QUAD ROTOR DESIGN, SIMULATION AND IMPLEMENTATION

W. M. Hussein **M. M. El-khatib** **A. Y. Elruby** **H. M. Haleem**
Egyptian Armed Force, Egypt *Arab Academy for science and Technology, Egypt*
wessam.hussein@gmail.com elkhatib.m@gmail.com roubi12@hotmail.com neo2k_al@hotmail.com

Abstract: Unmanned Aerial Vehicles (UAVs), also called unmanned aircraft systems, have recently reached unprecedented levels of growth in diverse military and civilian application domains.The goal of this paper is to design and construct a quadrotor that is capable of indoors and outdoors hovering using a Mechatronics system for flight stability and navigation aspects using gyros, accelerometers, pressure sensor, and GPS.Through working on this paper mathematical models had been studied, a CAD model had been built for estimating mass and inertial properties of the physical model, a Simulink had been implemented for estimating the response of flight dynamics, and finally a physical model had been built as a prototype for the UAV.

Keywords: Quad rotor, UFO, UAV, unmanned aircraft system .

1. INTRODUCTION

A Quadrotor is a rotary-wing UAV that has been the subject of several recent research projects. Small quad rotors have many exciting potential missions including flight indoors and in dense urban areas. However, the development of the control systems needed to fly these vehicles can be very challenging perception based actions [1]. A Quadrotor has four rotors and requires no cyclic or collective pitch. A Quadrotor UAV can be highly maneuverable, has the potential to hover and to take off, fly, and land in small areas, and can have simple control mechanisms. However, because of its low rate damping, electronic stability augmentation is required for stable flight. A Quadrotor has four motors located at the front, rear, left, and right ends of a cross frame, as shown in Figure 1.

The Quadrotor is controlled by changing the speed of rotation of each motor. The front and rear rotors rotate in a counterclockwise direction while the left and right rotors rotate in a clockwise direction to balance the torque created by the spinning rotors.

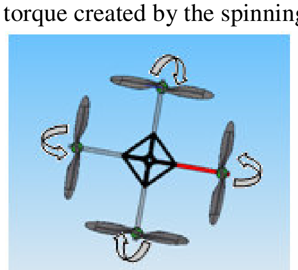

Figure 1 Drawing of a Quadrotor showing direction of motor rotation

A Quadrotor has some advantages over other rotary-wing UAVs. It is mechanically simple and is controlled by only changing the speed of rotation for the four motors. Since the yaw rate is controlled by changing motor speed, a tail rotor is not required to control yaw rate and all thrust can be used to provide lift [2].

A Quadrotor may also be able to fly closer to an obstacle than conventional helicopter configurations that have a large single rotor without fear of a rotor strike. The vehicles dynamics are good for agility and its four rotors can allow increased payload. Another advantage of a Quadrotor is that minimal cross-coupling simplifies the Quadrotor dynamics.

However, the dynamics of the Quadrotor and specifically its low rate damping can make the vehicle difficult to control. The challenge of controlling the vehicle can be even more difficult for a small, low cost Quadrotor.

2. SYSTEM DYNAMICS, MODELING, AND NAVIGATION ASPECTS

Dynamic attitude model was derived from Newton's Laws. The gyroscopic Procession of each rotor cancels out due to the counter-rotating pairs, which removes any coupling between the pitch and roll dynamics. Due to the low rotor inertia relative to the craft's rotational inertia, the response of the electric motor was faster than the attitude dynamics, so the motor response was neglected in this model. The total collective thrust F_T is the sum of all four rotor forces as in Eq.(1)[3]. (Subscripts are T = Total, F = Front, B = Back, L = Left, R = Right)

$$F_T = F_F + F_B + F_L + F_R \qquad (1)$$

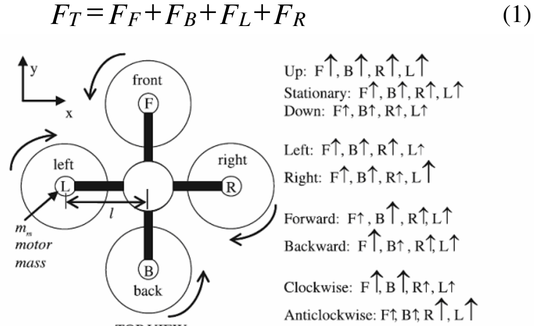

Figure 2: Plus configuration for flight control (size of arrow is proportional to thrust)

This collective thrust is nominally equal to the gravitational force when hovering; however, it can be varied by the pilot with the throttle input up to a maximum of($2\times F_g$), due to the 2:1 thrust/weight ratio. When quad rotor is in a stationary hover, F_T equals the weight force of the entire aircraft due to gravity.

2.1 Yaw dynamics

A quad rotor has two sets of counter-rotating propellers; therefore, the net yaw moment generated from aerodynamic drag is cancelled out in neutral flight. This eliminates the need for a tail rotor that normally wastes 12% of the power in a conventional helicopter. Furthermore, a yaw moment is induced on a quad rotor by proportionally varying the speeds of the counter-rotating pairs. The thrust variation V_ψ is given by [3]:

$$V_\psi \le \frac{\tau_{max}}{k} \tag{2}$$

$(k = 2\, or\, 4\, to\, avoid\, motor\, saturation, \tau_{max} = max.Torque)$

From $\tau_\psi = I_z \times \ddot{\psi}$, where I_z is the mass moment of inertia and yaw acceleration is [8]

$$\ddot{\Psi} = \frac{\tau_\psi}{I_z}(\, where\ \psi = Yaw\ angle\ ) \tag{3}$$

Yaw moment is the sum of all rotor torques (CW = Clockwise, CCW = counterclockwise)

$$\tau_\psi = \sum \tau_r = \tau_{CW} - \tau_{CCW} = (\tau_L + \tau_R) - (\tau_F + \tau_B) \tag{4}$$

In Fig. 2, the magnitudes of thrust forces are set so that $F_L = F_R$ are both larger than $F_F = F_B$. The increased drag of the motors with higher thrust will create a net reaction moment that will rotate the body in one yaw direction. Similarly, the body can be rotated in the opposite yaw direction by reversing the relative magnitudes of the above pairs of thrust forces. Note that during yaw movement of the quad rotor $\tau_\psi \ne 0$ (net torque on the body), i.e. the sum of reaction moments is non-zero. When the quad rotor body is not rising or dropping in altitude, the sum of all thrusts equals the weight force due to gravity. The torque on each rotor, caused by aerodynamic drag, is proportional to the thrust by a scalar constant k_τ

Therefore, Equation (4) becomes:

$$\tau_\psi = (k_\tau V_\psi + k_\tau V_\psi) - (-k_\tau V_\psi - k_\tau V_\psi) = 4 k_\tau V_\psi \tag{5}$$

The z-axis "Moment Of Inertia" (MOI) of the quad rotor is the sum of all point mass inertias about the z-axis (assuming battery and controller inertia is negligible due to their masses being located predominantly at the "Centre of Gravity", or COG).

$$I_z = \sum I_m = 4 m_m l^2 \tag{6}$$

$(\, where\ m_m\ is\ a\ motor\ \&\ arm\ mass\ )$

Therefore, substituting Equations (5) and (6) into (3), gives the equation of motion for yaw acceleration:

$$\ddot{\psi} = \frac{\tau_\psi}{I_z} = \frac{4 k_\tau V_\psi}{4 m_m l^2} = \frac{k_\tau V_\psi}{m_m l^2} \tag{7}$$

2.2 Pitch and roll dynamics

Due to the symmetrical nature of the quad rotor configuration, pitch and roll can be represented by the same model. Fig.2 illustrates the thrust variations required to induce a moment about the y-axis for rolling. The yaw deviation limit is thus [4]

$$V_{\phi,\theta} \le \frac{F_{max}}{k} \tag{8}$$

$(\, k = 2\, or\, 4\, to\, avoid\, motor\, saturation, F_{max} = Maximum\, Force\,)$

The equation of motion for this pitching or rolling moment is derived from the sum of moments about the y-axis:

$$\sum \tau_\theta = I_y \times \ddot{\theta} \tag{9}$$

The thrust deviation for one motor can be calculated as

$$V_\theta = (F_B - F_F)/2 \tag{10}$$

Therefore the sum of the moments is

$$\sum \tau_\theta = 2 V_\theta l \tag{11}$$

The y-axis moment of inertia of quad rotor is the sum of the two point mass inertias

$$I_y = \sum I_m = 2 m_m l^2 \tag{12}$$

We now substitute Equations (11) and (12) into (9) to find pitch acceleration.

$$\ddot{\theta} = \frac{2 V_\theta l}{2 m_m l^2} = \frac{V_\theta}{m_m l} \tag{13}$$

Due to symmetry of the quad rotor body, this also represents pitch dynamics. The dynamic equations discussed so far have treated the quad rotor as a flying "+" structure.

3. QUADROTOR'S DYNAMICS AND SIMPLIFIED MODEL

Linear Acceleration in the X-axis Direction [5]:

$$\ddot{X} = \frac{u(1)(\sin\psi \sin\phi + \cos\psi \sin\theta \cos\phi) - k_1 \cdot \dot{X}}{m} \tag{14}$$

Linear Acceleration in the Y-axis Direction:

$$\ddot{Y} = \frac{u(1)(\sin\psi \sin\theta \cos\phi + \cos\psi \sin\phi) - k_2 \cdot \dot{Y}}{m} \tag{15}$$

Linear Acceleration in the Z-axis Direction:

$$\ddot{Z} = \frac{u(1)\cos\theta \cos\phi - k_3 \cdot \dot{Z}}{m} - g \tag{16}$$

Pitching angular Acceleration in the X-axis Direction:

$$\ddot{\theta} = \left(u(2) - k_5 \dot{\theta}\right) i \Big/ \mathrm{I}_y \tag{17}$$

Rolling angular Acceleration in the X-axis Direction:

$$\ddot{\phi} = \left(u(3) - k_4 \dot{\phi}\right) i \Big/ \mathrm{I}_x \tag{18}$$

Yawing angular Acceleration in the X-axis Direction:

$$\ddot{\psi} = \left(u(4) - k_6 \dot{\psi}\right) i \Big/ \mathrm{I}_z \tag{19}$$

Equations of vertical forces produced by the four rotors [5]:

$$u(1) = F_1 + F_2 + F_3 + F_4 \tag{20}$$

$$u(2) = F_3 - F_1 \tag{21}$$

$$u(3) = F_4 - F_2 \quad (22)$$

$$u(4) = F_1 - F_2 + F_3 - F_4 \quad (23)$$

where:

F_1, F_2, F_3, F_4 Vertical forces produced by four rotors

I_x, I_y, I_z Moments of inertia x, y, z directions

θ, ϕ, ψ Pitch angle, roll angle, yaw angle

$K_{i=1,2,3,\ldots}$ Drag coefficients

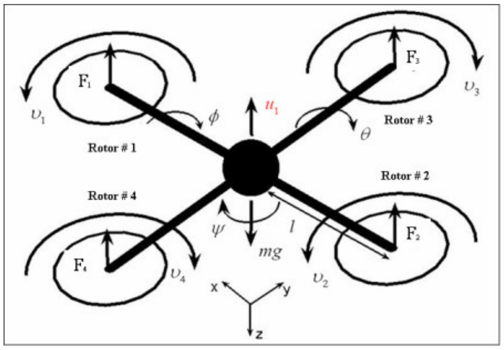

Figure 3 basic drawing of a Quadrotor showing the acting forces and moments

4. SYSTEM COMPUTER AIDED DESIGN AND SIMULINK MODELING

In this section simplified models to the quadrotor are introduced. The first model is a CAD model which was made using Solid Edge V20 and the second model is a Simulink model that was made using Matlab V7.1, both models are not complex ,they are simple and can guide through a future work on building complex model for the quadrotor.

4.1 Assembly of the model

The battery, camera, electronic circuits will be acting by weight forces only and the figure below shows the assembly of the model and showing the main axes of direction that will be considered the positive direction while studying the Simulink model of the quadrotor.

122.64 Mass and inertial properties

Mass properties

These properties were estimated using the inspection tool of Solid edge, the mass properties of each part is illustrated on table 1

Table 1 Mass properties

Item	Mass (grams)	Quantity	Total mass
Battery	223	1	223
Square tube	26	4	104
Central plate	4	2	8
Control circuits	90	1	90
DC motor	43	4	172
ESC	6	4	24
Receiver	9	1	9
Propeller	7	4	28
Fasteners	30	1	30
Quadrotor	688	Total	688

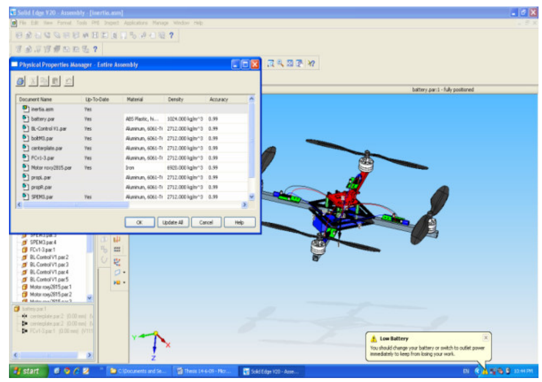

Figure 4 Mass properties

Inertial properties

These properties were estimated using the inspection tool of Solid edge to be used in the Simulink model parameters, the inertial properties of each part is illustrated on table 2

Table 1 Inertial properties

Axis	M.M. Inertia	Radii of Gyration
X	0.003325 kg.m^2	88.19 mm
Y	0.003263 Kg.m^2	87.36 mm
Z	0.006430 Kg.m^2	122.64 mm

4.3 Simulink model

Simplified quad-rotor Simulink model

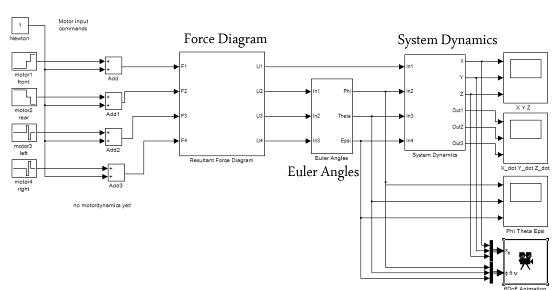

Figure 5 Simplified Quad-rotor Simulink Model

The simplified model of the quad-rotor consists of three subsystems:

- Resultant Force Diagram:

The inputs of this block diagram are the resultant forces (F1, F2, F3 and F4 of the motors) and it calculates the sum of forces acting on the quad-rotor due to variation of motors speeds in order to estimate the transitional and rotational motion of the quad-rotor.

- Euler Angles:

This block calculates Euler angles (Phi, Theta and Epsi) as a result of variation of forces acting on the quad-rotor.

- System Dynamics:

It contains the equations of the system dynamics and it calculates the position of the quad-rotor at any given time.

This is a cut down model and has a clear simple mathematical modeling. Some of the parameters affecting the system were neglected such as ground effect and residual angular speed of the motors.

4.4 Simulink of basic control system

Backstepping technique

In control theory, backstepping is an analysis technique for designing stabilizing controls for a special class of nonlinear dynamical systems. Because of the recursive structure these systems; the designer can start the design process at the known-stable system and "back out" new controllers that progressively stabilize each outer subsystem. The process terminates when the final external control is reached. Hence, this process is known as backstepping [6] and [7].

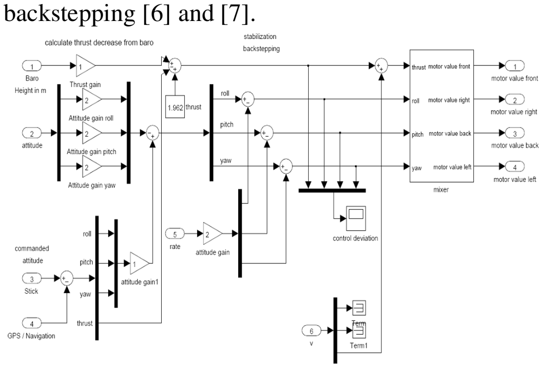

Figure 6 Simulink of basic control system

The block diagram in Figure 6 explains how the controller of the quad-rotor process data from sensors about the quad-rotor and the surrounding environment and execute commands applied by the operator accompanied by achieving stability of the system to insure safe flight.

The gyroscopes and accelerometer measure attitude of the flying machine with respect to itself while the GPS and the digital compass measure the attitude of the flying machine with respect to the surrounding environment. The altitude pressure sensor (Baro) measures the altitude of the quad-rotor in meters, the rate of change in angular velocity and the angular velocity can be measured by the accelerometer.

5. HARDWARE IMPLEMENTATION AND TESTING

The proposed system shows control capabilities which allow for autonomous balancing of a system which is otherwise dynamically unstable. A quadrotor poses a more challenging control problem than a single rotor or dual rotor inline helicopter because the controls demands include accounting for subtle variations which exist between the motors and cause each motor to provide a slightly different level of lift. In order for the quad-rotor craft to be stable, the four motors must all provide the same amount of lift, and it is the task of the control system to account for variations between motors by adjusting the power supplied to each one.
Also, the quad-rotor can change direction without having to reorient itself – there is no distinction between front and back of the craft. In the quadrotor, every rotor plays a role in direction and balance of the vehicle as well as lift, unlike the more traditional single rotor helicopter designs in which each rotor has a specific task - lift or directional control - but never both.
The controller of the Quad-rotor is developed to do the following functions:

- Stable, autonomous hover with active controls system taking dynamic information from sensors mounted on craft.
- Stable hover, with addition of variations in altitude based on human input for thrust.
- Stable hover, with addition of variations in altitude and directional movement based on human inputs for thrust, pitch, roll, yaw.

5.1 Hardware Implementation and interfacing

Four Brushless DC motor Robbe Roxxy 2824-34 Outrunner are used to implement the proposed system

Figure 7 Robbe Roxxy 2824 Brushless DC motor

In aircrafts it’s all about power to weight ratio. Outrunner brushless motors produce more torque output than conventional brushless motor. A Robbe

Roxxy outrunner motor can produce power up to 90 W when it only weights 48g.

The ESC board is a sensorless driver for brushless DC current motors. They are especially designed for use in quadrotor, where quick set-changes are necessary. The control of rushless motors is tri-phasic in groups of PWM pulses. The PWM frequency determines the hight of the phase-voltage (actually the arithmic mean of the voltage).

The phase voltage on the motor (as group of PWM pulses) determines the rotations per minute (RPMs) of the motor: a motor generates a countercurrent when turning (like a generator). The resultant RMPs will be the balance between current, coutercurrent and power output. At any time 2 of the 6 FETs are operational to power the motor. The time of commutation (the time at which the 2 FETs must be switched off and the next two switched on to go to the next phase), is determined by voltage measurement (actually comparison) of the unpowered phase of the three motor wires. To do this the different analog comparators of the Atmega8 are used.

The Atmega644 is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture used for controlling the motors. By executing powerful instructions in a single clock cycle, the Atmega644 achieves throughputs approaching 1 MIPS per MHz allowing the system designed to optimize power consumption versus processing speed.

One of the microcontroller's functions and the one that it provides in the control part is to take operator inputs (thrust, pitch, roll and yaw) form the receiver (PPM: Pulse Position Modulation Signal) and process it then transferred to the ESCs (PWM: Pulse Width Modulation Signal).

The receiver is connected to the Atmega644 through pin PD6, the transmitters signal is obtained by the receiver then transferred to the microcontroller as a PPM signal. After that the signal is processed and compared with data coming from the accelerometers and gyroscopes. Four Brushless ESCs are connected in parallel configuration to pins PC1 and PC0 used for SDA (Serial Data) and SCL (Serial Clock) respectively. Data is transferred to the four ESCs. Each ESC is identified individually using 3 nodes by connecting or disconnecting (soldering or not soldering) these points in four different configuration. The Brushless ESCs controls the corresponding rotors speed using PWM signal.

The integrated system acts as a closed-loop system to give the stability desired and maximum control on the Quad-rotor.

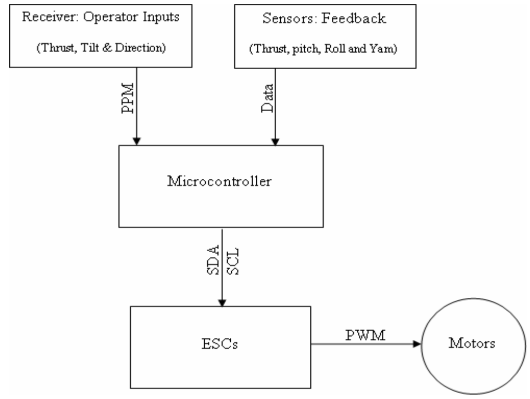

Figure 8 Control Block Diagram

5.2 Navigation Aspects

Quadrotor crafts naturally demand a sophisticated control system in order to allow for balanced flight. Uncontrolled flight of a quadrotor would be virtually impossible by one operator, as the dynamics of such a system demand constant adjustment of four motors simultaneously. The goal of the proposed system is to design and construct stabilized quadrotor aircraft.

5.3 Inertial Navigation System

Inertial sensors have been used in aircraft and navigation systems for a long time. It is not until recently that new technology has caused the price and size of gyroscopes and accelerometers to make them available in consumer electronics. Of particular importance is the MEMS technology that has allowed small, cheap and robust sensors to enter the market [8], [9].

Accelerometers measure the transactional force encountered due to their acceleration. To convert this to a velocity this output would need to be integrated once and to convert this to a position, integrated twice[10].

Gyroscopes measure the angular velocity that they are rotated at and to determine their angular position would require a single integration.

In the proposed systemt, three single-axis gyroscopes and one 3-axis accelerometers are used. Gyroscopes are mounted in the center of the craft in order to measure the Pitch, Yaw and Roll rates while in flight. The accelerometer provides $\ddot{X}$, $\ddot{Y}$ and $\ddot{Z}$ analog output signals. The outputs from the sensors are averaged for higher sensitivity.

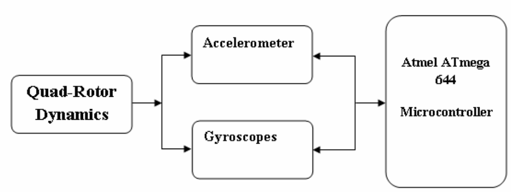

Figure 9 INS Diagram

The angular rate is obtained from the gyroscopic readings using the following equation [9]:

$$Angular\_velocity = \frac{\frac{5.25}{1023}(A_{reading} - B_{reading})}{0.00067} \qquad (24)$$

The value of gyroscopic reading (B_reading) when there is zero angular velocity is subtracted from the average gyroscope reading (A_reading) that was just calculated. This difference in gyroscope readings is multiplied by 5.25 (the output from the gyroscope is 2.7-5.5 volts) and divided by 1023 (the A/D conversion is 10 bit so the range of the result is 0–1023). This number is then divided by 0.00067 because the gyroscope output signal changes by 0.67 milli Volts for a change in angular velocity of one degree per second.

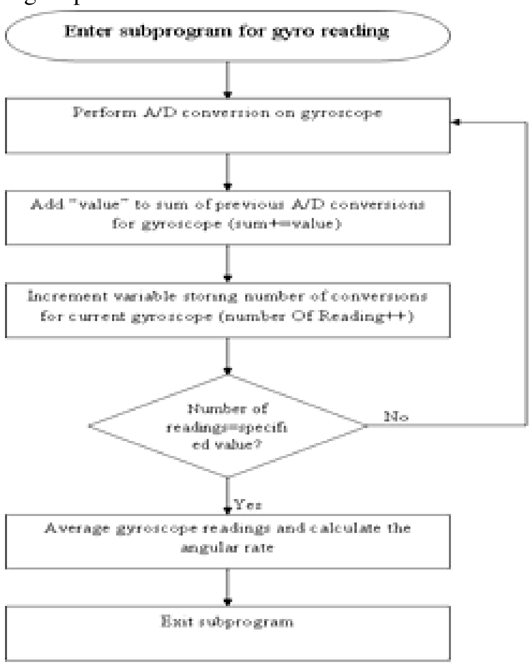

Figure 10 Flowchart showing the calculation of the gyro output

The accelerometer measures the tilt angles, which are assumed to represent the Euler angles. Therefore, unlike the gyroscopes, that measure only the angular rates, the tilt sensor placed as close as possible to the center of gravity. The mounting was done on to the lower PCB's center as shown in the Fig 11

Double integration is the process needed to obtain the position using the acceleration data. The integration step must be performed once to obtain velocity and then repeated to obtain position.

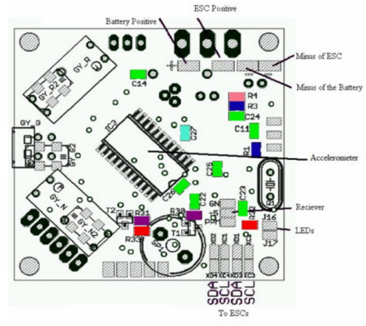

Figure 11 Main control board

Altitude Control (Atmospheric pressure sensor) serves to stabilize the flight altitude by making use of the relationship between changes in pressure relative to the altitude. This relationship is governed by the following equation:

$$h = \frac{\left(1 \; \left(\frac{P}{P_{ref}}\right)^{0.19026}\right) \times 200.15}{0.00198122} \qquad (25)$$

This equation is calibrated for an altimeter, up to 36,090 feet (11,000 m). Outside that range, an error will be introduced which can be calculated differently for each different pressure sensor. These error calculations will factor in the error introduced by the change in temperature as we go up.

Barometric pressure sensors can have an altitude resolution of less than 1 meter, which is significantly better than GPS systems (about 20 meters altitude resolution).

Inertial measurement unit (IMU) and global positioning system (GPS) data integration is a very typical application for sensor fusion. All the data corresponding to these sensors is in one form or another representative of a body's motion. It is simply a matter of manipulating the data to get a complete and meaningful interpretation of the body's position and attitude at any point in time. Clearly, this is the objective for the GPS/INS aided vision system.

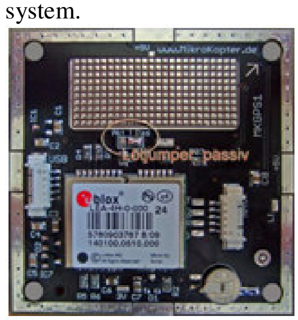

Figure 12 GPS Module

The GPS receiver included on the board is a U-blox LEA-4H. This receiver is an OEM module that is small, low power and has complete functionality. The LEA-4A can be used to provide an assortment of GPS data including position, velocity, heading, signal strength, number of visible satellites etc. This device can be used either as a USB device or a Serial device and has up to a 4Hz positional update rate. This device also has a compatible super sense version

which will obtain GPS information with higher accuracy and even indoors in some cases.
An INS is only capable of providing relative position, and only calculates its current position based on where it has been. This form of navigation is referred to as dead reckoning and is increasingly inaccurate with respect to time. These inaccuracies can be compensated for with additional information from a GPS receiver. An INS with GPS resetting is the simplest form of integration for these two sensors. This method involves using data from a GPS receiver as an initial condition for periodic INS calculations.
Generally, the sampling rate for an INS is much higher than that of a GPS receiver which is typically less than or equal to 4 Hz. During the period between GPS updates, the INS alone is used to calculate position, attitude, and velocity using the last GPS update as an initial condition for the calculation. At every GPS update the INS is reset with the most current GPS data.

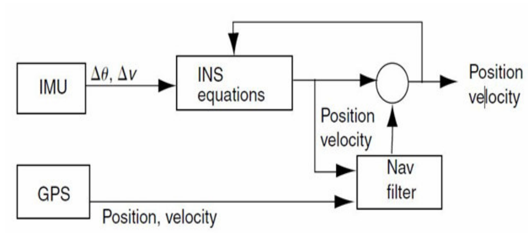

Figure 13 GPS/INS integration

It was essential for us to establish a real-time communication system between the flying machine and a ground station. It performs a two-way process where information is imparted from the quadrotor to base and the other way around. When information is available it's easier to develop an adequate monitoring system which helps in discovering of errors or make sure that the flying machine is performing a safe flight. Also it provides the ability to change system parameters to coop with the change in the surrounding environment.
Bluetooth is an open wireless protocol for exchanging data over short distances from fixed and mobile devices, creating personal area networks (PANs). It was originally conceived as a wireless alternative to RS232 data cables.
A Bluetooth module is mounted on the flying machine and it is attached to the main board. A wireless connection is created between the flying machine and ground based computer (must have Bluetooth card). Another advantage granted by Bluetooth connection it provides secured data line between the ground station and the mobile device.

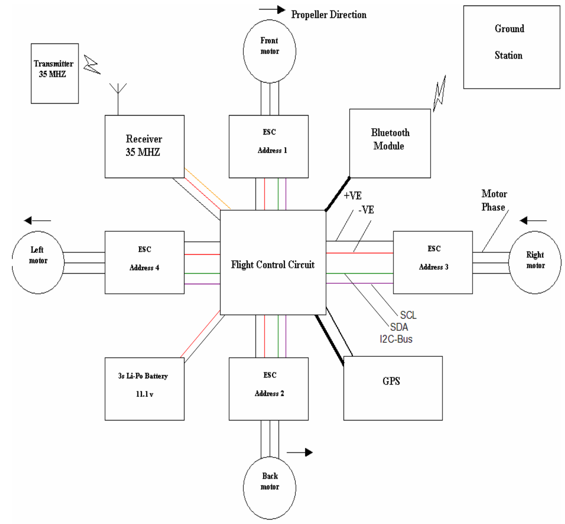

Figure 14 Layout of wiring connections

5.4 Hardware Testing

Before attempting to fly the quadrotor we had to perform some tests to insure that these sensors are functional. Bluetooth communication was established between the quadrotor and a PC. Tests were applied by manual moving or rotating the quadrotor.
Gyros
The diagram shown in Figure 15 was obtained by manually rotating the quadrotor around the Y axis then around the X axis followed by random movement. The figure shows the response of the angular rotation (pitch and roll) of the physical.

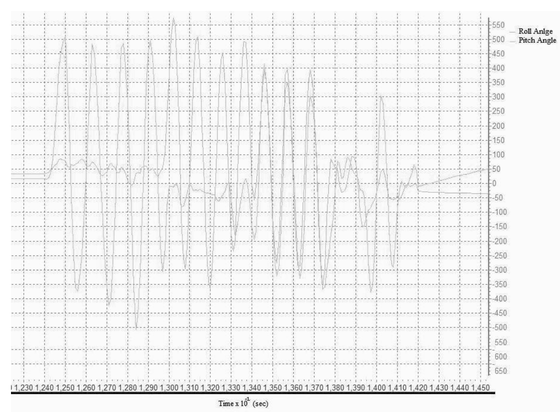

Figure 15 Gyro Testing

The same procedure used in testing gyros was applied to test the accelerometer. Figure 16 shows the response of angular acceleration of the physical model.

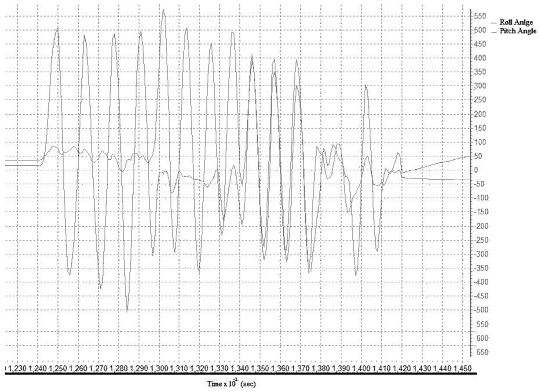

Figure 16 Accelerometer testing

In order to validate the simulink model, a comparison between the simulation model and the physical model is made using a step input for the two systems. Figure shows the output from the two systems which indicates an accepted results.

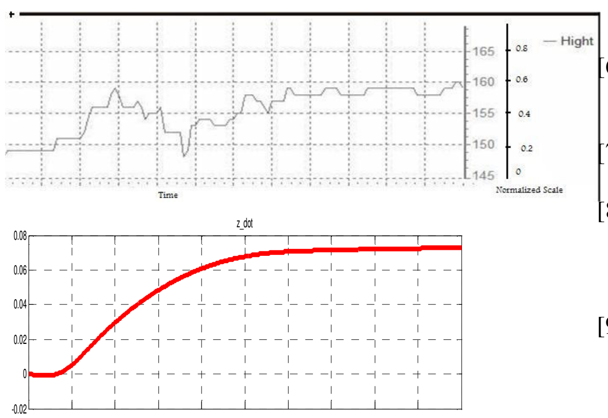

Figure 17 the comparison between the Simulink model and the hardware

6. DISCUSSION AND CONCLUSION

After finishing our work, a lot of points were figured out about the Quadrotor and the detection method. First the quadrotor is the optimum type of flying machine for the use in mine detection, due to the simplicity of control, high stability of attitude and the ability of hovering at low altitudes while its limitations are the high cost, the limited flight time (up to 25 min) depending on the payload and the limited payload (up to 0.7 kg). The estimated mass and inertial properties from the CAD model were very close to the real model, the simplified model of Simulink is good one to study for its simplicity while the complicated model is a good try for approaching an accurate work of modelling quadrotors, it has some limitations; ground effect, propeller model and the ESC model were not considered in it but it has some good results for the mean time. For the future work it considered to develop an efficient algorithm for stability analysis and stabilization.

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