Quadcopter: Design, Construction and Testing

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Abstract - *Unmanned Aerial Vehicles (UAVs) like drones and quadcopters have revolutionised flight. They help humans to take to the air in new, profound ways. The military use of larger size UAVs has grown because of their ability to operate in dangerous locations while keeping their human operators at a safe distance. Here quadcopter as a small UAV is discussed. It is the unmanned air vehicles and playing a predominant role in different areas like surveillance, military operations, fire sensing, traffic control and commercial and industrial applications. The main objective of the paper is to learn the design, construction and testing procedure of quadcopter. In the proposed system, design is based on the approximate payload carry by quadcopter and weight of individual components which gives corresponding electronic components selection. The selection of materials for the structure is based on weight, forces acting on them, mechanical properties and cost.*

Keywords: *UAV, Quadcopter, BLDC, ESC, Propellers, Motion, Thrust, Lift, Microcontroller, Test*

1. Introduction

A quadcopter is an aircraft heavier than air, capable of vertical take-off and landing (VTOL), which is propelled by four rotors, positioned in the same plane, parallel to the ground. Unlike standard helicopters, a quadcopter uses fixed-pitch blades in its rotors and its motion through the air is achieved by varying the relative speed of each propeller. The first quadcopter was the Omnichen 2, invented in 1920 by Etienne Omnichen. This craft made 1000 successful flights and flew a recorded distance of 360 meters. Then the convert a wings model a quadcopter designed by Dr. George E. Bothezat, appeared in 1956.[10] Nowadays there is an incredible evolution in 21st century in quadcopters. To introduce more robust controller and modeling,techniques,Universities,studentes and researchers are working continuosly , so that they can provide detailed and accurate representations of real-life quadrotors.

Nikita Guliaev (2017) explained view of quadcoter price. In department stores and specialized shops, the average consumer can now purchase a quadcopter of the approximate size. The prices for such aerial craft range is very high. The chief objective of this article is to give information of design, construction and demonstration of a quadcopter that could perform a variety of tasks in various fields so students can easily manufacture quadcopter at home with very less price. Anudeep et. Al. (2014) gives quadcopter classification. They are differentiated in two categories such as micro and mini airvehiles ,this classification totally depends on size and weight. Stafford Jesse (2014) explains the procedure of working of quadcopter. It uses two pairs of identical fixed pitched propellers in which two rotate clockwise (CW) and remaining two counterclockwise (CCW). These use independent variation of the speed of each rotor to achieve control. By changing the speed of each rotor it is possible to specifically generate a desired total thrust; to locate for the centre of thrust both laterally and longitudinally; and to create a desired total torque, or turning force. Quadcopters differ from conventional helicopters, which use rotors that are able to vary the pitch of their blades dynamically as they move around the rotor hub.

2. Structure of Quadcopter

The main part of the quadcopter is frame which has four arms. The frame should be light and rigid to host a LIPO battery, four brushless DC motors (BLDC), controller board, four propellers, a video camera and different types of sensors along with a light frame. The speed of BLDC motors is varied by Electronic Speed Controller (ESC).For higher stability i.e. to have lower C.G. the batteries are placed at lower half. The motors are placed equidistant from the centre on opposite sides. To avoid any aerodynamic interaction between propeller blades the distance between motors is roughly adjusted. All these parts are mounted on the main frame or chassis of the quadcopter as shown in Fig.1. The detail quadcopter part list is given at the end of this article in section Appendix. Nowadays, main structure consists of a frame made of carbon composite materials to increase payload and decrease the weight.

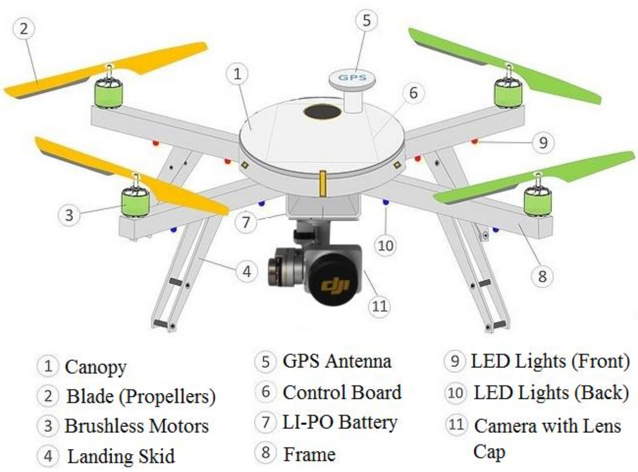

Fig. 1 Quadcopter Structure

2.1 *Brushless DC Motors (BLDC Motor)*

Brushless DC motors are exclusively used in Quadcopter because they superior thrust-to-weight ratios compare to brushed DC motors and its commutators are integrated into the speed controller while a brushed DC motor's commutators are located directly inside the motor. They are electronically commutated having better speed vs torque characteristics, high efficiency with noiseless operation and very high speed range with longer life. BLDC motors do not use brushes for communication. They are typically given two ratings: Kv ratings and current ratings. Kv rating is the relationship between the RPM and the voltage. Kv rating indicates how fast the motor will spin (RPM) for 1 V of applied voltage. The current rating indicates the max current that the motor may safely draw. By measuring the electro-mechanical relationship, the torque constant K_t can be determined from that K_v rating which is calculated as, [7]

The torque can be calculated as,

$$T = I \times K_t \quad (1)$$

Then, Kv rating is the selection criteria for motors. K_v rating is calculated by,

$$K_t = (0.01794) K_v \quad (2)$$

It is also calculated by using rpm (N) speed formula as,

$$N = K_v \times \text{ Voltage input} \quad (3)$$

Generally BLDC motors are referred in Kvs like 850 KV to1800 KV depending upon application. If 1 volt is applied on 1000 KV BLDC motor, it will spin at 1000 RPM while 12 volts applied on motor, it will spin at 12000 rpm.

2.2 *Propellers*

A lifting thrust is provided to quadcopter by providing spin to the propeller. as shown in Fig.2. Propellers come in many sizes and materials. They are measured by their diameter and their pitch, in the format (diameter x pitch). Pitch is a measurement of how far a propeller will *travel* in one revolution. Propeller selection is important to yield appropriate thrust for the hover or lift while not overheating the motors. Each BLDC motor has a propeller. The four propellers are actually not same. The front and back propellers are tilted to the right, while the left and right propellers are tilted to the left.

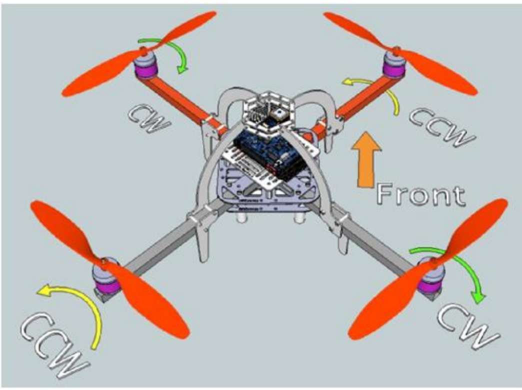

Fig. 2 Quadcopter Motor Rotation Directions [6]

2.3 *Electronic Speed Controller (ESC)*

The commands are given in the form of PWM signals ,which are accepted by individual ESC of the motor and output the appropriate motor speed accordingly. ESC convert 2 phase battery current to the 3 phase power and also regulates the speed of brushless motor by taking the signal from the control board. The ESC as used in radio controlled craft performs having two functions. The first is to act as a Battery Elimination Circuit (BEC) allowing both the motors and the receiver to power by a single battery. The second function is to take the receiver's and flight controller's signals to apply the right current to the motors. Every ESC has a current rating, which indicated the maximum current provide to motor without overheating. The ESC rating is higher than motor Amp, so [10]

$$\text{ESC rating} = (1.2 \text{ to } 1.5) \times \text{Max. Ampere rating of Motor} \quad (4)$$

2.4 *Battery*

Lithium Polymer (LIPO) rechargeable batteries are used for quadcopters because they have high specific energy and light in weight. Electric power is provided to motor and all electronic components of quadcopter by the batteries. The capacity rating, in milliamp-hours (mAh) indicates how much current the battery may output for one hour. Discharge rating indicated by the letter "C", show how fast the battery may be safely discharged. LIPO batteries can be found in packs of everything from a single cell (3.7V) to over 10 cells (37V). The cells are usually connected in series, making the voltage higher but giving the same amount of Amp in hours. The ESC rating is higher than motor Amp, so maximum current withdrawn by motor is given as,[11]

$$\text{Maxi. current withdrawn by Motors} = \text{No. of Motors} \times \text{Maxi. current withdrawn by Single Motor} \quad (5)$$

2.5 *Servo Leads*

Servo leads are the connection cables between the receiver - control board and ESC board. These have three leads which connect the signal, power (+) and earth (-) connection.

3. Design of Quadcopter

Quadcopter system works on the principle of air lifting phenomena with high pressure. There is no particular design for such type of UAV because ongoing research in new designs is unstable with nature of the conventional designs. Every new design is aimed to be more stable and manoeuvrable. The stable flight of a UAV heavily depends on the design and complexity in the designing control system arises due to lower stability of the system. The motion of UAV depends on the resultant forces and moments about the centre of gravity. A good quantitative relation of forces and torque about C.G. of the body can be obtained by the Newton-Euler model. For example, if a UAV needs to hover at a particular height, the moments about the centre of gravity need to be zero. The forces and moments applied at the centre of gravity depend on the structure and design. [1]

The design of quadcopter has both mechanical engineering and computer engineering aspects. The brief about computer engineering aspect is given in Fig. 3. It is carried out in two stages as software and hardware respectively [3].

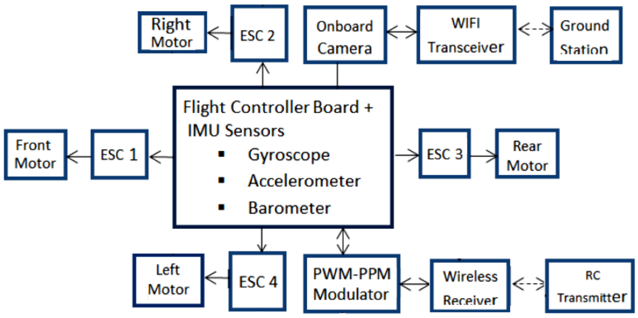

Fig.3 Block Diagram of Quadcopter

The quadcopter design is based on the embedded system platform. It consists of microcontrollers which control the overall performance of quadcopter such as flying mechanism and live streaming of videos. After the microcontroller ESC is used to control the propeller speed depending on the signal from the computer. The power supply of the quadcopter is achieved by the battery. These requirements make sure that the quadcopter maintains stable flight while moving or hovering.

Generally X type frame used in the quadcopter because they are thin strong enough to withstand deformation due to loads as well as light in weight . Usually the frames are indicated as motor to motor distance or the diameter of the circle of frame area. Generally diameter of the circle of frame area for mini aerial vehicle ranges between 1/4m and 1m. For the mini aerial vehicle 1/2 m area is chosen as per application. [11] When the frame is subjected to bending or twisting load, the amount of deformation is related to the cross-sectional shape section. For quadcopter generally closed cross sectional hollow frame is used to reduce weight .Whereas stiffness of solid structure and torsional stiffness of closed circular section is lower than closed square cross-section This reduces overall weight. The stiffness can be varied by changing cross sectional profile dimensions and wall thickness.

3.1 *Selection*

Study of parts involved in quadcopter is very essential for stability of structure. The selection of BLDC, ESC and the battery vastly depend on the payload. The ESC ratings depend on the ratings of the brushless DC Motors. Selection of BLDC depends on high Kv (rpm/volts) ratings, high thrust, less weight and high efficiency. The rating of the motors depends on the specification of propeller blade and payload required. If payload is high, choose high ratings motor which require higher current rating ESC. The thrust produced depends on the diameter and the pitch of the propeller. To increase the payload, the motors need to be changed and consequently an entire new set of BLDC motors, ESCs, and battery would be required.

3.2 *Stable Structure*

Gyroscope (roll, pitch, and yaw) send input to control board via microcontroller to stabilize the copter during flight. As per code burnt in microcontroller, it processes these signals to the ESC. These signals instruct the ESC to make fine adjustments to the motors rotational speed which in turn stabilizes the quadcopter.

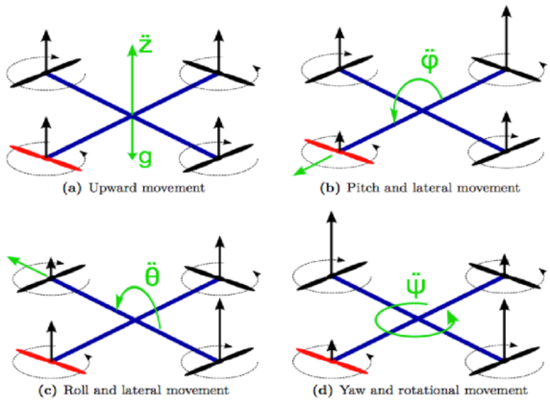

Fig.4 Quadcopter Orientation [5]

The control board also recives signals from the radio system receiver (Rx) and passes these signals to the microcontroller via the aileron, elevator, throttle and rudder inputs. Once this information has been processed the IC will send varying signals to the ESC which will adjust the rotational speed of each motor to induce controlled flight like (up, down, backwards, forwards, left, right, yaw) as shown in the Fig. 4 Gyro-gain for all 3 axis (Roll, Pitch and yaw) is controlled by using 3 adjustable potentiometer .The gyro reaction can be reversed if necessary during pre-flight setup

3.3 *Mechanism and Motion*

Takeoff,Landing,Forward,Backward.Right&Left motion these are the six major operations to be controlled

3.3.1 Take –Off and Landing Motion (Throttle Control)

Take-off is movement of quadcopter that lifts up from ground to hover position and vice versa for landing position as shown in Fig.5. It is controlled by increasing or decreasing speed of four rotors simultaneously which means changing the vertical motion.

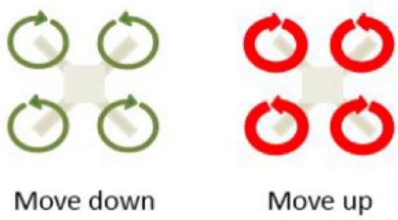

Fig. 5 Take-off (Move up) and Landing Motion (Move Down) [4]

3.3.2 Forward and Backward Motion (Pitch Control)

Forward and backward motion is controlled by increasing or decreasing speed of rear or front rotor as shown in Fig.6. It also affect the pitch angle of the quadcopter.

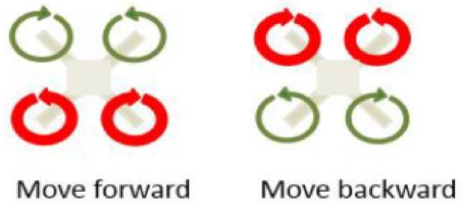

Fig. 6 Forward and Backward Motion [4]

3.3.3 Left and Right Motion

Bend left and right motion of quadcopter is controlled by changing the roll angle as shown in Fig.7. Rotate left and right motion of quadcopter is controlled by changing the yaw angle as shown in Fig.8.

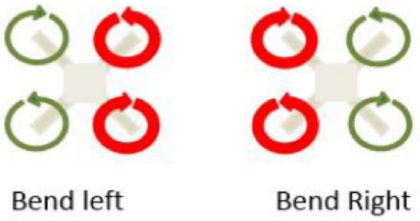

Fig. 7 Bend Left and Right Motion *(Roll control)* [4]

Yaw angle control by increasing /decreasing counter-clock wise or decreasing /increasing clockwise rotor speed.

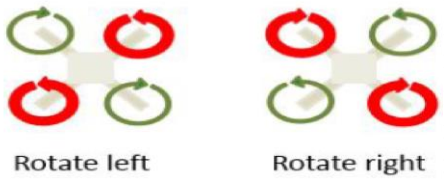

Fig. 8 Rotate Left and Right Motion *(Yaw control)* [4]

The Roll, Pitch and Yaw of quadcopter decide the movement and motion in particular direction by varying the speed of rotors with help of ESC as is shown in Fig.4.

3.4 *Force Analysis*

The resultant forces are transferred to rod by the propeller then rod to clamp and then clamp to the top and bottom plates. For static strength testing, the forces applied on the Rod are given as the thrust, centrifugal force and the moment created by the propeller. [2]

$$F_c = mR\omega^2$$

(6)

Here F_c= Centrifugal Force (N)

m=Mass of propeller (Kg)

R =Radius of the propellers (m)

N=Speed of the propeller (rpm)

$$\omega = \frac{2\pi N}{60}$$

ω=Angular speed (rad/sec)

$$Moment = F_c * \left(\frac{Perpendicular\ Distance}{Bet^n\ Propcenter\ and\ Road\ Surface} \right)$$

(7)

Then, we know twisted portion of the propeller is generally termed as pitch. The propeller is specified on the basis of its pitch and diameter. Diameter of propeller (D) is calculated by using equation of power (in Watt), [11]

$$Power = K_p \times D^4 \times P \times N^3 \qquad (8)$$

Here, K_P= Propeller constant (1.11 for APC Controller)

P=Pitch of the propellers (m)

Thrust and Weight Analysis: [3, 11]

The thrust (in Newton) can be given as:

$$Thrust = \frac{\pi \times D^4 \times \rho \times v \times \Delta v}{4}$$

(9)

Here, ρ = Density of air (kg/m^3)

v =Velocity of air (m/s)

Δv =Velocity of the air accelerated by propeller

Then, total mass lifted by the quadcopter is calculated as, Here, M= Total mass lifted by the quadcopter (kg)

$$M = \frac{Thrust}{Acceleration\ due\ to\ gravity\left(i.e.\ 9.81m/s^2\right)} \qquad (10)$$

Lift and Weight Analysis: [3]

In design, our interest is to reduce weight (Wt.)by increasing the lifting ability of the flight system.

Weight to Rpm Ratios:

Unknown weight of quadcopter is given as,

$$W = \frac{Required\ rpm}{Refernce\ rpm} \times Refrence\ Wt.$$

(11)

Here, W= Unknown weight of quadcopter (N)

Propeller Length to Weight Ratios: [3]

Unknown propeller length is given as,

$$Y = \frac{Required\ Wt.}{Refernce\ Wt.} \times Refrence\ Propeller\ Lenght \qquad (12)$$

Here, Y = Unknown propeller length (cm)

The relationship governing the lift capabilities of flight system is,

$$Lift(kg) = \frac{W \times D^4 \times N^2 \times \left(\frac{\rho \times 24}{C_f \times 29.9} \right)}{2.2} \qquad (13)$$

where C_f= Lift coefficient

Expected duration (in Hours) of quadcopter flight is given as, [10]

$$Duration = \frac{Capacity\ of\ battery\ \text{in Ah}}{Max.\ \text{Current drawn by Motor}} \qquad (14)$$

The above equation gives us information about pair of DC motors with speed and load carrying capacity of quadcopter.

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4. Controller Unit

Control board is connected to ESC& reciver,where as control board is the main system. Then it is pre loaded with different set option from single copter to octocopter. This board is used to different operations performed by the quadcopter like roll, pitch and yaw. The microcontroller provides a set of digital and analog I/O pins that can be interfaced to various expansion boards (shields) and other circuits. The boards feature serial communications interfaces, including USB on some models for loading programs from personal computers.

Table 1 Parameters of Microcontroller [1]

Parameters	Sample Value
Flash	32 Kbytes
Ram	2 Kbytes
Pin count	28
Max. operating frequency	20MHZ
CPU	8-bit AVR
Touch channels	16
Max I/O pins	26
External interrupts	24

The Arduino project provides an Integrated Development Environment (IDE) based on the processing project, which includes support for the C and C++ programming languages for programming the microcontrollers. For example of ATmega328 is a single chip micro-controller created by Atmel and belongs to the mega AVR series. In these project the microcontroller is programmed by the software's called Embedded C, Keil, and Proload. The various parameters included in the microcontroller are listed in the Table 1.

Generally use C++ programming language with a few python and embedded C programming codes as subroutines to enable a more robust platform for the quadcopter to receive a wide variety of inputs from the different hardware options present. Fig. 9 gives the program architecture for the flight control. [3]

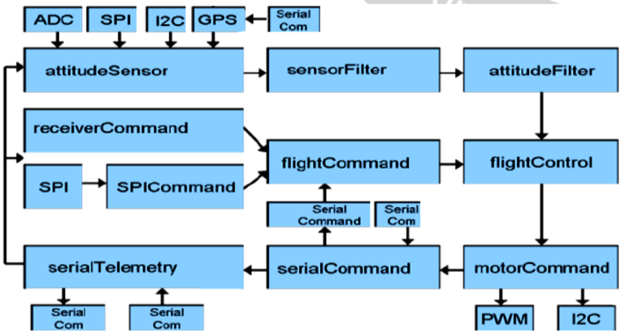

Fig. 9 Program Architecture

The assembly and connections of the various electronic components of the quadcopter is shown in Fig.10

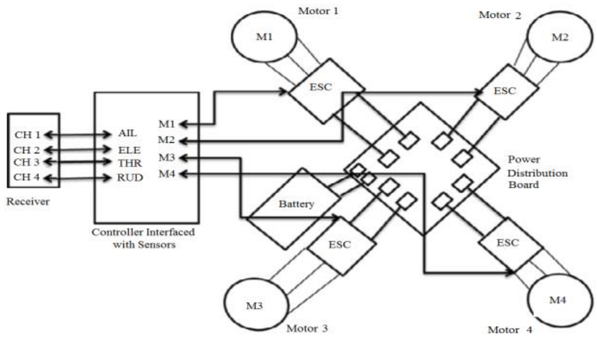

Fig. 10 Electronic components connection [11]

5. Testing

The testing procedure of quadcopter with help of flow chart is given in Fig. 11. The structure was built bit by bit. Then motors are tested with different speeds and thrust characteristics. For this test a spring arrangement is used where one end the spring was attached to the motor and the other was attached to the ground. The thrust applied by the motor is predicted by observing the deflection, here spring stiffness is known. The remote needs to be calibrated so that motors get the same pulse at the starting for takeoff. Small mechanical inaccuracies in fabrication are taken care of by introducing trim setting in the remote unit. For safety of the quadcopter flight, various tests are carried out on the individual components and as whole unit to ensure everything is functioning properly. Generally, two test stages are carried out on the quadcopter which are given as below. [3]

5.1 Unit Tests

For basic flight control of the APM 2.6 is tested by PID (Proportional-Integral-Derivative) tuning and flying the quadcopter. There number of sensors are needed for the tracking algorithms. The barometer and compass on-board of flight controller are unit tested to ensure optimal performance.

5.2 Flight Tests

For pre-flight testing (tethered) and post-flight testing (untethered) methods are used in testing of the quadcopter. For the pre-flight testing a checklist was used to ensure that the quadcopter was in sound condition before the post-flight testing. Quadcopter need calibration and test sequence before takeoff. When this is completed the main control loop will run continuously which control the Euler angles of the quadcopter.

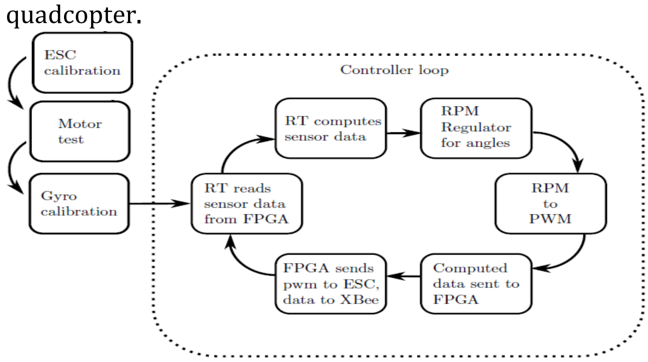

Fig.11 Flow chart of Control System [8]

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6. Advantages, Limitations and Applications

The Quadcopters are having so many applications due to its advantages are as [2]

- Gearing is not required between the motor and the rotor
- Variable propeller pitch is not required for alternating quadrotor
- Minimal mechanical complexity
- Low maintenance cost
- Less loads on the center plates
- Payload augmentation

Privacy of human being is disturbed because of quadcopter. This is the only major limitation compare to other major advantages quadcopter as used in various fields. A quadcopter is not merely a pilot's flying toy. It has other beneficial uses as well which are given as below, [10]

- Research Field
- Military, law enforcement and community agencies
- Commercial use and aerial photography
- Augmented reality games
- Solving problems with motion
- Delivering food and medicine
- Journalism and Sports

7. Discussion

This article present mechanical structure and describe all parts of quadcopter which gives good solution for a quadrotor design when its dimension and cost are the main constraints. The quadcopter configuration has a greater stability as compared to the other configurations and it is able to hover close to its target, unlike its other counter parts. This type of project plays a major role in civilized countries for surveillance of the terrestrial areas, film industries, managing traffics and city planning. The core intention of this work is to study complete designing and manufacturing process of quadcopter from the engineering prospective and improving their balance and stability system. As per future aspects, there is advancement in technology of quadcopters dramatically. In recent days, a companies like Boeing, Airbus, DJ Innovations, Parrot, Walkera, Blade and Heli-Max are working on some projects like Bell Boeing Quad TiltRotor, AeroQuad and ArduCopter, Parrot AR. Drone, Nixie, Zano (drone), Lily Camera drone, etc.

Terminology

ADC	Analog-to-Digital Converter
BEC	Battery Elimination Circuit
BLDC	Brushless DC Motor
CPU	Central Processing Unit
CW	Clockwise
CCW	Counterclockwise
CPU	Central Processing Unit
ESC	Electronic Speed Controller
FPGA	Field Programmable Gate Arrays
GPS	Global Positioning System
IDE	Integrated Development Environment
LiPo	Lithium Polymer
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
RPM	Revolution Per Minute
Rx	Receiver
SPI	Serial Peripheral Interface
UAV	Unmanned Air Vehicle
VTOL	Vertical Takeoff and Landing

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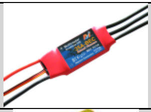
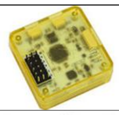
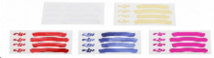
References

1. Faiyaz Ahmed, Y. Shivraj Narayan (2016), Design and Development of Quad copter for Surveillance *International Journal of Engineering Research*, Volume No.5 Issue: Special 2, pp: 312-318
2. Anudeep M., G. Diwakar, Ravi Katukam(2014), Design of A Quad Copter and Fabrication, *International Journal of Innovations in Engineering and Technology*, Volume No.4 Issue: 1, pp: 59-65.
3. BO Omijeh, VM Oden, KJ Joseph, JA Erameh (2016), Design and Construction of a Quadcopter with Payload for Pipeline Inspection and Surveillance, *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Volume No.5 Issue: 6.
4. Harsha, Sree. (2014). Quadcopter, San Jose State University. San Jose, California. (Online:http://www.socialledge.com/sjsu/index.php?title=S14:_Quadcopter#Acknowledgement)
5. Saleh Abo Elmakarem (2014),Quadcopter Mechanics, UAV Society. Egypt. (Online:http://uavsociety.blogspot.com/2014/06/quadcopter-mechanics.html)
6. Jespersen, Thomas (2012), Quadcopters – How to get started, TKJ Electronics. Denmark. (Online:http://blog.tkjelectronics.dk/2012/03/quadcopters-how-to-get-started/)
7. Nikita Guliaev (2017), The Design, Construction and Implementation of an Autonomous Outdoor Quadcopter using an RPi microcomputer and a MultiWii flight controller, Saimaa University of Applied Sciences, Finland. (Online:https://www.theseus.fi/bitstream/handle/10024/133527/Guliaev_Nikita.pdf?sequence=1&isAllowed=y)
8. Øyvind Magnussen, Kjell Eivind Skjønhaug (2011), Modeling, Design and Experimental Study for a Quadcopter System Construction, University of Agder (Online:https://brage.bibsys.no/xmlui/handle/11250/136686)
9. Stafford, Jesse (2014), How a Quadcopter works | Clay Allen, University of Alaska, Fairbanks. Retrieved 2015, pp:01-20.
10. Mahen M.A, Anirudh S. Naik, Chethana H.D, Shashank A.C (2014), Design and Development of Amphibious Quadcopter, *International Journal of Mechanical And Production Engineering*, Volume No.2 Issue 7, pp: 30-34.
11. Anand S. S, Mathiyazaghan R. (2016), Design and Fabrication of Voice Controlled Unmanned Aerial Vehicle, *Journal of Aeronautics & Aerospace Engineering*, Volume 5, and Issue 2.
12. https://quadcopterarena.com/the-history-of-drones-and-quadcopters/

Appendix:

The quadcoter component list is given as below,

S. N.	Component Name	Qt.	Image
1	Frame	1	
2	Propeller Pairs	4	
3	Motor	4	
4	Remote Control	1	
5	LI-PO Battery	1	
6	ESC	4	
7	Flight Control	1	
8	Servo Leads	4	
9	Micro SD Card	1	
10	Camera with Lens Cap	1	
11	Gimble Clamp	1	
12	Propeller Detaching Wrench	1	
13	AA Batteries	4	
14	DJI Smart Flight Battery	1	
15	Charger	1	
16	Power Cable	1	
17	Plug Set	1	
18	Micro-USB Cable	1	
19	Stickers	1	
14	Spare Dampers	4	
15	Spare Screws	11