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Design and Implementation of a Quadcopter Based on a Linear Quadratic Regulator (LQR)

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Abstract—The Unmanned Aerial Vehicle (UAV) industry is growing at an unprecedented rated with the emergence of many critical and exciting applications. This growth is also followed by a number of quality requirements including stability and accuracy of trajectory during navigation. This paper presents the design and construction of a quadcopter using robust control strategy with promising stability and accuracy. The frame of the drone was designed using CadDian Software and the parts were printed using a 3D printer. The flight controller was based on Arduino board with GSM, GPS and GPRS boards for sending data over the internet and also enhancing long range flight. A feedback control system based on Linear Quadratic Regulator (LQR) was developed and tested to control the stability of drone. The proposed control strategy of the drone was assessed for a case of trajectory tracking and also for stability of navigation. The findings were positive confirming the appropriateness of the control measures for independent and autonomous flying with promising precision. This UAV fitted with IoT has the capability of collecting and sending data over the internet and therefore can be used in many applications that required data exchange. The developed quadcopter demonstrated superiority in terms of stability and tracking accuracy over counterpart UAVs controlled with PID techniques.

Keywords—Unmanned Aerial Vehicle (UAV), Linear Quadratic Regulator (LQR), PID, stability, accuracy, 3D printing, CadDian, IoT.

1 Introduction

Over the last decades, Unmanned Aerial Systems (UASs) have gained much attention due to their various applications in medicine, mining, agriculture, surveying [1]–[6]. Drones are a form of UAV that are most often remotely controlled and without humans on board. The principle of drones dates back to the 1940s during World War II. However, over the years it has undergone monumental changes owing to the miniaturization and discovery of advanced electronic components. Even with a general principle relatively easy to understand, the design of drones is rather a complex task requiring skills in many areas such as aerodynamics, electronics, computing and wireless transmission [7]–[9].

Drones were initially developed for military applications, but are now accessible to civilians with a growing number of applications. Although these UAVs have not yet gained widespread use, they are gradually being used in the production of video contents, recording of events etc. Drones have the potential to increase tourism which contribute to socio-cultural development of countries. In addition to recreational applications, drones have a significant development potential in sectors such as agriculture, supervision of power lines, supervision of borders, cartography, security, etc [10]–[13]. In agriculture for instance, drone technology can be used to spread fertilizers, water and monitor crops, and estimate production throughout a season etc. In topography, drones provide new means of mapping plots by aerial photography and facilitate the division of land. Drones are also increasingly used in security of territory and surveillance of sensitive sites.

The main scientific challenge with the conception of drones lies in the complexity of their design, dynamic behavior, speed of response to command and stability during navigation [14]. Even though most of the existing control techniques for drones used simple control techniques including PID controllers, recent advances in technology have brought some robust control strategies with improved results in term of accuracy to follow a given trajectory, stability and speed of response.

This paper demonstrates a new design of UAV based on an artificial intelligence programmed in an Arduino board connected with GPRS and GSM modules. The paper innovatively presents a feedback control system to improve upon the stability of the drone in the air. The control system was based on Linear Quadratic Regulator (LQR) which derives its source from control theory and machine learning. Various parts of the drone were equally designed with the CadDian Software and printed with 3D printer.

2 Literature Review

A study of the literature reveals that emerging issues regarding autonomous navigation has to do with accurate positioning and mapping issues. [15] adopted the “Network-based Real-time Kinematic (NRTK) system” which has been extensively used in other fields including agriculture and surveying to improve upon accurate positioning of drone. The accuracy was mainly limited due to ionospheric conditions in the close environment. [16] worked intensively on the mapping aspect by conducting a survey with drone and assessing the accuracy of different models based on ground control point (GCP) system. Drone stability can also be investigated from a structural perspective [17].

Moreover, stability of UAV is highly dependent on the availability of GPS. In the absence of GPS, UAV stability is highly challenged. There have been a number of studies considering the design of wide area network that can extend over hundred meters with low power consumption to overcome the reliance on GPS [16]. However, the limitations in battery capacity and payload which are necessary for effective operations are highly challenging. Modular design are being considered to reduce the power consumption and sustain the battery capacity for a longer period [18].

Several command strategies have been used previously to control drones. These strategies range from the classic control strategy such as Proportional, Integral, and Derivative (PID) to more advanced control strategies qualified as robust and intelligent control strategies.

The PID control was one of the first methods used to control quadcopter drones. There have been extensive simulation works done to model a quadcopter drone and control it with PID controllers using MATLAB software and its SIMULINK extension. The PID control yielded satisfactory results in controlling the trajectory of drone. In addition, considering the experimental conditions in [19], it can be argued that PID control strategy is sufficient to pilot a quadcopter in environment with little disturbances. However, PID controllers do not overcome the stability challenges in presence of sustained and pronounced disturbances.

In some cases, PID tuning has been combined with Raspberry Pi 3 to control the stability of drone but this still has limited performances under dynamic environmental conditions. An existing approach used to enhance the capability of this control system is to add ANFIS (adaptive neuro-fuzzy inference system) to the PID, so as to make the control system more robust. In [20], for instance the stability of drone was enhanced with the combined ANFIS-PID tuning and yielded improved results than the PID only, although, the stability problem under dynamic environment was still not completely resolved. These findings are similar to [21] that considered a number of newly integrated strategies to augment drone stability.

Robust and optimal control algorithms are generally stronger in determining the right trajectory for a drone to follow while optimizing resources. Thus in [19], [22], the control strategies adopted LQR (Linear Quadratic Regulator) and LQG (Linear Quadratic Gaussian) which resulted in improved performances.

Nevertheless, in the presence of strong disturbances, the performance of these controllers is also considerably degraded. [23]–[25] developed robust adaptive controllers based on linear and nonlinear models of quadrotor. Their proposed technique can handle different types of uncertainties, such as external forces and modeling errors using Lyapunov energy function. [24], [26], [27] applied the Non-linear Model Predictive Control (NMPC) technique which is an optimal control method used to solve the trajectory determination problem and resulted in better-quality results.

The modelling of the movement of solid object like drone in space is governed by two main modeling methods. The major difference between the two methods is in the representation of the orientation of the system in three-dimensional space. The first way, more intuitive and easier to visualize, uses Euler and yaw angles while the second, a little more difficult to comprehend, uses quaternions which are hyper-complex numbers with three imaginary parts.

Any system based on a representation by the Euler angles inherits a singularity problem called “Gimbal Lock” [9]. A Gimbal is considered to be a ring that can actually be suspended to rotate about an axis. When nested one within another, Gimbals can accommodate rotation about many axes. The term Gimbal Lock simply mean a loss of one degree of freedom in a three-dimensional space. This occurs as a result of two axes being driven into a parallel configuration forcing the system to behave as if it was a two-dimensional one. This Gimbal Lock is quickly encountered when the determination of angles is based on trigonometric equations. This singularity problem reduces the performance of drone; For instance, if there is a sudden need to inverse flight trajectory, the model based solely on Euler's angles is unable to accurately represent the attitude of the drone.

On the other hand, a quaternion-based attitude representation provides a more complete description of the orientation of drone without having to deal with Euler's angle singularity problem. For vehicles that achieve attitudes greater than about 5 degrees in pitch or roll, the use of many trigonometric functions is necessary with Euler angles. This use of the trigonometric functions is expensive in terms of calculation time and could potentially slow down the speed of the control loop in the drone. Approximate small angles can be used together with the Euler angles for attitudes below 5 degrees, but this severely limits the capabilities of the quadrotor [28].

Additionally, the use of quaternions requires a single trigonometric function only when a non-zero yaw angle is included in the desired orientation. Otherwise, the operations on quaternions are only algebraic and therefore inexpensive in computing time. The main advantage of Euler angles over quaternions is their ease of visualization. With a pitch, roll and yaw angle, it is much easier to visualize the orientation of the drone than with a quaternion.

Contributions of the Study

The contributions of this paper are listed below:

1) The study designed and constructed the part of the drone using 3D printer and also assembled the overall drone;
2) This study adopted the use of quaternions to model the three dimensional dynamic control of quadcopter;
3) The study developed an innovative control algorithm based on LQR strategy to improve upon the stability and accuracy of the drone (the capability of following complex trajectories with high fidelity);
4) A set of Arduino, GSM, GPS and GPRS boards have been programmed together to implement the develop control strategy and tested on the constructed drone.

3 Methodology

This section presents the list of material used, the block diagram of the drone, the modelling and control of the drone stability.

3.1 Components

The list of components used to assemble the drone is presented in Table 1 below.

Table 1. List of Components

S/N	Name	Specifications
1	Arduino Board	ATMEGA328P
2	2.4Ghz Radio Transceiver	NRF24L01
3	GSM AND GPRS MODULE	SIM900
4	Battery	12volts 5000mAh Li-Po battery
5	Electronic Speed Controller	4 x 15A/30A E300 OPTO ESCs
6	GPS Module	GPS/Compass Module with Mount
7	4 x Propellers	Gemfan 1045(CW+CCW) Black Propeller
8	Telemetry	3DR Telemetry

3.2 Diagram of Electronic Section of the Drone

Figure 1 shows the diagram of electronic section of the drone. It comprises of an Arduino board which acts as the brain of the system and it is interconnected to a number of modules including GPS module, GSM module and GPRS modules in addition to a set of four brushless motor needed to control the movement of the drone.

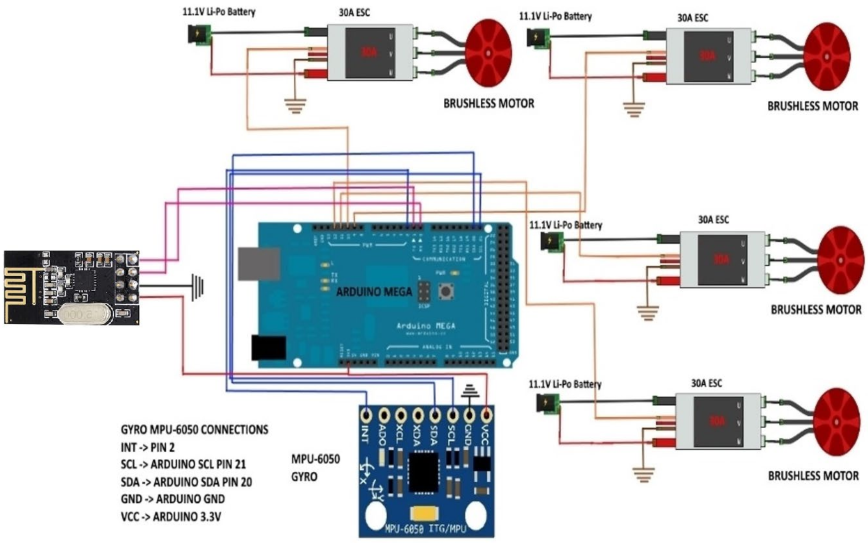


Fig. 1. Diagram of the electronic section of the drone

3.3 Modelling and Control of the Quadcopter

A quaternion is an extension of complex number representation that provides a convenient mathematical notation for representing orientations and rotations of objects in three dimensions. The positions of the drone in the space has been modelled in this study with quaternions. The model of a quadcopter using Newton-Euler equations with quaternions is described as follows:

$$\dot{x} = \frac{d}{dt}\begin{bmatrix} p \\ \dot{p} \\ q \\ \omega \end{bmatrix} = \begin{bmatrix} \dot{p} \\ q \circ \frac{F_{th}}{m} \circ \bar{q} + g \\ \frac{1}{2} q \circ \omega \\ J^{-1}\left(\tau + G_a - \omega \wedge J . \omega\right) \end{bmatrix} \tag{1}$$

Where $p \in \mathbb{R}^3$ *and* $\dot{p} \in \mathbb{R}^3$ are the position and velocity vectors with respect to the inertial frame, $F_{th} \in \mathbb{R}^3$ defines the thrust vector generated by the Quadcopter;

Parameters m *and* $g \in \mathbb{R}^3$ represents the vehicle mass and gravity vector respectively, q describes the quaternion that represents the vehicle orientation with respect to the inertial frame, $\omega \in \mathbb{R}^3$ denotes the angular velocity of the Quadcopter with respect to the body-fixed frame, $J \in \mathbb{R}^{3\times 3}$ represents the multi-copter moment of inertia, $\tau \triangleq [\tau_x, \tau_t, \tau_z]^T$ represents the moments generated by the propellers in the body axes and $G_a \in \mathbb{R}^3$ represents the gyroscopic torques

The relationships between the inputs and the propellers angular velocity is described as follows:

$$\begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \\ F_{th} \\ G_a \end{bmatrix} = \begin{bmatrix} l\frac{\sqrt{2}}{2}\,(k_1\overline{\omega}_1^2 - k_2\overline{\omega}_2^2 - k_3\overline{\omega}_3^2 + k_4\overline{\omega}_4^2) \\ l\frac{\sqrt{2}}{2}\,(-k_1\overline{\omega}_1^2 - k_2\overline{\omega}_2^2 - k_3\overline{\omega}_3^2 + k_4\overline{\omega}_4^2) \\ \sum_{i=1}^{4} (-1)^i\,(d_i\overline{\omega}_i^2) \\ \sum_{i=1}^{4} k_i\overline{\omega}_i \\ \sum_{i=1}^{4} J_{RP}\,(\omega \wedge e_3)\,(-1)^{i+1}\,\overline{\omega}_i \end{bmatrix} \tag{2}$$

Where the coefficient k_i and d_i are respectively the coefficient of thrust and the drag of the propeller $i, \overline{\omega}$ its angular velocity, l the lengh of the Quadcopter's arm (from the center of mass to the motor axis of action), $e_3 \triangleq [0, 0, 1]^T$ the axis around which the gyroscopic torque is acting and J_{RP}, the total moments of inertia of the entire rotor and the propeller about their axis of rotation.

The control scheme is divided in two control loops; the inner and the outer loop controller. The inner loop is the attitude controller, which is used to control the pitch, roll and yaw angle. The outer loop is designed to control the trajectory (x, y and z) of the quadcopter in the earth frame. A summary of the feedback control system is depicted in Figure 2.

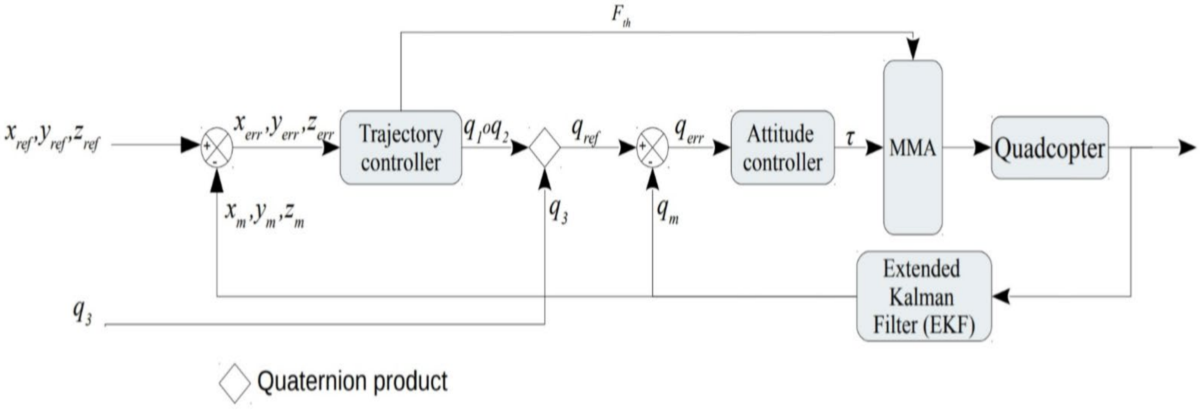
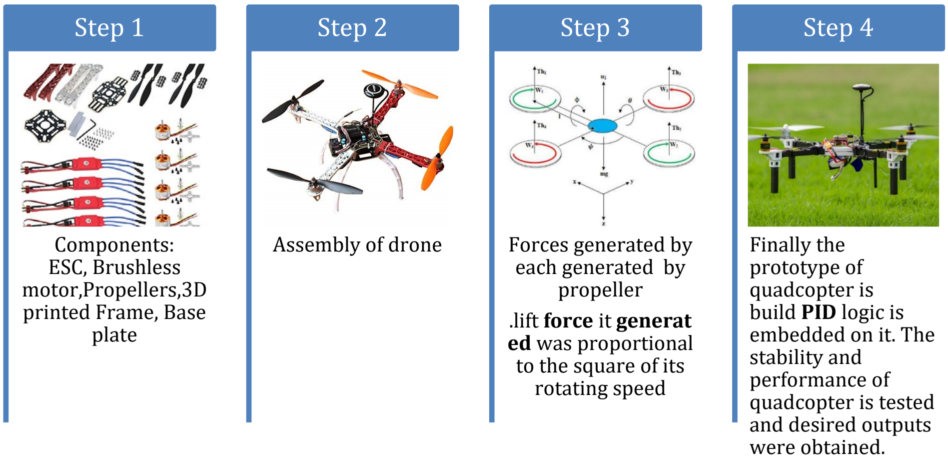


Fig. 2. Proposed Feedback Control System for Drone Stability

3.4 Assembly

Figure 3 below illustrates the different stages of the drone assembly.



Step 1

Components: ESC, Brushless motor,Propellers,3D printed Frame, Base plate

Step 2

Assembly of drone

Step 3

Forces generated by each generated by propeller

.lift **force** it **generated** was proportional to the square of its rotating speed

Step 4

Finally the prototype of quadcopter is build **PID** logic is embedded on it. The stability and performance of quadcopter is tested and desired outputs were obtained.

Fig. 3. Drone Assembly

4 Results

This section presents simulation results of the proposed control systems as illustrated in Figure 4. It further covers results on the 3D printing and the operation of the assembled drone.

Figure 4 has the shape of a linear time invariant, first order systems with interesting parameters. The settling time seems much reduced indicating a short transient regime while the maximum overshoot is merely negligible. There are sustained oscillations in permanent regime, however they have been sufficiently damped.

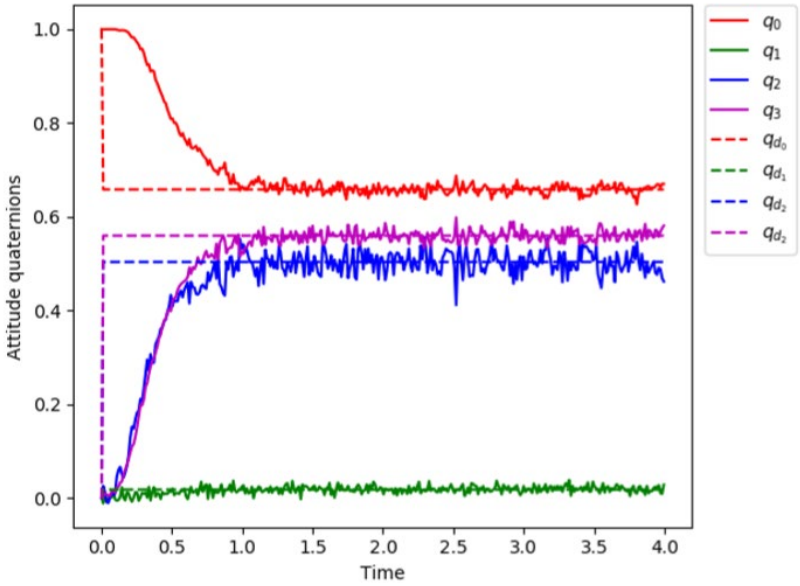


Fig. 4. Control system output on the altitude stability

Figure 5 shows the 3D printing of various parts of the drone while Figure 6 illustrates the constructed drone in a flight mode.

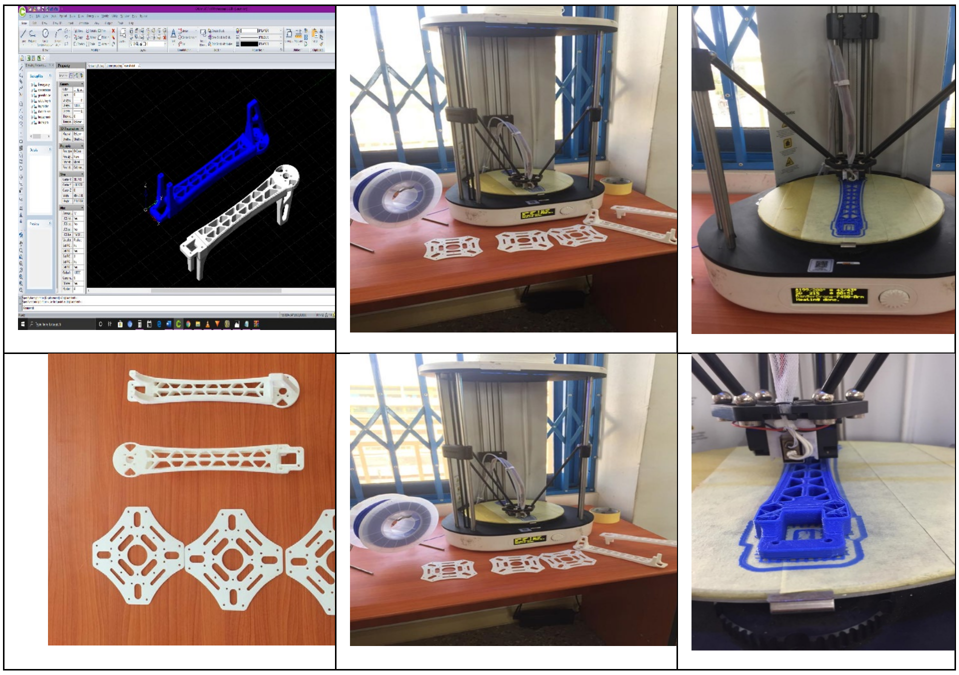


Fig. 5. 3D printing of drone's part

Figure 6 illustrates the constructed drone in operation.

Fig. 6. Pictorial view of the constructed drone

Additionally, the main advantage of a position controller is to follow defined trajectories with accuracy. To assess this functionality on our proposed control strategy in this paper, this section considers as trajectory, a circle of diameter 7 m and this to be covered in 8 s as well as a rotation of the drone on itself equivalent to 1 revolution in 8 s all at a distance of 7 m from the ground. The commands to be sent to the system over time are expressed as follows:

$$x_{ref} = 7sin\left(\frac{2\pi}{8}t\right) \tag{3}$$

$$y_{ref} = 7cos\left(\frac{2\pi}{8}t\right) \tag{4}$$

$$z_{ref} = 7 \tag{5}$$

$$\varphi = \frac{380}{8}t \tag{6}$$

Figure 7 shows the trajectories obtained for these commands and the desired trajectories for a simulation made over 15 s. Figure 7a shows the evolution of the position in a 3D space. In this same Figure, the dotted blue graph represents the reference trajectory and the red graph represents the trajectory made by the drone. Considering the fact that a rotation of the drone on itself was requested during the same simulation, Figure 7b displays the evolution of the orientation of the drone over time. The dotted curves represent the desired evolution of each component of the quadrotor describing the orientation and the second curve in solid line represents the orientation obtained.

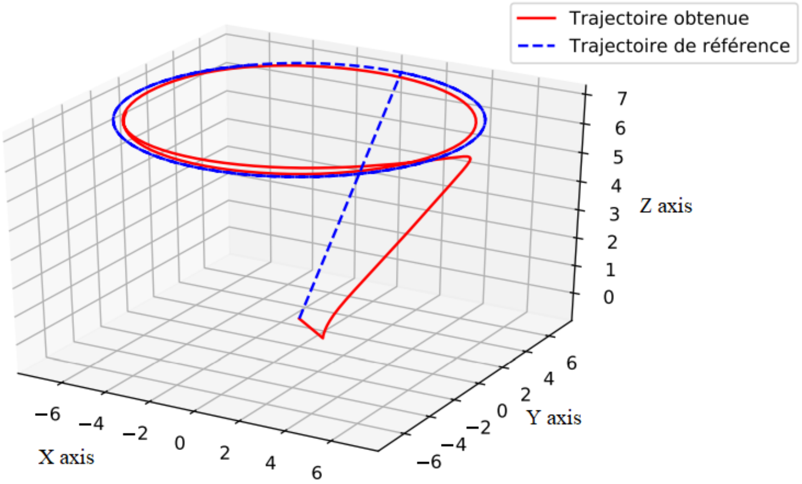


Fig. 7a. Trajectory tracking

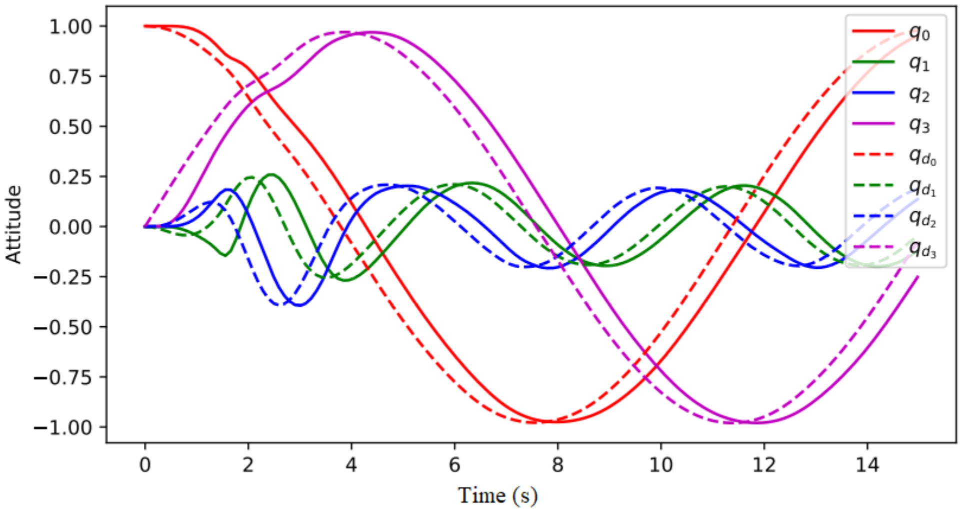


Fig. 7b. Orientation tracking

It is remarkable from Figures 7a and 7b above that the drone is able to follow a Complex trajectory without with negligible deviation. The accuracy of the proposed control strategy is therefore commendable and the controller can thus be recommended for autonomous flying. These findings corroborate previous studies in the same line including [7], [9], [19], [22], [24], [26], [27], [29]–[31].

5 Conclusion

In summary, this paper presents the design and construction of drone. The parts of the drone were designed with the CadDian Software and printed using a 3D printer. The parts were further assembled and the control system for the drone covering its stability and tracking of trajectory, was designed with feedback control system using a Linear Quadratic Regulator that was implemented on an Arduino board. Findings revealed that the drone demonstrated a great stability during navigation. The drone was further tested for tracking of arbitrary trajectory and also was equally proved to be accurate, and reliable in this regard. The constructed drone has the advantage to cover large distances and communicate data in real-time.

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