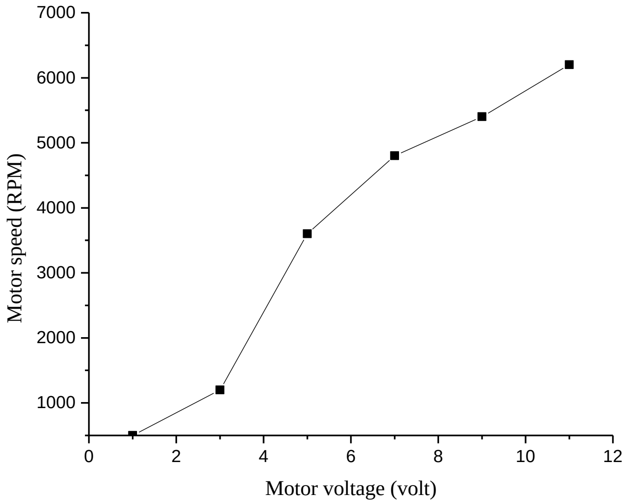

Figure 7. The response of Motor speed with supplied voltage

Here the designed Quadcopter model has the gross weight of 900 grams. According to the basic law of physics, nearly 1.8kilo-gram of thrust is required here to lift this flying model. Each rotor has the tendency to generate at-least .45 kilogram of thrust during the operation. It was clearly identified that when four motors were attaining the constant speed of 6200 RPM, then it is maintained throughout the flight test which is more sufficient to produce required thrust with the accelerating voltage of 11v.

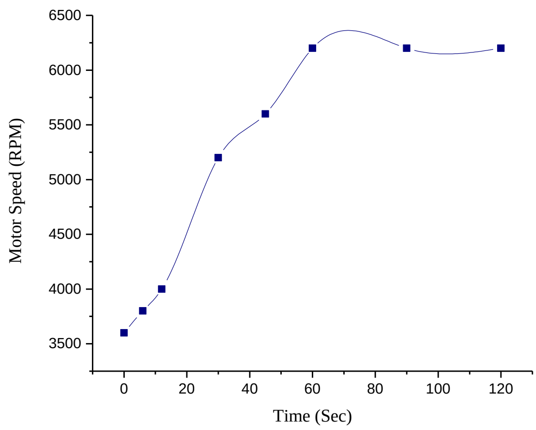

Figure. 8. The response of Motor speed with supplied voltage

Here in this design, fixed pitch propellers were used and only by changing the Motor RPM the variation in thrust with respect to time has been plotted. Also, the variation in Motor RPM versus voltage levels has been projected for the convenient flight.

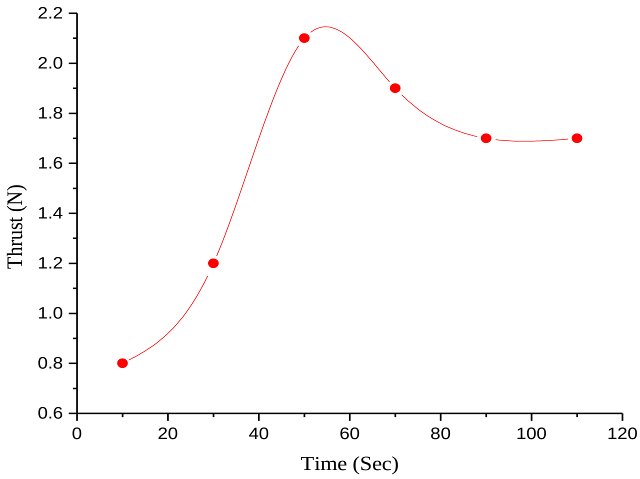

Figure. 9. Variation in Thrust Level

It was captured that the kinetic energy of motor-propeller is always more during the Quadcopter hovering and therefore the kinetic energy has been converted into thrust based on the increases in propeller rpm. The constant coordinates at the end of the plot which expresses the variation in thrust when the motor speed maintained constantly with respect to time.

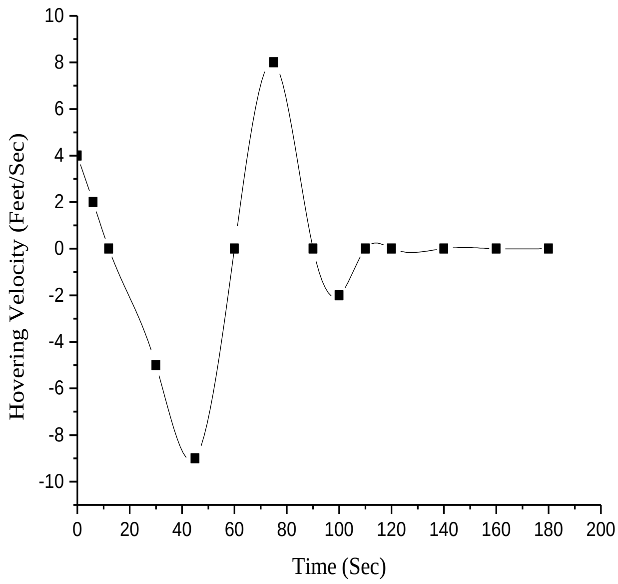

Figure. 10. Quadcopter Hovering with Time interval

The Hovering velocity of Quadcopter with respect to time has been graphically represented. It was represented that the displacement response for a fixed pitch propeller reaches the excellent accuracy when the battery power is varied from zero to maximum. The angular velocities produced on the fours rotors have been recorded.

5. Conclusion

In this research paper, an introduction about the Quadcopter is exemplified followed by the physical structure. Highly reliable, reusable kind of low-cost hardware specifications has been suggested in this research paper to build an autonomous Quadcopter. The Quadcopter test-bed was prepared and programmed using Arduino 2.8 mega flight controller. It was observed form the flight test that the endurance level rotary wing Quadcopter depends on the availability of battery power as well as the stability responses of its components. Later the dynamic responses of Quadcopter were also represented with flight test analysis. The designed Quadcopter model achieved the endurance limit with the support of avionics panel unit. A small 0.15gram of a small and 360-degree movable camera was fitted on the frame and photographs were been taken during the flight test. Variation in thrust, propeller RPM, angular velocity, endurance time, pitch, roll, and yaw angle was determined from the flight test.

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