Qatar University First Generation of Autonomous Quadrotor Platform for IARC Competition

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ABSTRACT

This paper discusses the design and development of a quad-rotor platform for the International Aerial Robotics Competition (IARC) that is to be held in the summer of 2013. The paper is about the design of a quad-rotor that, in addition to being stable at the time of flight, is able to hover autonomously, recognize and pick objects as per its requirement. A considerable amount of research was done in order to choose methodologies and controlling techniques that would be feasible for the project. A number of achievements have been made, including the design and implementation of different parts of the quad-rotor, such as the power distribution board, controller board, sensors for attitude and height sensing, and wireless communication setups for remote control over-ride purposes. In addition, a pre-fabricated controller board is experimented on and attempts are made to control the quad-rotor wirelessly through a PC, for the sake of using this methodology as a parallel plan (Plan B) for the competition.

I. INTRODUCTION

The aim of this project is mainly to represent Qatar University in the International Aerial Robotics Competition (IARC) in 2013. The competition is basically all about designing an autonomous UAV capable of undertaking a certain "mission". The objective is to design and develop a quad-rotor capable of hovering autonomously in an unknown environment, identifying and obtaining a certain object to accomplish the mission.

The plan is to use a quad-rotor equipped with a robotic arm that holds the ability to pick things up. The quad-rotor will implement simultaneous localization and mapping SLAM to find its way in the competition, however hardcoding the quad-rotor path will also be used as an alternative navigation method. The estimation of the position and orientation of the quad-rotor is transmitted and logged on to a ground station that in turn graphically presents and maps the UAV's location. Transmission is done wirelessly through a Wi-Fi ad-hoc module for a higher data transmission rate. The ground station also has limited control over the UAV. As per the guidelines of the competition, the UAV can be controlled by a remote controller that can over-ride the autonomous flying mode of the UAV. Also a kill switch was designed with the purpose of instantly cutting off power of the UAV in case of unpredictable and risky behavior. The link between the kill switch and the UAV is made through an RF module known as the Xbee chip. Figure 1 shows a diagram for the overall quad-rotor system.

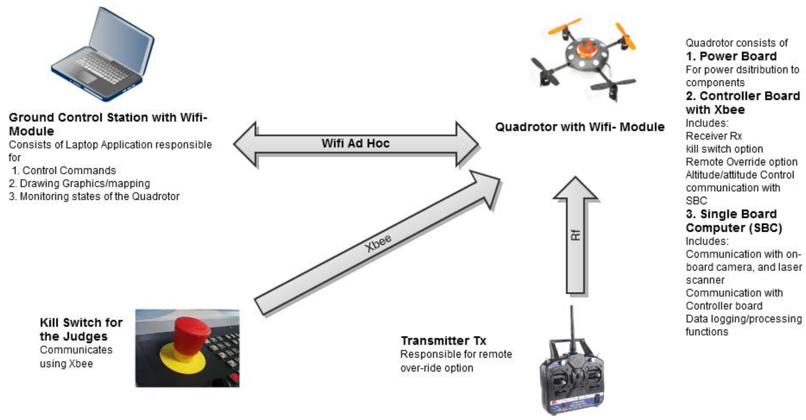

Figure 1: Representation of the general plan.

II. AIR VEHICLE

The main frame for the quad-rotor is the AeroQuad Typhoon frame made of aluminum and its structure ensures that the electric speed controllers (ESCs) used to drive the motors are covered and protected from damage [1]. The selected brushless DC motors are A2212-13 Motors [2]. In order to operate, the brushless DC motors need ESCs. The ESCs used for this project are the Plush 18A Brushless TURNIGY BASIC Speed Controllers [3]. The propellers used for this project are the APC 8x3.8 Propellers [4].

A. Guidance, Nav., and Control

Stability Augmentation System

A PID controller is used to stabilize the quad-rotor because of its ease of implementation and simplicity. The PID controller used in the project stabilizes the quad-rotor by ensuring that the Euler angles are steady at zero degree. The controller is implemented within AVR 32bit AT32UC3C0512C microcontroller (MCU). Figure 2 shows the basic structure of the quad-rotor which will be used to illustrate the control process.

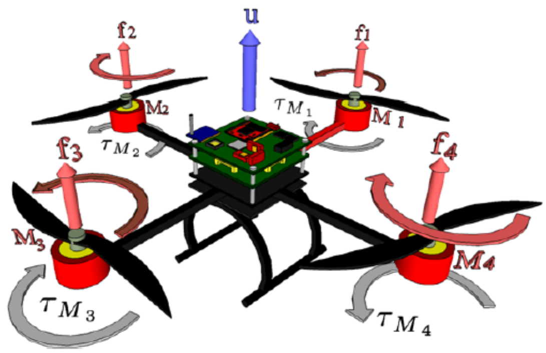

Figure 2 Basic structure of the quad-rotor [5].

If motor number 1 M1 specifies the front direction of the quad-rotor, then controlling the pitch angle is done via controlling the motors M1 and M3. Since each motor with its propeller produces a vertical force by pushing the air downwards, the pitch torque will follow equation (1) [6].

$$\tau_{pitch} = l(F_3 - F_1) \tag{1}$$

where l is the arm length, similarly, controlling the quad-rotor roll angle is done via controlling the speed of the motors M2 and M4. The roll torque will follow equation (2) [6].

$$\tau_{roll} = l(F_2 - F_4) \tag{2}$$

Notice that the order of the forces in these equations depends on the quad-rotor axis. To control the yaw angle, two motors must rotate faster than the others. For a downward positive z-axis and clockwise positive yaw angle the yaw torque will follow equation (3) [6] Notice that the yaw torque is also proportional to the air drag coefficient.

$$\tau_{yaw} = -\tau_1 + \tau_2 - \tau_3 + \tau_4 \tag{3}$$

The summation of forces produced by all the motors should be fixed since it will determine the altitude of the quad-rotor. This fixed value is the thrust and it follows equation (4) [6].

$$F_t = F_1 + F_2 + F_3 + F_4 \tag{4}$$

Since the relationship between the force and speed of each motor connected to a propeller is governed by equation (5).

$$\mathrm{Fm} = \mathrm{k} \times \Omega^2 \tag{5}$$

where Ω is the speed of the motor in rad/s and k is the thrust coefficient. Solving for the speed in the equations (1) to (5) will give the speed controlled speed of each motor at any time. The solution for these equations is as follow:

$$\Omega_1 = \sqrt{\frac{C}{4b} + \frac{U_{yaw}}{4d} - \frac{U_{pitch}}{2bl}} \tag{6}$$

$$\Omega_2 = \sqrt{\frac{C}{4b} - \frac{U_{yaw}}{4d} + \frac{U_{roll}}{2bl}} \tag{7}$$

$$\Omega_3 = \sqrt{\frac{C}{4b} + \frac{U_{pitch}}{2bl} + \frac{U_{yaw}}{4d}} \tag{8}$$

$$\Omega_4 = \sqrt{\frac{C}{4b} - \frac{U_{yaw}}{4d} - \frac{U_{roll}}{2bl}} \tag{9}$$

Notice that the output of the PID controller is the torque for each of the different angles: Pitch, Roll, and Yaw. An outer control loop is used to control the quad-rotor position. The outer loop read the quad-rotor position and altitude using simultaneous localization and mapping and from a Sonar sensor respectively. It controls the quad-rotor position by controlling the reference angle given to the inner control loop.

Navigation

There are two ways for the quad-rotor to navigate its way in its environment. These are using a remote control or using a computer module which guides the quad-rotor. For the first method, the "Orange Rx DSM2" receiver [7] and "Spektrum DX4" remote control [8]. The quad-rotor is expected to be capable of doing on-board computations to know its location and guide itself, and also to identify the objects around it. For this reason the Beagleboard xM single board computer SBC was brought. The Beagleboard xM has all the functionalities of a basic computer and its laptop-like features and small size make it very suitable for the UAV [9]. The computer module communicates with the microcontroller through UART protocol and the microcontroller will communicate with the group station using a WiFi module. Moreover, a robotic arm and a sonar sensor are also connected to the microcontroller. Figure 3 shows the overall main system structure.

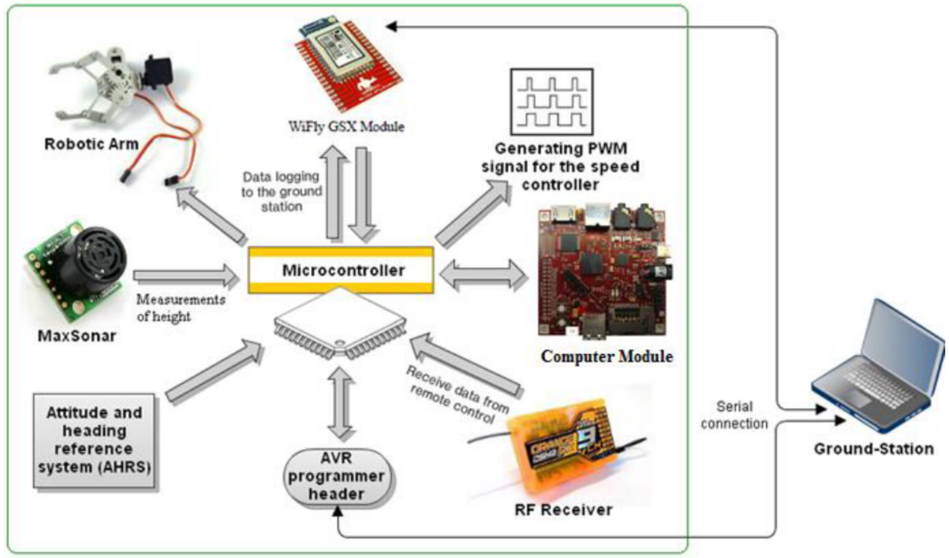

Figure 3: The Overall main Control System Structure.

The quad-rotor termination unit is composed of an Xbee module. The module has a feature called "IO Passing". With this feature, a specific general purpose pin in one module (that is bound to a second module) can pull up or down the same pin on the other module. This feature is used in the design of a "kill switch" for the quad-rotor. The details of how this module was used to cut the powr off the motors are disscussed in the power management section.

III. PAYLOAD

A. Sensor Suite

A very important element of the controller board is the Attitude and Heading Reference System (AHRS). This is an ultra miniature orientation sensor that combines rate gyros, accelerometers, and magnetometers to measure the orientation of the quad-rotor. The chip used for this purpose is called "UM6-LT". The communication with this chip is done through SPI protocol with a clock rate of 400kHz [10].To measure the altitude between the quad-rotor and ground, a high performance sonar module is used. The sonar chosen for this task is LV-MaxSonar-EZ0 which has a detection range from 0 m to 6.45 m [11]. The need of a device that detects surroundings of the UAV so it can map and locate itself led to the installation of an on-board laser scanner. Hokuyo URG-04LX-UG01 laser scanner was chosen because of its small size and light weight (160g) [12].

B. Communications

The microcontroller will communicate with the ground station through a Wi-Fi module called "WiFly GSX" [13]. The module has a transmission data rate of 1 Mbps and it can be configured via

UART or SPI using simple ASCII commands. The module works as a fully standalone wireless LAN device that has an on-board TCP/IP stack.

C. Power Management System

A special circuit was built to manage the flow of power to the motors and to give an alarm that the battery voltage is too low. The low voltage alarm system consists of a comparator circuit, oscillation circuit, and a buzzer. The comparator is built using an op-amp that takes the battery voltage through a voltage dividing circuitry in the non-inverting terminal and a regulated 5v in the inverting terminal. A potentiometer is connected to the non-inverting terminal to control the tolerance of the alarm unit. The comparator is designed so that whenever the battery voltage gets below 10 voltage then the output voltage of the comparator will change from the actual battery voltage to zero volt. This action will turn on (change from cut off to saturation region) the P-channel transistor connected to the 555 timer circuitry. The capacitor and resistors connected to the 555 timer chip were chosen to provide a signal with a frequency of 4650 Hz:

$$f = \frac{1}{\ln(2)xCx(R1+2R2)} = \frac{1}{\ln(2)x0.22uFx(470+2x470)} = 4650.8Hz \tag{10}$$

This frequency was chosen to get the highest sound pressure from the buzzer which has the sound pressure to frequency relationship given in the buzzer datasheet. The output signal of the timer chip goes to a transistor that turns on the buzzer. The buzzer circuitry will produce an alarm-like sound to indicate that it is important to stop the quad-rotor and replace the battery. The power cut system consists of an opto-coupler that isolates the controller board signal from the rest of the circuit. The resistors connected to the anode pin of the opto-coupler were chosen to limit the current supplied from the microcontroller in the controller board. The output of the opto-coupler is connected to the gate of a power transistor which will control the flow of current to the motors. The led connected to the opto-coupler is used to indicate whether the transistor is delivering power to the motors or not. The opto-coupler circuitry will decide whether to turn on and off the quad-rotor motors based on the signal arriving to it from a 3-state buffer circuitry explained later. This signal should come from two different units, these are the microcontroller and the quad-rotor killing unit. However, the priority is for the killing unit to decide whether to allow the power to flow to the quad-rotor motors or not. To achieve this objective, an octal 3-State Non-inverting Line Driver/Line Receiver chip is used. The chip name is MC74HCT244ADT and it gets its input signal from the microcontroller and give it as an output signal if the chip is enabled via the active low pin OE. This bin is connected to the killing unit which will give it the priority to either allow the power to flow to the motors or not. The overall schematic is shown in Figure 4.

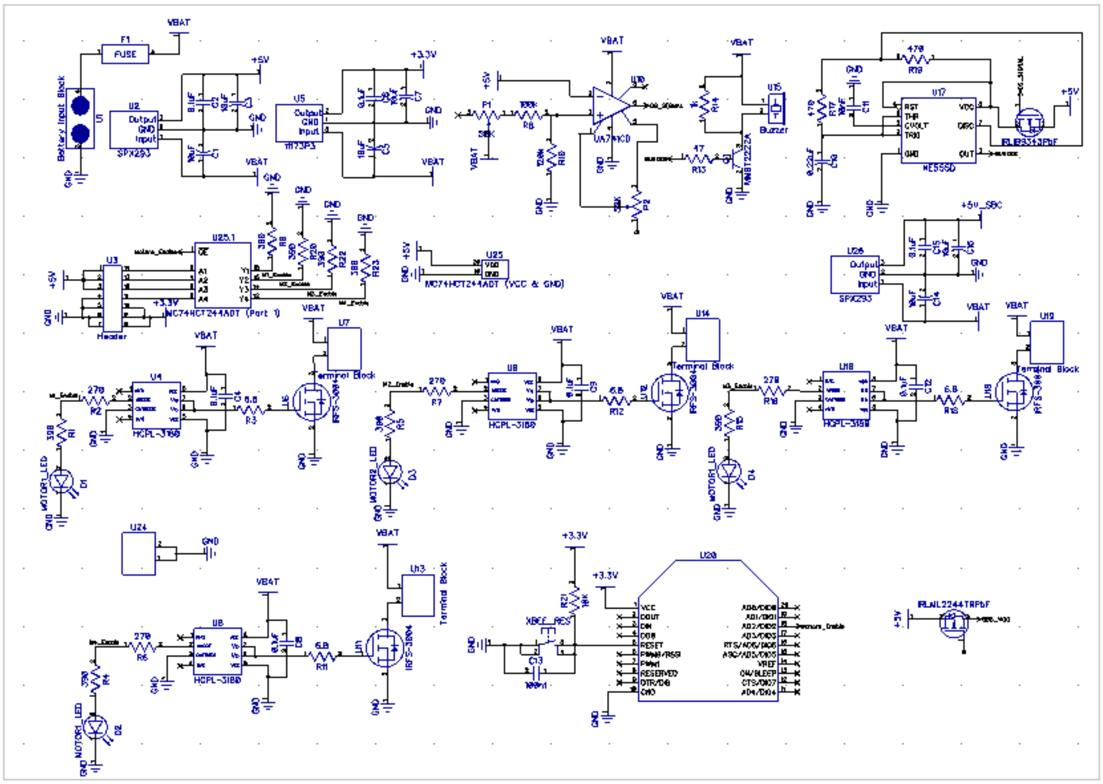

Figure 4: Power Management circuitry.

IV. VIECHILE 2

Along with the main Quad-rotor platform, a side-task or a parallel plan that can be thought of as a back-up plan for the completion was considered. Unlike the original plan of designing a controller board from scratch, this aspect of the project involved the use of an off-the-shelf controller board. A board by the name of PX4 Flight Management Unit (PX4FMU) was chosen. It is developed as part of the PIXHAWK Project by the Swiss Federal Institute of Technology [14]. The PX4FMU is an auto-pilot, which basically means that it is a system that is able to guide a vehicle (in this case a UAV) without the assistance of a human being. The communication between this board and the ground station is done via Xbee module.

V. RISK REDUCTION

A. Modeling and Simulation

The dynamic model of the quad-rotor is achieved using two methods; the Newton-Euler technique and the Lagrange-Euler formalism. These methods are used to derive dynamic models of various types of systems, and are used extensively in the area of robotics. Before presenting the quad-rotor model, the earth frame ($\mathcal{F}^e$) and body fixed frame ($\mathcal{F}^B$) should be defined. The earth coordinate system, sometimes called inertial frame, is a reference frame in which the law of inertia, Newton's first law, holds [15]. Figure 5 shows the earth coordinate frame in which the x-axis points toward the North, the y-axis points toward the East, and the z-axis points into the Earth.

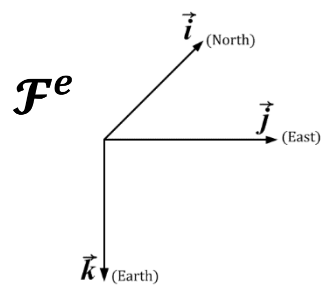

Figure 5 The Earth coordinate frame

Body-fix frame means that the origin and the axes of the coordinate system are fixed with respect to the geometry of the rigid body. Hence, it is convenient to express the rotations of the quad-rotor whose origin is located at the centre of gravity. The way to go from the Earth frame to the body-fixed frame and the rotation matrix relating the two was mentioned before. Figure 6 shows the quad-rotor's body-fixed frame, where the x-axis points toward the nose of the quad-rotor, the y-axis points out the right wing, and the z-axis points toward the belly.

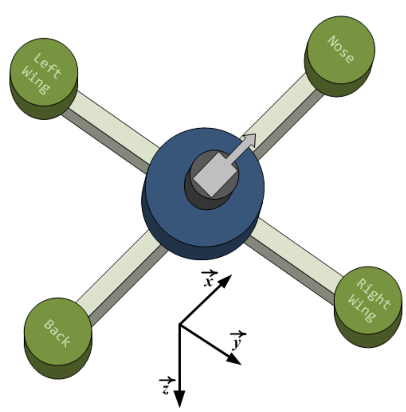

Figure 6 The body frame.

As it has been mentioned earlier, the Newton's second law is only hold in the Earth frame; since $\mathcal{F}^B$is rotating with respect to the reference frame $\mathcal{F}^e$, the acceleration in one frame cannot be directly used in the other one.

Since the states of any system are not unique, they need to be defined. The twelve state variables of the quad-rotor are defined as follows:

$\boldsymbol{p_n}$: The position of the quad-rotor in the inertial frame along $\overrightarrow{\imath^E}$ pointing toward north,

$\boldsymbol{p_e}$: The position of the quad-rotor in the inertial frame along $\overrightarrow{\jmath^E}$ pointing toward east,

$\boldsymbol{h}$: The position of the quad-rotor in the inertial frame along $\overrightarrow{k^E}$ opposite to Earth,

$\boldsymbol{u}$: The velocity of the quad-rotor in the body-fixed frame along $\overrightarrow{\imath^B}$,

$\boldsymbol{v}$: The velocity of the quad-rotor in the body-fixed frame along $\overrightarrow{\jmath^B}$,

$\boldsymbol{w}$: The velocity of the quad-rotor in the body-fixed frame along $\overrightarrow{k^B}$,

$\boldsymbol{\varphi}$: The roll angle as defined in section 2.1,

$\boldsymbol{\theta}$: The pitch angle as defined in section 2.1,

$\boldsymbol{\psi}$: The yaw angle as defined in section 2.1,

$\boldsymbol{p}$: The roll rate in the body frame measured along $\overrightarrow{\imath^B}$,

$\boldsymbol{q}$: The pitch rate in the body frame measured along $\overrightarrow{\jmath^B}$,

$\boldsymbol{r}$: The yaw rate in the body frame measured along $\overrightarrow{k^B}$.

Thus the complete model describing the quad-rotor is obtained using equations 11, 12, 13, and 14.

$$\begin{pmatrix} \dot{p_n} \\ \dot{p_e} \\ \dot{h} \end{pmatrix} = \begin{pmatrix} c\,\theta\, c\,\psi & c\,\psi\, s\,\theta\, s\,\phi - s\,\psi\, c\phi & c\,\psi\, s\,\theta\, c\,\phi + s\,\psi\, s\phi \\ c\,\theta\, s\psi & c\,\phi\, c\,\psi + s\,\psi\, s\,\phi\, s\,\theta & s\,\psi\, s\,\theta\, c\,\phi - c\,\psi\, s\phi \\ -s\,\theta & c\,\theta\, s\,\phi & c\,\theta\, c\phi \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} \tag{11}$$

$$\begin{pmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{pmatrix} = \begin{pmatrix} rv - qw \\ pw - ru \\ qu - pv \end{pmatrix} + \frac{1}{m} \begin{pmatrix} f_x \\ f_y \\ f_z \end{pmatrix} \tag{12}$$

$$\begin{pmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 & \sin(\varphi)\tan(\theta) & \cos(\varphi)\tan(\theta) \\ 0 & \cos(\varphi) & -\sin(\varphi) \\ 0 & \sin(\varphi)\,/\cos(\theta) & \cos(\varphi)\,/\cos(\theta) \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix} \tag{13}$$

$$\begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} \frac{(I_y - I_z)}{I_x} qr \\ \frac{(I_z - I_x)}{I_y} pr \\ \frac{(I_x - I_y)}{I_z} pq \end{pmatrix} + \begin{pmatrix} \frac{\tau_\varphi}{I_x} \\ \frac{\tau_\theta}{I_y} \\ \frac{\tau_\psi}{I_z} \end{pmatrix} \tag{14}$$

The control inputs to the system are the forces expressed in the body frame, as well as the input torques generated by the propellers.

B. Testing

The testing bench shown in Figure 7 was designed and built to test the quad-rotor's performance before flying it. The bench is made in such a way to allow us to test the PID controller for the Pitch and Roll angles separately.

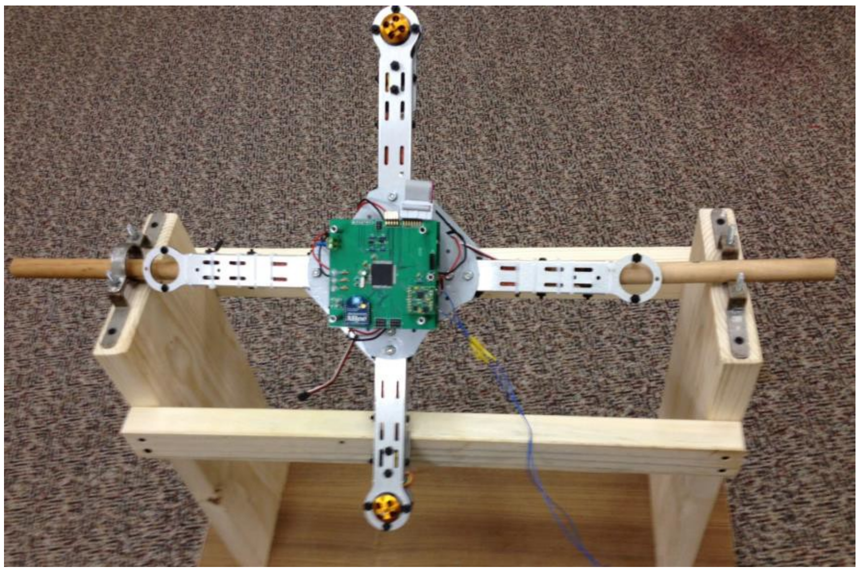

Figure 7 Testing bench for Roll and Pitch angles.

Different PID constants were used to tune to the controller. Figure 8 shows the variation of Pitch angle and Pitch torque with time for a Pitch derivative constant of 2, Pitch integral constant of 0.5, and Pitch proportional term of 55. However, since the thrust coefficient was not found accurately, it is not possible to say that thrust value used in the test has a unit of Newton. But that has no effect over the performance of the controller. Figure 8 shows the variation in the Pitch angle after implementing the controlling loop for a starting angle of 23 degrees. The figure also shows the change in the Pitch torque which is the output from the Pitch PID controller.

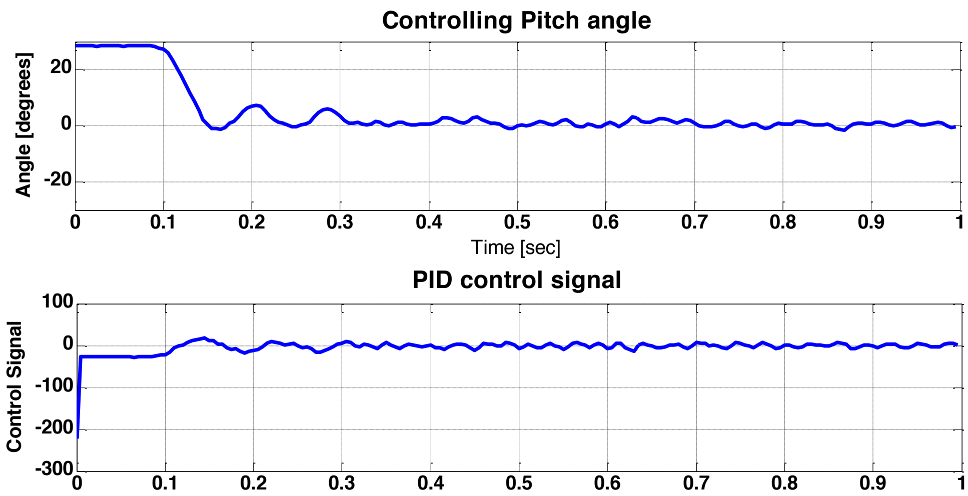

Figure 8 Tuning Pitch control loop.

Figure 9 also shows the performance of the Roll control loop with the same PID constant terms mentioned before.

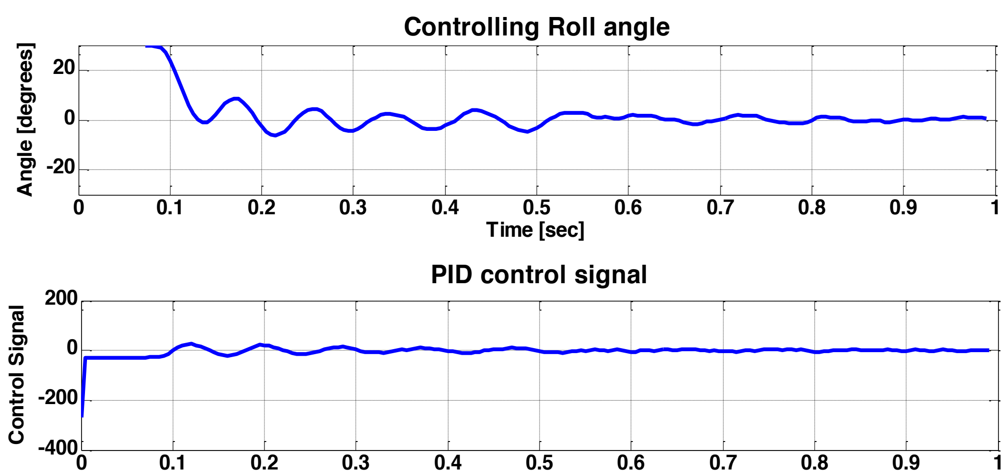

Figure 9 Tuning Roll PID controller.

VI. CONCLUSION

The overall quad-rotor system is ready and finalized, but a proper tuning for the PID controller is yet to be achieved. The main aim to participate in the IARC competition this year is learn from other teams how they designed and built their vehicles and also to study the behavior of our quad-rotor in an actual test.

VII. References

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