Implementation and Modeling of a Quadrotor

Ersan Aktas, Eren Turanoğuz

Abstract**—**In this study, the quad-electrical rotor driven unmanned aerial vehicle system is designed and modeled using fundamental dynamic equations. After that, mechanical, electronical and control system of the air vehicle are designed and implemented. Brushless motor speeds are altered via electronic speed controllers in order to achieve desired controllability. The vehicle's fundamental Euler angles (*i.e.,* roll angle, pitch angle, and yaw angle) are obtained via AHRS sensor. These angles are provided as an input to the control algorithm that run on soft the processor on the electronic card. The vehicle control algorithm is implemented in the electronic card. Controller is designed and improved for each Euler angles. Finally, flight tests have been performed to observe and improve the flight characteristics.

Keywords—Quadrotor, UAS applications, control architectures, PID.

I. Introduction

QUADROTORS have a significant amount of market percentage in the commercial UAV market. In addition, the interest into quadrotors would continue to rise each year. Quadrotors are better in hovering, tracking of low speed targets, elimination of the runway need for take-off and landing, stability in windy weathers. On the other hand, these advantages come with the penalty in endurance reduction, since lift is provided via rotors, rather than lifting surfaces.

Quadrotor, as its name implies, is an aerial vehicle possessing four engines, but rotor number could be either four or eight. Equipped with the airborne high-precision sensors like laser range finder, onboard camera, global position system (GPS) receiver and so on, the UAV can execute much more complicated tasks, such as target localization and tracking [1], [2], three-dimensional (3D) reconstruction [3], environmental exploration and surveillance [4], military, search & rescue missions, disaster monitoring as well. The vehicle does not need to change the incidence angle of its propellers like conventional helicopters. Consequently, these benefits facilitate the design process in terms of aeromechanics. However, great attention should be paid during controller design since the translation and rotation of the vehicle is achieved by variation of rotor angular speeds. The designed and manufactured vehicle is shown in Fig. 1.

II. Architecture

A quadrotor system needs various airborne sensors to be able to fly autonomously, and one of these systems is AHRS (Attitude Heading Reference System). AHRS sensor is one of the essential part of the system, providing Euler angles by converting incoming data from sensors. AHRS system consists of accelerometer, gyro, and magnetometer sensors [5]. These Euler angle outputs are the input of the flight control algorithms to stabilize air vehicles.

Fig. 1 Designed and Manufactured Quadrotor

Brushless motors are widely used in servo robotic positioning actuators, traction, fans, and blowers due to their high reliability, high efficiency, low maintenance, and high cost efficiency [6]. Due to the given benefits, brushless motors have been chosen to propel the vehicle. In our design configuration, these motors are operated with delta connected three-phase alternating current. In fact, the direct current from Li-Po battery (DC current source) to the system is supplied to the motor after conversion to alternating current by the electronic speed controller (ESC). Single ESC is used for each quadrotor motor, and engine speed control could be achieved by PWM signal commands. One Altera's Cyclone III FPGA (field programmable gate array) is used as the main part of the system and a smart device. One soft processor called NIOS II is included by FPGA. Closed loop control algorithm is run over this processor. Furthermore, analog distance sensors are placed to the quadrotor’s arms to prevent hitting any place uncontrollably. The RF (radio frequency) communication module is used to manage quadrotor via a computer wirelessly. In short, the whole system is composed of the following components.

- Digital NIOS II soft processor,
- SRAM,
- E2PROM,
- AHRS,
- Analog distance sensors,
- Electronic speed controller,
- GPS receiver,
- MicroSD card (Memory unit for data storage),
- XBEE RF (for wireless communication),
- Li-Po Battery,
- Analog to digital converters (for distance sensor),

Eren Turanoğuz is with the Aselsan Inc., Ankara, Turkey (e-mail: erenturanoguz@gmail.com).
Ersan Aktas is with the Aselsan Inc., Ankara, Turkey.

- Graupner propellers 28x12.5 cm (thrust force producer for the system),
- Current transducer (for measuring consumed current),
- Command and control interface on the computer,
- Quadrotor mechanical frame,
- System test serial port interface,
- Brushless out-runner engines.

One of the essential considerations for the quadrotor frame is its weight and robustness. Light frame is essential for both endurance and controllability of the platform. Additionally, the frame must be resistant to the vibration emitted by the engines. Current engineering applications employ carbon fiber composite technology since it combines the desired mechanical properties, such as robustness and strength, with lightweight. In short, this type of material could be described as a melting pot. Therefore, the entire quadrotor frame is made of carbon fiber composites. In addition, the vibration-absorbing material have been employed where the frames were connected with the engines in order to reduce the vibration effect on the system as much as possible. Despite the imposition of the vibration-absorbing material, vibration sensitive instruments like AHRS could be still affected by the vibrations which are emitted by the motors. There are two AHRS in the system. One of the AHRS is placed on the electronic board. Especially, AHRS located on the electronic board has low sensitivity, and is separated from quadrotor frame with wire rope insulators. Other AHRS system with high precision, located on the top side of the plate is connected to the system with the rubber isolators in order to isolate from frame. Thus, the system control algorithm is kept away from the vibrations emitted by the engines at high angular speeds. After the completion of the mechanical frame, electronic board and computer interface software and various mechanisms are employed to test control algorithms. First, tests have been performed for the single-axis of the vehicle. For the given purpose, the vehicle is restricted in a way that it can be only rotated in a single axis. After achieving stabilization in one axis one by one, other test setup has been initiated. The final test setup, which is performed for three axes (roll, pitch and yaw), has the ability to move in all directions.

III. Theory

As depicted previously, a quadrotor platform could achieve its movement in three Euler axes by altering rotor angular speed. A simplified form of the acting forces on the quadrotor is described in Fig. 2.

In Fig. 2, thrust forces are shown in blue arrows, while green arrows describe the running direction of the propellers. Since the overall system is symmetrical, the total weight can be defined by a vector passing through the center of the system.

Assume that F1, F3, F2 and F4 are front, rear, right, and left rotor forces, respectively. In order to achieve displacement parallel to the ground, the equations F1 = F3 and F2 = F4 have to be satisfied. Thus, to progress forward, rear motor angular speed must be greater than that of in the front engine. On the other hand, for backward movement, angular speeds of the front and rear motors should be vice versa. To be able to move left side, right motor angular speed must be greater than that of in the left one. For right side displacement, the angular speeds of the rotors should be vice versa. The following assumptions were used to create a mathematical model for quadrotor [7]:

- Quadrotor structure is assumed to be rigid;
- Geometric center of the system coincidents with the center of mass of the system;
- The structure of the system is symmetrical;
- Lift and drag forces applied to propellers are directly proportional to the square of the angular velocities of propellers;
- Neglectance of friction of air;
- Neglectance of response delay times of the actuators and sensors.

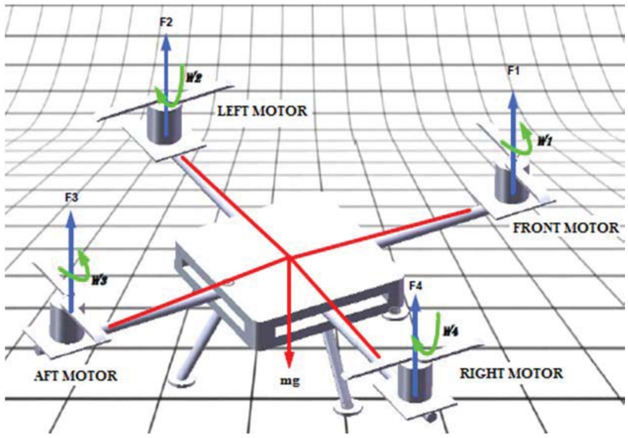

Fig. 2 Acting Forces on a Quadrotor Platform

Thrust could be described in terms of lift coefficient (b) and angular speed (Ω) [8]. Therefore, the force generated by each rotor could be expressed by:

$$F_i = b\Omega_i$$

Drag torque is an opposite torque, generated by applied force to the rotating propellers. The given moment is proportional to the square of the angular velocities of the rotors. Drag torque could be described in terms of drag coefficient (d) and angular speed (Ω) [8]. It is expressed by:

$$D_i = d\Omega_i$$

It is also necessary to define whole acting torques over the quadrotor for stabilization. These torques are created by propellers. Using one of the fundamental formulas of physics, one could define the net torque on each axis as:

$$\tau_\theta = L(F_1 - F_3)$$

$$\tau_\Phi = L(F_1 - F_3)$$

$$\tau_\psi = d\left(\left({\Omega_1}^2 + {\Omega_3}^2\right) - \left(\left({\Omega_2}^2 + {\Omega_4}^2\right)\right)\right)$$

where the term “L” defines the distance between the center of the quadrotor and propellers. In addition, the acting torque could also be found by the multiplication of inertial moment and angular acceleration. Angular accelerations for each axis could be described by using the following equations:

$$\ddot{\psi} = \frac{\tau_\psi}{I_{zz}}, \ddot{\theta} = \frac{\tau_\theta}{I_{yy}}, \ddot{\Phi} = \frac{\tau_\Phi}{I_{xx}}$$

where I_{xx}, I_{yy} and I_{zz} are moment of inertias for x, y and z axes respectively.

Angular acceleration or angular velocity is directly related with revolutions per minute (rpm) value of the motors. In the present study, the relation between motor rotational speed and thrust force is also obtained on the test setup. The first order transfer function in which the output is the angular velocity could be obtained in the following form:

$$S\omega(s) = B \times PID_{terms}\,(s)$$

$$\frac{Output}{Input} = \frac{\omega(s)}{PID_{terms}\,(s)} = \frac{B}{s}$$

The second order transfer function in which the output in which the output is the angular velocity could be obtained as:

$$S\Phi(s) = B \times PID_{terms}\,(s)$$

$$\frac{Output}{Input} = \frac{\Phi(s)}{PID_{terms}\,(s)} = \frac{B}{s^2}$$

IV. Controller, Hardware and Software

In the present study, a PID control algorithm has been implemented in the quadrotor controller system (Control System, 2012). Impact of the PID controller parameters of the controller system on the above-mentioned systems is analyzed, then controller has been tested and validated on the real system. Analyzes were conducted in the control toolbox of MATLAB/Simulink environment. As it can be deduced, the convergence of the output to desired values is better when the order of the transfer function is higher. Second order systems reach an agreement between accuracy and simplicity with respect to the low and higher order systems.

$$H(s) = \frac{K{W_n}^2}{s^2 + 2\zeta W_n s + {W_n}^2}$$

Usual expression of a second-order transfer function of the system is given in the above equation. Here, K indicates DC gain of the system. ζ term is referred to the damping ratio of the system. W_n could be referred as the natural frequency of the system. While $\zeta = 0$, system continuously oscillates at the natural frequency of the system.

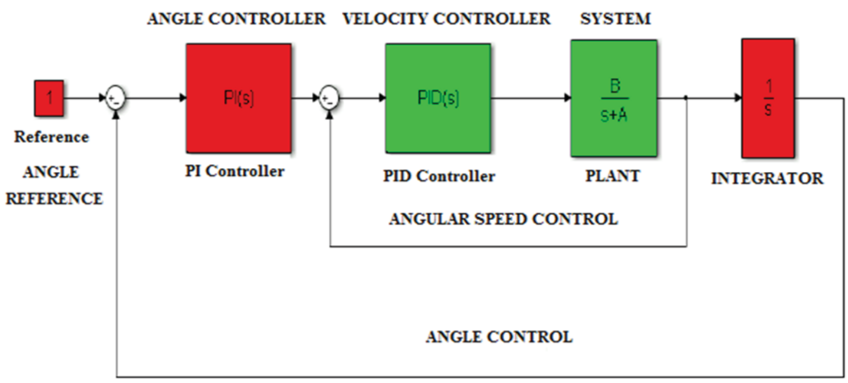

Fig. 3 Quadrotor System and Nested Control Loop

The PID controller output in time domain could be described in:

$$u(t) = K_p\, e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

where e(t) is the error signal, u(t) is the controller output, and K_p, K_i, and K_d are the controller coefficients for proportionality, integral, and derivative terms, respectively. System gets feedback from output of the system, then the feedback value is subtracted from the reference value, and the error signal is calculated. This error signal is used in three different terms. The first term is the proportional term. Error signal is multiplied by this proportional term. The second term is the integral term. Integral of the error signal is obtained, and the result is multiplied by an integration coefficient. The third term is the term of the derivative. A derivative of error signal is calculated, and then result is multiplied by a derivative term. These three terms are summed to obtain the controller output that is given to the plant input. For each individual axis (roll, pitch, yaw) a PID controller is designed. The main nested control loop diagram of the quadrotor is presented in Fig. 3. In addition, controller structure for Euler angles and the step responses are given in Figs. 4-9.

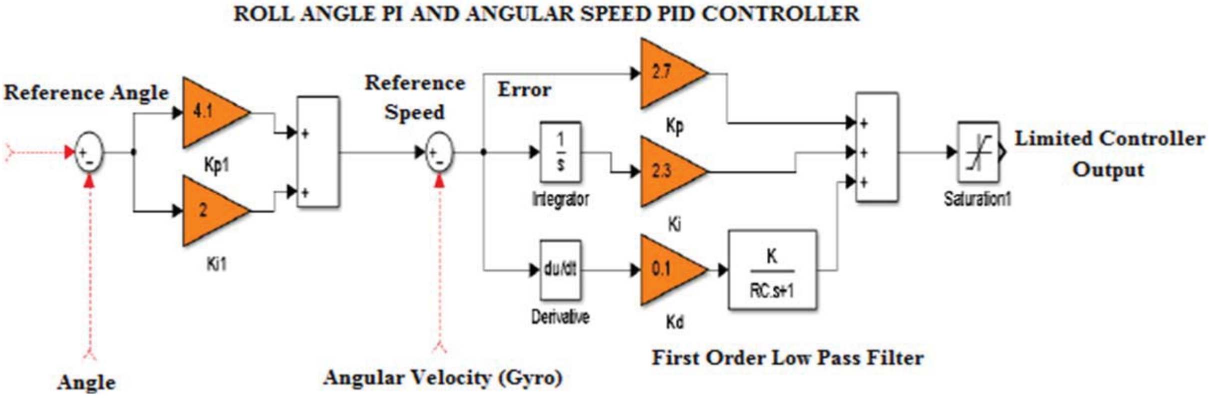

Fig. 4 Quadrotor Roll Axis Controller

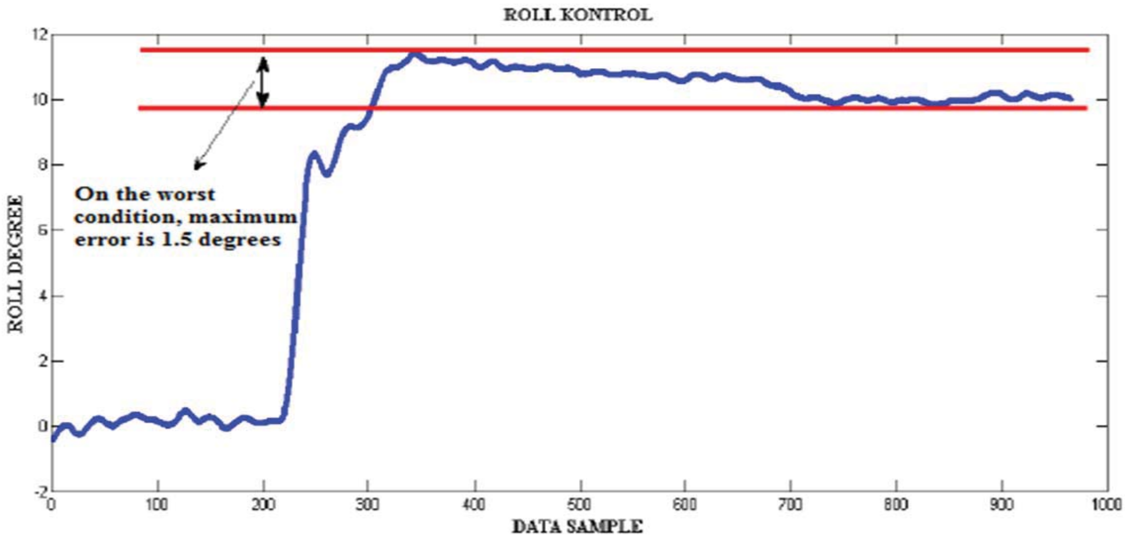

Fig. 5 Quadrotor Roll Axis Step Response

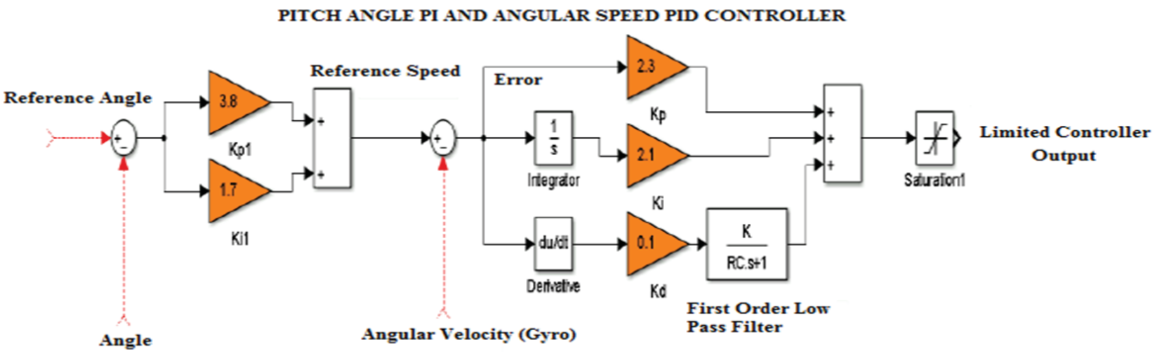

Fig. 6 Quadrotor Pitch Axis Controller

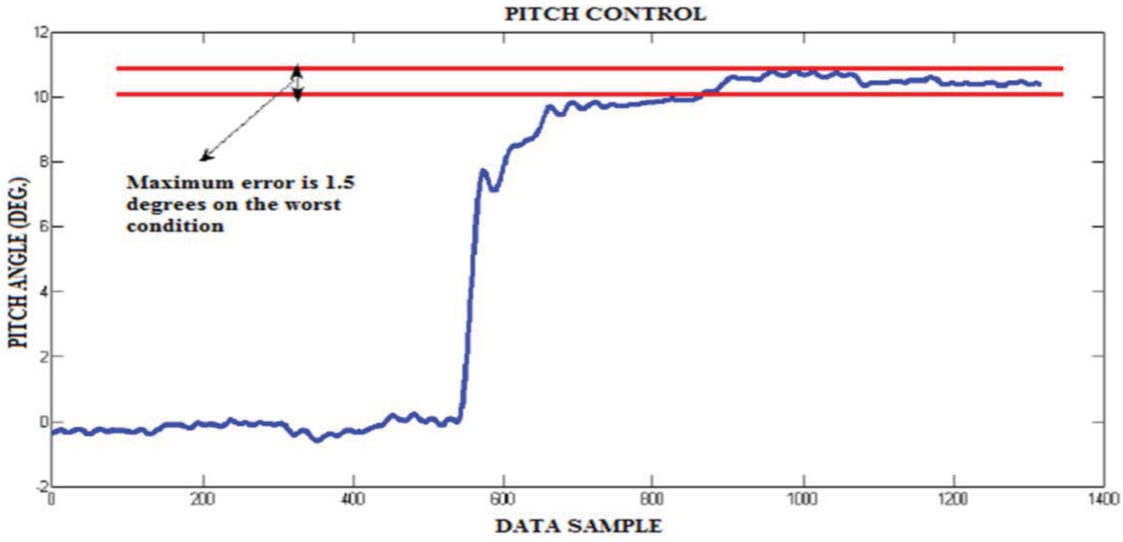

Fig. 7 Quadrotor Pitch Axis Step Response

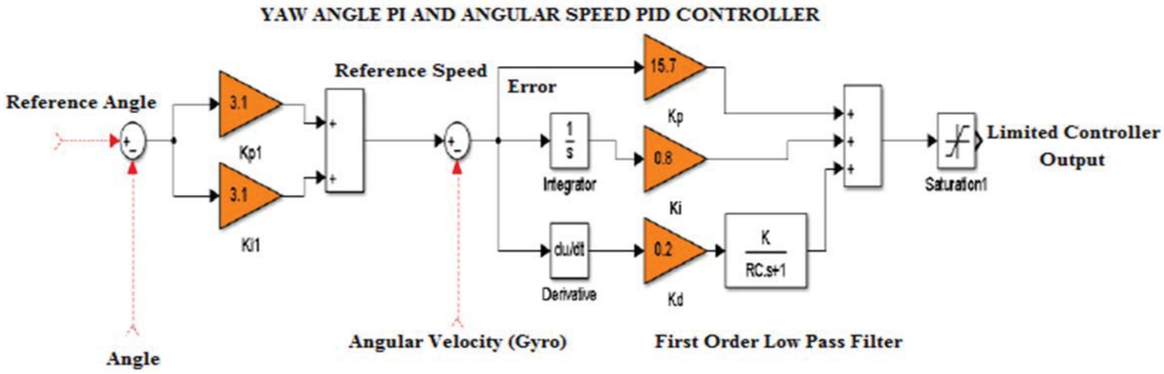

Fig. 8 Quadrotor Yaw Axis Controller

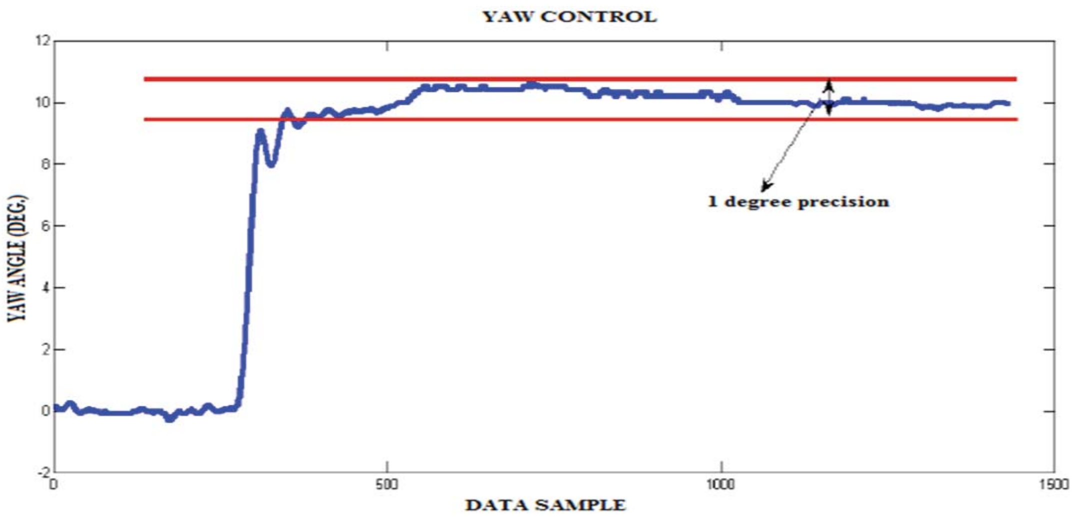

Fig. 9 Quadrotor Yaw Axis Step Response

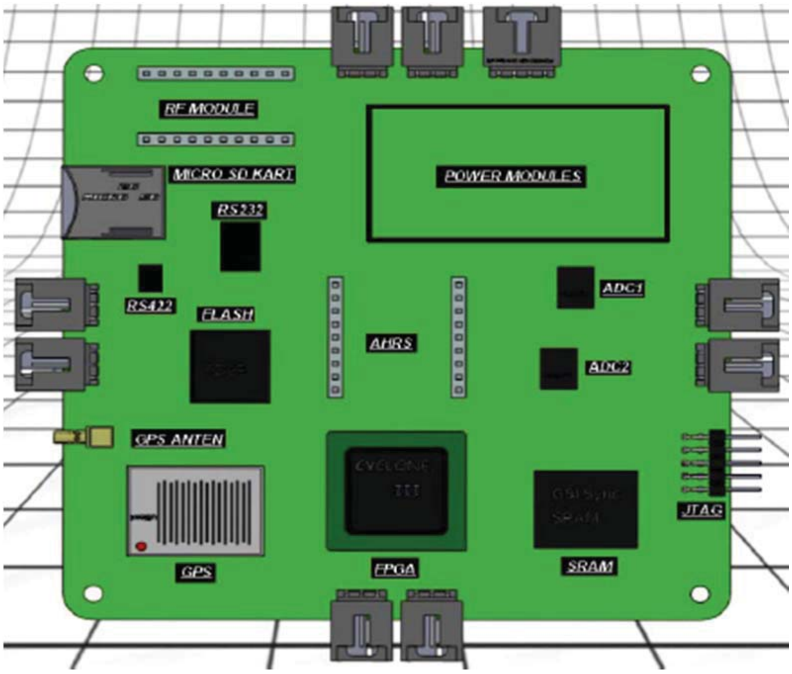

Fig. 10 Autopilot Board Computer Aided Drawing

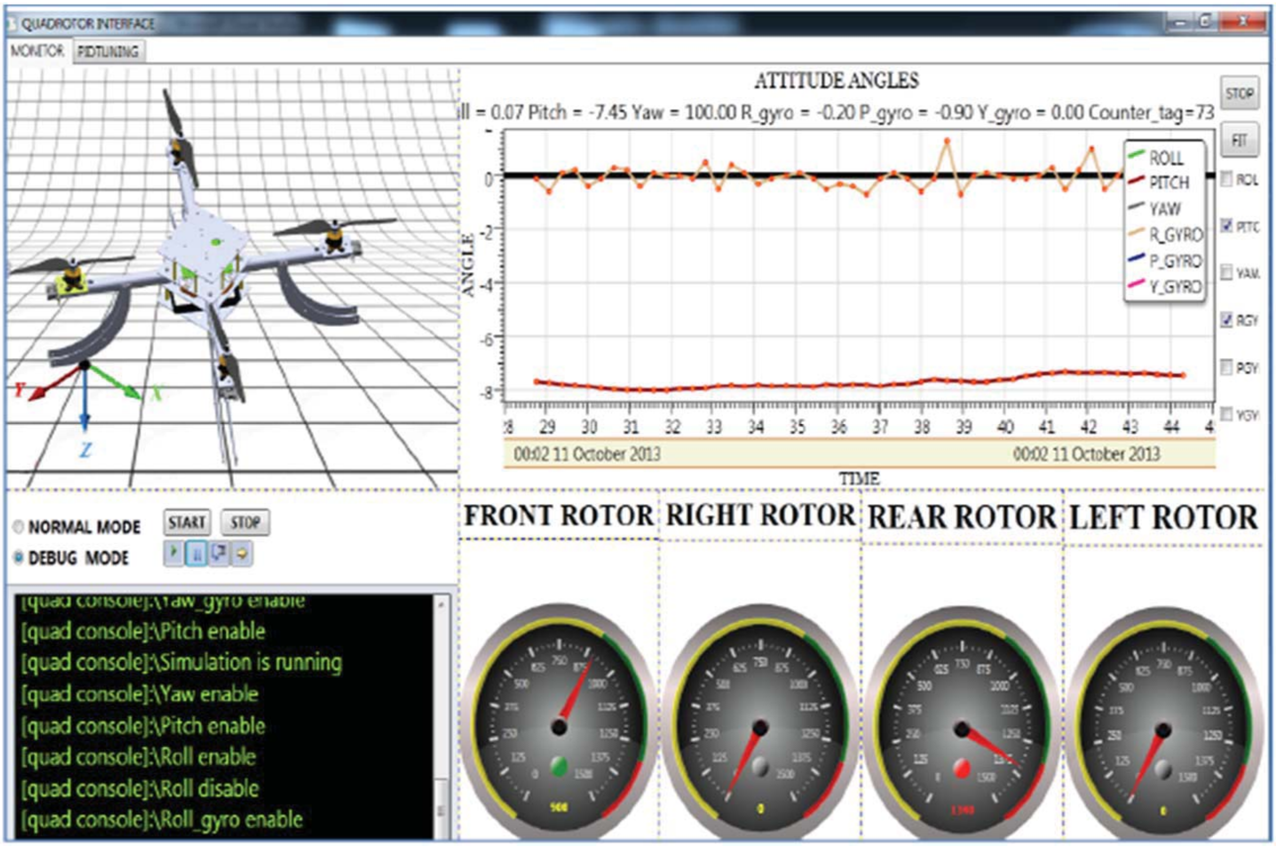

Fig. 11 Genuine Quadrotor Interface

One of the essential hardware of the quadrotor system is the autopilot board in which the remaining devices communicate among them through this board. Cyclone III FPGA produced by Altera is used as smart device in this board [9].

Synchronous SRAM GS832136GE is used as RAM. The software code runs on this ram. FPGA configuration data and software code are stored in the serial flash called as EPCS64 [10]. Quadrotor position information is received from GPS UBLOX LEA6T which communicates with the processor via the RS232 protocol [11]. System data are stored on the microSD card. For testing purposes, two LEDs are located onto the autopilot board. 3.3V to 5V level shifters are used to provide connection between FPGA pins and electronic speed controllers. The oscillator of FOX firm, coded as FXO-HC536R-20, is used in the board. Operating frequency is set as 20 MHz. Current transducer is used to measure the current draw of the system. Computer aided drawing of the Autopilot board is given in Fig. 10.

Quadrotor computer interface is used for motion control, system data monitoring and recording of system data. Quadrotor interface is written as a WPF (Windows C # language) environment. Euler angles and angular velocities of the quadrotor are shown in the graphs in real time. Engine rpm values are shown in rpm gauges for each run times. Quadrotor displacement can be shown in three dimensions. The genuine interface for the application is shown in Fig. 11.

In the second section of the genuine quadrotor interface, controller coefficients can be altered while the quadrotor is active.

V. Conclusions

In the present study, a quadrotor unmanned aerial vehicle is designed and balanced in free space. This study consists of the creation of the skeleton of the structure of carbon fiber and related equipment, design and realization of FPGA-based autopilot board, preparation and implementation of PID control algorithm, and user interface program.

The advantages of the use of short-circuit protections autopilot board and the importance of real-time data record has been revealed. The effect of the PID controller parameters on the system has been observed experimentally. In the axis position control, a single closed-loop position control has been tested at the first stage.

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