Modelling and Implementation of Autonomous Control for Octocopter UAV

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Abstract

This paper presents the modeling and implementation of autonomous control system for octocopter UAV. In the first part, the details of dynamic and kinetic model of octocopter UAV are derived by applying the Newton-Euler method. The formulated model is detailed including aerodynamic effects and rotor dynamics that are omitted in other literatures. Different hardware materials and frame layout is introduced and then construction is also continued. In this work, the frame design of this vehicle is developed. The arm of the frame is inclined to three degrees to get more lift force and it can get more stable than normal frame. The octocopter's stability is implemented using the PID controller in real flight. After implementing above these steps, autonomous flight tests of octocopter Unmanned Aerial Vehicle (UAV) is also performed in real field.

1. Introduction

In recent decades, the development of unmanned autonomous vehicles has been of great interest, and different kinds of autonomous vehicles have been studied and developed all over the world. An autonomous UAV designed to perform tedious and risky tasks and to be cost-effective substitutes for their human counterparts. Depending on the shape of the vehicles, UAV differs into fixed wings and rotatory wings. Therefore, fixed-wing UAVs need a runway to take-off and land or use some systems for launching and safe landing such as catapult launch mechanisms or parachute landing. Rotary-wing UAVs use rotors instead of fixed-wings to provide lift and thrust force. Rotary-wing UAVs don't require long and smooth runways for take-off and landing since they can vertically take-off and land. Therefore, their main advantage is VTOL ability which enables to operate in complicated and limited environments which are not appropriate for fixed-wing UAVs [1].

Depending on the number of rotor, rotatory wings differ into tricopter, quadcopter, hexacopter and octocopter. In octocopter, eight rotors are applied to produce the lift force. Over the last decade, various control methods have been implemented to investigate the attitude and altitude control problem of unmanned aerial vehicles (UAV). In [1], PID controller is used to control the attitude and altitude of the octocopter. In the frame design, it is designed with different arm length with the arm length is 0.445m for long arm and 0.349 mm for short arm. The total mass is 2.67 kg. The design has not been successfully verified in the actual flight tests and it make the flight in Hardware in the loop simulation and get the top level flight performance in this simulation Interval type-II fuzzy neural network based adaptive sliding mode controller is used for attitude control in [2]. In [3], Fuzzy+PID Attitude Control of a Co-Axial Octocopter is implemented. In this paper, the vehicle can stabilize it in roll, pitch and remain within 4 degrees. Response of yaw was slow and also has a little big drift range. Although, some of these controller found to be very attractive choices to control the attitude and altitude control of octocopter, but still there is a need to improve the performance of these algorithms for obtaining better results. In [4], the stability test is made in test apparatus and in indoor test. In this condition, the external force is not effected and the results from this test is suitable in simulation results. In this research, real flight test is performed to applied in real field. In [5], open source platform of octocopter is applied. In this condition, the platform design and other materials cannot change from the market.

In this research, own platform design is implemented depending on the mission. Vehicle weight can reduce to get more lift. The consideration of frame design is contributed in frame design with inclination of the frame arm. The frame arm is inclined in three degrees to makes the aircraft more stable when rolling and pitching and more flexible when rotating. It can get more lift force since all the motors thrust are pushing toward center. In the first part, an accurate and detailed mathematical model of the octocopter UAV is derived. In the second part, the frame design, components selection and construction are presented. And then stability test is implemented using PID controller. Finally, the results of autonomous flight test are also presented.

2. Dynamic Modeling of Octocopter

The octocopter is modeled as a rigid body using a north-east-down and a body fixed reference frame. In Figure 1, body frame moves freely with respect to a fixed inertial frame is shown.

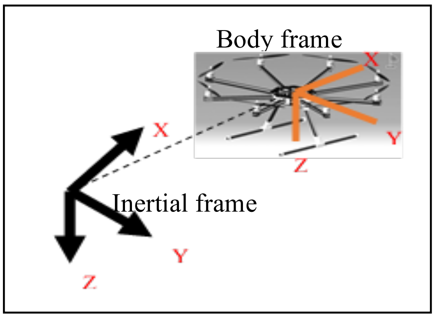

Figure 1. The body frame moves freely with respect to a fixed inertial frame

The rotation from one frame relative to the other frame can be described using a rotation matrix, comprised of three matrices describing the vehicle rotation about each of the earth frame axes.

$$R_{B\text{-}E} = \begin{bmatrix} c\psi c\theta & -s\psi c\varphi + c\psi s\theta s\psi & s\theta s\psi + s\psi s\theta c\varphi \\ s\psi c\theta & c\psi c\varphi + s\psi s\theta c\varphi & -c\psi s\varphi + s\psi s\theta c\varphi \\ -s\theta & c\theta s\varphi & c\theta c\varphi \end{bmatrix} \quad (1)$$

where C and S denote Cos and Sin functions respectively. The dynamic equations of motion of the Octocopter UAV based on the Newton-

Euler equations can be extended as:

$$m(\dot{V}_B + \omega^B v^B) = F^B$$

$$I\dot{\omega}_B + \omega^B (I\omega^B) = \tau^B \quad (2)$$

Where v^B is the translational velocity and ω^B is the angular velocity. F^B is the total force and τ^B is the total torque affected in the body frame of vehicle. By applying these equation, the translational and rotational dynamics of Octocopter can be obtained.

$$\ddot{X} = \frac{1}{m}\begin{bmatrix} (c\psi c\theta)F_x + (-s\psi c\varphi + c\psi s\theta s\psi)F_y \\ +(s\theta s\psi + s\psi s\theta c\varphi)F_z \end{bmatrix}$$

$$\ddot{Y} = \frac{1}{m}\begin{bmatrix} (s\psi c\theta)F_x + (c\psi c\varphi + s\psi s\theta c)F_y \\ +(-c\psi s\varphi + s\psi s\theta c\varphi)F_z \end{bmatrix}$$

$$\ddot{Z} = \frac{1}{m}\left[\{(-s\theta)F_x + (c\theta s\varphi)F_y + (c\theta c\varphi)F_z - mg\}\right]$$

$$\ddot{\varphi} = \frac{\dot{\theta}\dot{\psi}(I_{zz} - I_{yy})}{I_{xx}} + \frac{\dot{\theta}\Omega_r J_r}{I_{xx}} + \frac{lU_2}{I_{xx}}$$

$$\ddot{\theta} = \frac{\dot{\varphi}\dot{\psi}(I_{xx} - I_{zz})}{I_{yy}} + \frac{\dot{\varphi}\Omega_r J_r}{I_{yy}} + \frac{lU_3}{I_{yy}}$$

$$\ddot{\psi} = \frac{\dot{\varphi}\dot{\theta}(I_{xx} - I_{yy})}{I_{zz}} + \frac{J_r \dot{\Omega}_r}{I_{zz}} + \frac{dU_4}{I_{xx}} \quad (3)$$

Where $\ddot{X}$, $\ddot{Y}$ and $\ddot{Z}$ is the position of the vehicle second derivative and m is the total mass of vehicle, g is the gravity constant, F_x, F_y and Fz is the force in x, y and z axis. Φ, θ and Ψ is the roll angle, pitch angle and yaw angle. Ω_r is the total speed of propeller. U_1, U_2, U_3 and U_4 are system input. I_{xx}, I_{yy}, I_{zz}, is moment of inertia of each axis. J_r is the rotor inertia.

3. Frame Design and Hardware Selection

The most important target of this design process is to arrive at the correct set of requirements for the aircraft, which are often summarized in a set of specifications. The mission of this research is to build an octocopter suitable for autonomous outdoor flight in safe condition, as well justify the decisions and equipment chosen for achieving this purpose. The specifications for octocopter are:

- Flight autonomy between 10 and 20 minutes.
- Overall mass not superior to 3 kg.
- Ability to transmit live telemetry data and receive movement orders from a ground station wirelessly.
- The octocopter should fly over 100m far from ground station.

The components used to implement the octocopter are selected according to certain requirements, specifications and design considerations. The octocopter payload, flight duration, power consumption, maximum altitude and many other factors are necessarily taken into account during the selection process. In the design section of the octocopter, starting with the planning of the propulsion system and airframe and other electronic devices.

2.1. Propulsion System

During the process of planning the propulsion system of the octocopter, several constraints have to be taken into account. All of the engine should be powerful enough to carry the copter. To ensure a good mobility the combined thrust should be equivalent to two times the weight. When testing in the thrust meter with the DJI motor 2212 920 Kv, 9x4.5 propellers, 30A ESC (Electronic Speed Controller) and 10000mAh 4 cells lipo battery, each motor produces the thrust of 1120g each motor draws the current of 16A at full throttle. For eight motors, the total thrust is 8.96kg. To carry the 3kg, the thrust must be twice of the desired weight of the octocopter. So, these selected components are suitable for the desired octocopter.

2.2. Airframe Design

Airframe must be designed to optimize durability, stability, aerodynamic, and cooling system. Design has to be suitable to attach payload easily and quickly which helps to gain lots of time and allow to repair easily. From two octocopter configurations : plus type and cross type, cross type is choosed in this paper. In octocopter design, the tip to tip distance of the propeller must be at least of (frame size)/2.613 or (frame size x 0.383). So the frame length is designed to the 652 mm to get the space of 49.22mm(1.9in) between two propeller tip. The arm composed of carbon tubes attached with a composite hub from their ends forming a cross shape. At the other ends of the carbon tubes motor-propeller assemblies are attached. The 0.25 m carbon tubes are used because of their light weight (15 g) and high stiffness properties. Total frame assembly weighs about 0.5 kg without any electronic hardware.

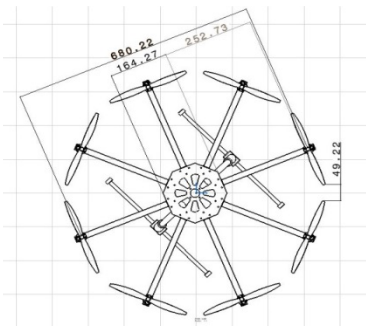

Figure 2. General dimension of octocopter

2.3. Electronic Components Selection

An octocopter used four pairs of brushless DC motor as the propellers driver. Each motor is controlled by ESC. The feedback data to monitor the level and the heading are generated by sensors included three degree of freedom of accelerometer, gyroscope and magnetometer. Ublock M8N of global position system (GPS) is used to known the location of vehicle. The system is a wireless, while data is real time monitored. Following table shows the electronic components chosen for construction of octocopter.

Table1 Electronic components chosen for octocopter construction

Component	Name
Motor	DJI 2212 920kv
ESC	Fly color 30A OPTOESC
Propeller	DJI 9x4.5
Battery	TATTU Liop 4s 10000mAh
Flight controller	Pixhawk
GPS	Ublock M8N
Telementry	3DR 915Mz
Radio Control	Futaba 2.4 Ghz

3. Construction of Octocopter

In the process of making Octocopter consists of several main stages, namely:

1. Making the octocopter frame,
2. Installation of electronic circuits

The main construction of octocopter frame exists of two center octagon plates, arms, landing gear (legs), engine mounts, battery mount.

3.1. Making the octocopter Frame

Manufacture of airframe begins with the arms designed to have a good precision with long arm 252.73 mm and 12 mm diameter. The eight carbon rods must be the same. The next process is the manufacture of the center plate with shape of octagonal in 3 mm thickness and a diameter of 164.27 mm sides.

The center plates are made with the composite material. Firstly, the printed paper with octagon shake put onto the composite sheet and then cut the composite sheet in this shape. To get the desired thickness, the carbon sheet is overlapped layer by layer. And then, this sheets are cut using hand saw. A number of holes drilled into the center plate serves a dual purpose: to lessen the total weight of the frame by using a smaller quantity of material, and to ease the fastening of all the necessary electronic equipment. The step by step implementation is shown in figure 3.

Figure 3. Center plate implementation

The eighth arm then mounted on the centre plate held together with nuts, bolts with an arm angle of 45˚. After implementing this step, battery mount is mounted to the bottom side of the frame.

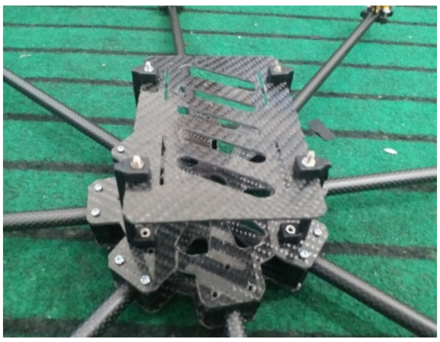

Figure 3. Center plate implementation

3.2. Installation of electronic circuits

Electronic components started to be installed after a mechanical frame installed. Electronic circuit of an octocopter consists of motors, ESC, PDB Pixhawk controller, GPS, buzzer, telemetry and battery.

The first step after all electronic equipment prepared is doing the soldering process distribution board. Eighth ESCs connected in parallel to the distribution board connected to the battery. Once done soldering, the next step is the installation eighth motor is placed on the end of the arm aircraft previously created the holder to these motors

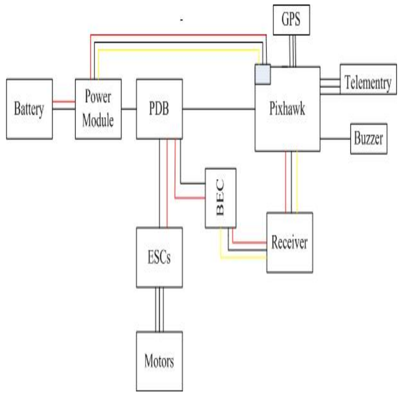

Figure 4. Electronic devices connection on octocopter

There are two configurations available for octocopter, X-configuration and +-configuration, according to this, the Pixhawk Board is mounted on the frame core to give the correct orientation with respect to control signals received from the user. Vibration is a serious issue that leads to Pixhawk operation. A thick-layer insulator is placed between the Pixhawk board and the frame core upper surface to provide the necessary isolation.

The RC receiver is connected to the Pixhawk board is placed next to it on the same core surface. The RC channels must be connected in a certain order according to the required operation.

The LiPo battery is placed on the frame core lower surface which is the power distribution board. The regulator input terminals are welded to the power distribution board and its output terminals are fed to the Pixhawk Board. The ESC power cables are welded to power distribution board and the control wires are connected to the Pixhawk board.

Figure 5. Complete installation of octocopter

The motors have three high-power wires which are power, ground and data wires. These wires are connected to ESC high-power wires in the same order. The ESC provides the essential pulse widths to the motor through the data wire. In order to reverse the motor direction, the motor power and ground wires are swapped. The motors of each octocopter must rotate in the same direction alternately and motors of the different diagonals rotate in opposite directions, according to this, the propellers are mounted to specific motor according to its direction of rotation to provide the necessary lifting.

As soon as installation is complete, Mission Planner software is firstly installed in ground station computer. After installing Mission Planner GCS, program is input to the pixhawk flight controller. The pixhawk sensors (Magnetometer and accelerometer) are calibrated to determine the correct orientation. Remote control and sensors calibrations is also performed. After implementation of all of these steps, the octocopter UAV is ready to make flight test and to check the stability and to test the autonomous flight in real field.

4. Flight Test Results

To verify the performance of the proposed autonomous system, experimental tests are performed. Firstly, stability of the UAV is tested in altitude and attitude with roll, pitch and yaw. For tuning of the PID controllers, several tuning algorithms have been developed. To get the optimized PID parameters, auto tune method is applied. The optimized PID parameter to get the best stability of octocopter is shown in following table.

Table 2. PID parameter

	Roll Rate	Pitch Rate	Yaw Rate
P	0.1942784	0.2081184	1.381407
I	0.1942784	0.2081184	1.381407
D	0.00804490	0.01160422	0

At this flight test, the air speed is the air speed is about 8 meter per second. Figure 6 shows the octocopter flying in altitude 120m.

Figure 6. Flight test in altitude 120m

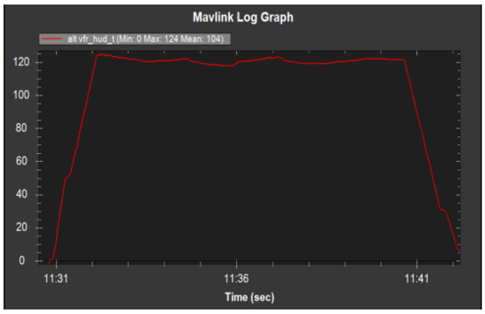

Figure 7. Altitude response of flight test

From the response curve, the altitude of the vehicles reaches to the desired altitude.

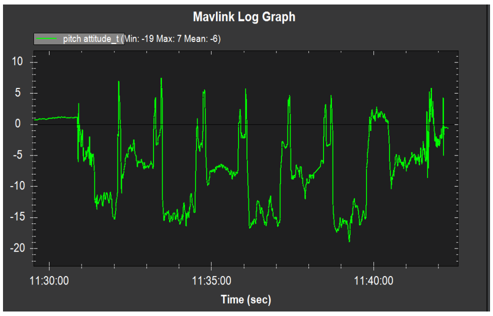

Figure 8. Pitch response of flight test

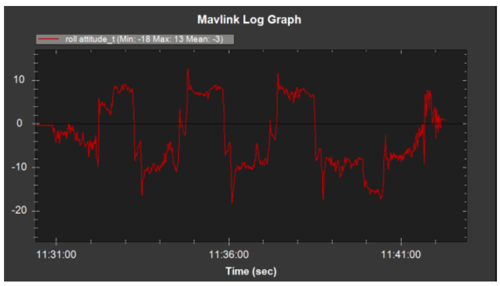

Figure 9. Roll response of flight test

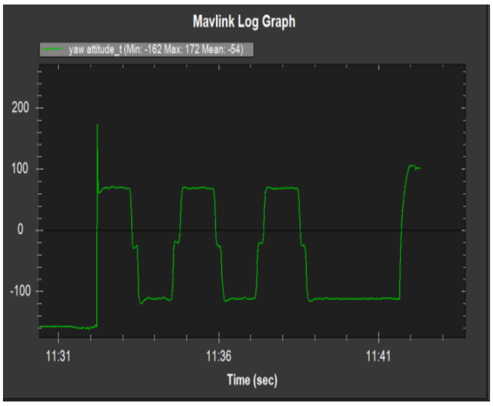

Figure 10. Yaw response of flight test

In the stability test, pitch angle varied from -19 to 7 degree as shown in figure 8 and the roll angle is varied from -18 degree to 13 degree in figure 9. From the figure 10, it is seen that yaw angle varied from -162 to 172 degree. In this flight, the flight path is face to the wind direction. So, the pitch angle is caused the more oscillation to get to the desired value. But all of these results are acceptable range for outdoor mission.

Figure 11. Flight path on mission planner

After implementation the stability test, continued to the autonomous flight of the vehicles. For the autonomous flight, the flight path is firstly planned on ground control station using mission planner as shown in figure 11.

When the AUTO mode was triggered, the aircraft immediately flew to the first waypoint of the mission. It then followed the mission without any issue. When the aircraft completes the mission it returns to its HOME position. In figure 12, waypoint following for the autonomous flight test is presented.

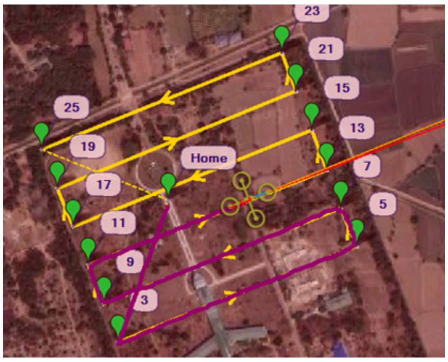

Figure 12. Autonomous flight

In this figure 12, the yellow color is the desired flight paths and the purple color is the actual paths that the aircraft fly. Octocopter UAV flies in exactly following the desired flight paths. The total area is about 153691-meter square and it taken about the 10 minutes with the altitude of 120m to complete mission. In this condition, the battery percent remains 40 percent. It can fly about 17 minutes until the octocopter fly the battery is off.

Conclusion

This paper presents modeling and implementation of autonomous flight of octocopter. In this research, many advantages can get from new frame design. By inclination of frame arm of the vehicle, the vehicle can get more lift than normal octocopter because all of the force collect to the center of the vehicle. The cost is very low compared to the commercial flight. But, this vehicle can compare the performance to the other commercial octocopter in flight endurance, payload and stability and other performances. The results from this research satisfied the desired specification (endurance, payload and altitude) of the octocopter. In future work, we will try to get the more flight endurance and will add more sensors to fly preciously in autonomous flight than now.

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