Effect of Polytetrafluoroethylene Material on Dynamic Behaviour of an Underactuated Unmanned Aerial Vehicle

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Abstract-**An unmanned aerial vehicle (UAV) is an aircraft capable of flight without a human operator. This aircraft can be controlled remotely or autonomously via a preprogrammed flight path. A quadrotor UAV is one of the best unmanned aerial vehicles. It is an aircraft whose lift is generated by four DC motors and it is able to take off and land vertically. It also has the advantage that it can be controlled by varying the speeds of the four motors in a systematic manner. In this paper, we present the design, development, testing and implementation of a quadrotor unmanned aerial vehicle. The primary goal of the research was to find a way of reducing the effect of the vibrations generated by the rotors in order to ensure that those vibrations are not transmitted to the electronic hardware. For this purpose, polytetrafluoroethylene (PTFE) was chosen for designing the hub and motor's mount. PTFE is composed of carbon and fluorine and is suitable for absorbing the vibration generated by the rotors. A complete simulation was developed and used to tune a proportional controller in MATLAB. This controller was then implemented in hardware using a PIC 16F876 microcontroller. Experimental results show the effectiveness of this material in reducing the effects of the motor's vibrations, and thus improving the measurement quality of the inertial measurement unit (IMU).**

Keywords-Unmanned Aerial Vehicle, Quadrotor, PIC16F876 Microcontroller, Polytetrafluoroethylene, Inertial Measurement Unit.

I.   INTRODUCTION

A quadrotor is a small flying robot with four propellers driven by four DC motors. The motors are placed at the end of four arms and attached to a single hub. The quadrotor is unstable and must be stabilized by a suitable control system. Researchers have proposed and developed a very large number of control systems for such vehicles. Many of these are based on a linearization model with a conventional proportional-integral-derivative (PID) controller [1], [2], [3], while others are based on non-linear feedback controllers [4], [5].

As shown in Fig. 1, the quadrotor has four identical rotors grouped into two pairs and spinning in opposite directions. Each rotor is attached to a blade and displaced from the center of mass by distance D. The blade produces both thrust and torque with respect to aircraft's center of mass. The front (R2) and rear (R4) motors both rotate clockwise and the other two rotors (left R3, right R1) rotate counter-clockwise. Due to the rotors spinning in opposite directions, the torques on one side of the aircraft cancels out the torques on the other side. Thus, if all rotors are spinning with the same angular velocity, the net torque is equal to zero and the thrust raises the aircraft up. On the other hand, in order to achieve either roll or pitch, a mismatch must be induced into the aerodynamic torque balance by increasing or decreasing the speed of the rotors rotating in the same direction.

The quadrotor has many advantages over other types of UAVs in terms of safety, weight and cost. They can also take off and land in a limited area and can easily hover above stable or moving targets. Over the last ten years, quadrotors have been used as scientific research tools [6], [7], [8], [9], [10], [11], [12]. More recently, quadrotors have been equipped with communication systems and sensors and have been used for such applications as search and rescue, surveillance, and remote inspection. Another advantage is that a quadrotor can also fly closer to obstacles/targets than a conventional helicopter and thus protect human life in many dangerous environments.

One of the largest problems of this type of vehicle is the construction of the hub and frame that are used to hold the motors and all of the electronic components. To

the best of our knowledge, no studies of the behavior of the quadrotor as a result of changing the material used to construct the quadrotor airframe or the hub. In this paper, we propose a new material that can tolerate vibrations and through the simulation we compare our results with those based on the commercial quadrotor airframe. In order to overcome some of the limitations of previous approaches, a new quadrotor airframe has been developed and a test bed was created to test the proposed material. A proportional controller was designed and implemented using PIC16f876 hardware.

The remainder of this paper is organized as follows: in the next section, we survey current research regarding the quadrotor. In section III, we present the mathematical model of a quadrotor. In section IV, we explain and present the hardware design. In section V, we present and discuss the simulation and implementation results. Finally, we conclude and discuss future work in section VI.
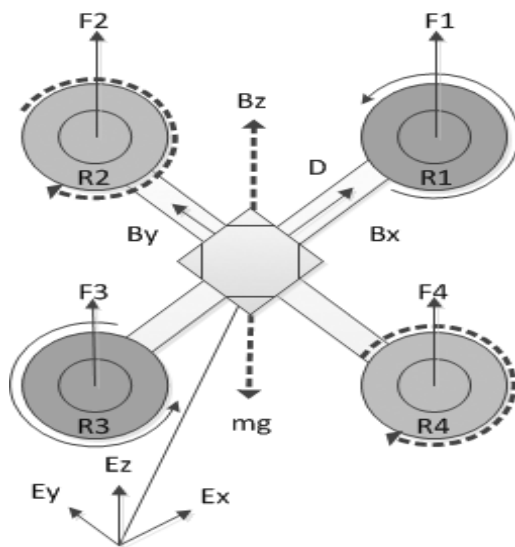

Figure 1. Quadrotor Schematic Showing the Direction of Rotation.

II.   RELATED WORK

Over the last five years, several algorithms have been investigated for use in quadrotors [13], [14]. Some algorithms have focused on its structure [15], while others have focused on the control system. One of these control algorithms is based on the linear quadratic regulator (LQR) [16]. Dynamic and visual feedback techniques have also been used in this field [17], and finally, neural networks have also been employed [18].

The use of sensors for the estimation of quadrotor attitude is also important. The author in [19] proposed a controller based upon the compensation of the Coriolis and gyroscopic torques and the PD controller. Their experimental set-up was restricted to relatively small torque levels and thus the combination of the Coriolis and gyroscopic torques did not make much difference. The author in [20] proposed a controller based on Lyapunov analysis using a nested saturation algorithm. Their experimental set-up was also restricted to relatively low speed. Finally, all control methods in the literature require accurate information from a gyroscope, an accelerometer, and other measuring devices [21].

As a result of improvements in the technology, different sizes of quadrotors such as the Mesicopter [22] and the DraganFlyer [23] have been developed. The Draganflyer has carbon fiber and a high impact nylon frame. It has a length of 30 inches from rotor tip to rotor tip, weighs 17 ounces and can lift a payload of four ounces in addition to its onboard electronics. Quattro Copter [24] is 65 cm in length, weighs about half a kilogram, has flight range of 1 km and has a detachable fuselage.

X-4 Flyer [25] has a weight of 2 kg, a 70 cm frame length, and 11 inch diameter rotors. It has an onboard power supply that allows two-minute flights, and has a wireless serial link and a camera system. It also includes a rotor hub with a teetering design that has springs to provide tensional stiffness. Different models of the X-4 Flyer are also presented. The authors state that the greater weight of the commercial IMU negatively affected the performance of the X-4.

The HMX-4 [26], [27] is another name for a quadrotor that is similar to the Draganflyer. A research group at the University of Pennsylvania developed this quadrotor using a commercially available model. Three onboard gyroscopes are used to stabilize the quadrotor but due to the weight limitations of the HMX-4, no GPS or additional accelerometers are used.

At Cornell University, two other quadrotor projects were implemented [28]. The second was done as a Master's thesis project and focused on the structure of the quadrotor. The quadrotor designed in this project was heavier (6.2 kg) than the first design. Two control algorithms [29] were tried out on the quadrotor by a team from the Swiss Federal Institute of Technology: PID and optimal linear quadratic (LQ) control. The authors state that the classic PID control was more successful than the optimal control.

The commercial Draganflyer quadrotor used at Stanford is also being used by a research team from France [30]. They used the vehicle to study the stabilization of a quadrotor with the goal of using new multi-agent control techniques to allow several quadrotors to act as individual agents in a system. Due to this research, the original Draganflyer electronics redesigned.

III. MATHEMATICAL MODEL OF THE QUADROTOR

As shown in Fig. 1, the quadrotor's lift is generated by two pairs of DC motors as described above. Two frames are shown, the earth-fixed frame which is used to specify the location of the vehicle, and the vehicle body frame used to specify the vehicle orientation. In order to transform the body-fixed frame into the earth-fixed frame, the following direction cosine matrix is used:

$$R_{zxy} = \begin{bmatrix} S_\theta S_\Phi S_\psi + C_\psi C_\theta & S_\Phi S_\theta C_\psi - C_\theta S_\psi & S_\theta C_\Phi \\ C_\Phi S_\psi & C_\psi C_\Phi & -S_\Phi \\ C_\theta S_\psi S_\Phi - S_\theta C_\psi & C_\theta S_\Phi C_\psi + S_\theta S_\psi & C_\theta C_\Phi \end{bmatrix} \quad (1)$$

where θ, Φ and ψ are the roll, the pitch and the yaw angles, respectively. S represents the sine, C represents the cosine, and t represents the tangent. The dynamic behaviors of the quadrotor are expressed as:

$$\ddot{x} = -\frac{S_\theta C_\Phi}{m} u_1 \quad (2)$$

$$\ddot{y} = \frac{S_\Phi}{m} u_1 \quad (3)$$

$$\ddot{z} = -\frac{C_\theta C_\Phi}{m} u_1 + g \quad (4)$$

where $u_1 = \tau_1 + \tau_2 + \tau_3 + \tau_4$ represents the total thrust, τ_1 is the normalized thrust, m is the total mass, and g is the acceleration due to gravity. To relate the Euler angular rates to the body angular rates, the following equations are used:

$$\begin{bmatrix} \dot{\Phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} C_\psi & -S_\psi & 0 \\ \frac{S_\psi}{C_\Phi} & \frac{C_\psi}{C_\Phi} & 0 \\ S_\psi t_\Phi & C_\psi t_\Phi & 1 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (5)$$

thus,

$$\begin{bmatrix} \ddot{\Phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} =$$

$$\begin{bmatrix} -\dot{\psi} * S_\psi & -\dot{\psi} * C_\psi & 0 \\ \frac{\dot{\psi}*C_\psi C_\Phi + \dot{\Phi}*S_\psi S_\Phi}{C_\Phi^2} & \frac{\dot{\psi}*C_\psi C_\Phi + \dot{\Phi}*C_\psi S_\Phi}{C_\Phi^2} & 0 \\ \dot{\psi} * C_\psi t_\Phi + \frac{\dot{\Phi}*S_\psi}{C_\Phi^2} & -\dot{\psi} * S_\psi t_\Phi + \frac{\dot{\Phi}*S_\psi}{C_\Phi^2} & 0 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} +$$

$$\begin{bmatrix} C_\psi & -S_\psi & 0 \\ \frac{S_\psi}{C_\Phi} & \frac{C_\psi}{C_\Phi} & 0 \\ S_\psi t_\Phi & C_\psi t_\Phi & 1 \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \quad (6)$$

$$\rightarrow \begin{bmatrix} \ddot{\Phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & -\dot{\psi} * C_\Phi & 0 \\ \frac{\dot{\psi}}{C_\Phi} & \dot{\Phi} * t_\Phi & 0 \\ \dot{\psi} * t_\Phi & \frac{\Phi}{C_\Phi} & 0 \end{bmatrix} \begin{bmatrix} \dot{\Phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} +$$

$$\begin{bmatrix} C_\psi & -S_\psi & 0 \\ \frac{S_\psi}{C_\Phi} & \frac{C_\psi}{C_\Phi} & 0 \\ S_\psi t_\Phi & C_\psi t_\Phi & 1 \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \quad (7)$$

$$\vec{\omega} = \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (8)$$

$$\frac{d(I\vec{\omega})}{dt} = \begin{bmatrix} u_2 \\ u_3 \\ u_4 \end{bmatrix} = I \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} + \vec{\omega} \wedge (I\vec{\omega}) \quad (9)$$

$$\rightarrow \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = I^{-1} \begin{bmatrix} u_2 \\ u_3 \\ u_4 \end{bmatrix} + I^{-1}(I\vec{\omega}) \wedge \vec{\omega} \quad (10)$$

where u_2 is the pitching moment and it is equal to $(\tau_3 - \tau_4)$, u_3 is the rolling moment and it is equal to $l(\tau_1 - \tau_2)$, u_4 is the yawing moment and it is equal to $v_1 + v_2 - v_3 - v_4$, v is the normalized torque, and ω is the angular velocity of the rotor. If we assume that the moments of inertia along the x axis and y axis are equal, then

$$\ddot{\Phi} = -\dot{\psi}\dot{\theta} * C_\Phi + \frac{C_\psi}{I_{xx}} u_2 - \frac{S_\psi}{I_{yy}} u_3 + \frac{I_{yy}-I_{zz}}{I_{xx}} \left(\dot{\psi} - \dot{\theta} * S_\Phi \right)\dot{\theta} * C_\Phi \quad (11)$$

$$\ddot{\theta} = \frac{\dot{\psi}\dot{\Phi}}{C_\Phi} + \dot{\Phi}\dot{\theta} * t_\Phi + \frac{S_\psi}{C_\Phi I_{xx}} u_2 + \frac{C_\psi}{C_\Phi I_{yy}} u_3 - \frac{I_{yy}-I_{zz}}{I_{xx}} \left(\dot{\psi} - \dot{\theta} * S_\Phi \right)\frac{\Phi}{C_\Phi} \quad (12)$$

$$\ddot{\psi} = \dot{\Phi}\dot{\psi} * t_\Phi + \frac{\dot{\Phi}\dot{\theta}}{C_\Phi} + \frac{S_\psi t_\Phi}{I_{xx}} u_2 + \frac{C_\psi t_\Phi}{I_{yy}} u_3 + \frac{1}{I_{zz}} u_4 - \frac{I_{yy}-I_{zz}}{I_{xx}} \left(\dot{\psi} - \dot{\theta} * S_\Phi \right)\dot{\Phi} * t_\Phi \quad (13)$$

IV. HARDWARE DESIGN

The main structure of the quadrotor consists of two parts. The first part consists of the mechanical parts,

while the second part consists of the electronic parts. The following section presents our proposed approach for improving the measurement quality of the IMU through dynamic vibration damping, and then a detailed description of the printed circuit board.

A. Mechanical Structure of the Quadrotor

The body of the quadrotor is shown in Fig. 2. The main structure of the quadrotor consists of a set of separate pieces which make up a hub joining the four aluminum arms. At the end of each arm, a motor mount is attached to hold a brushed DC motor, gear box and propeller assembly. The resulting physical structure weighs approximately 500 gm and measures 43x 43 cm without the propellers.
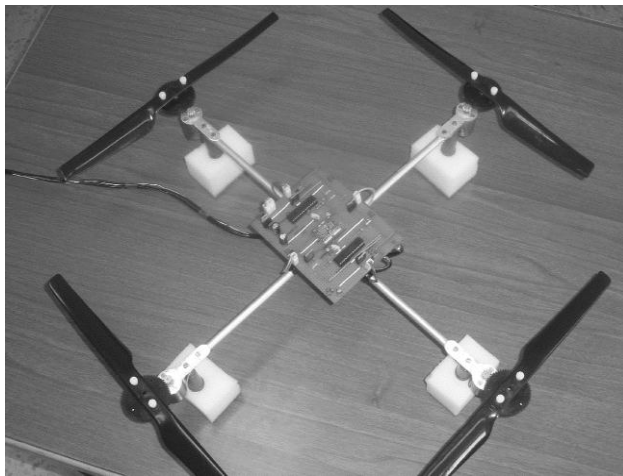
Figure 2. Physical Structure of Quadrotor.

The materials for our design include aluminum and polytetrafluoroethylene. Aluminum is light and strong, inexpensive and will not introduce unnecessary vibration into the system. Polytetrafluoroethylene absorbs vibration very well, is inexpensive, light, and can be machined very easily. The new design, which differs from the current commercial hubs, is shown in Fig. 3. It includes the hub itself and four aluminum arms. The new design ensured that the arms and the motors were perfectly aligned.

As shown in Fig. 3, the arms of the quadrotor need to be light and strong enough to withstand the stress caused by the weight of the motors and the central hub. The length of each arm is 19 cm long with an inner diameter of 0.8 cm.
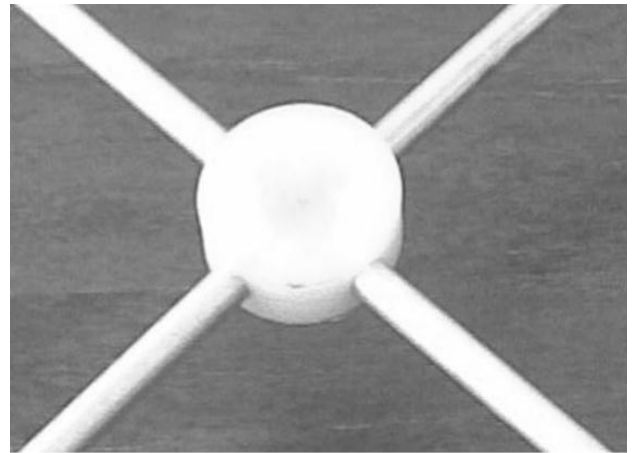

Figure 3. The Central Hub Attached to Four Aluminum Arms.

An AUTOCAD program is used for the propeller design. The propellers are 31.8cm from tip to tip. Two of them are tractors and the other two are pushers. As shown in Fig. 4, a propeller with a shallow angle of attack was designed using thin aluminum sheets. This, along with the hub design, provides the vertical lift for stable hovering.

(a)
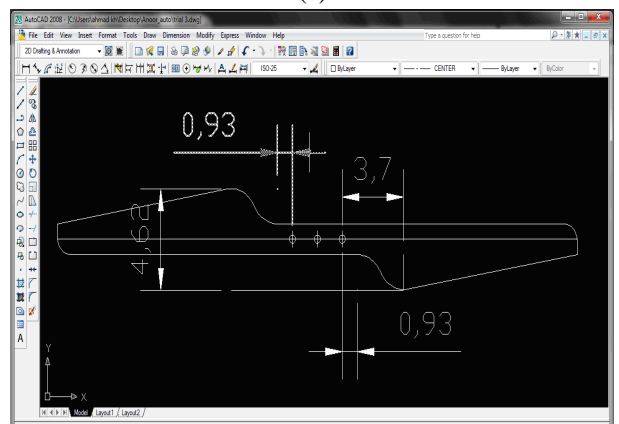
(b)

Figure 4. (a) Aluminum Propeller, (b) Propeller Design.

Fig. 5 shows the gearbox and the motor mount. The gearbox has a 6:1 gear ratio. It is used in our design so that the speed of the propeller will be slower than the speed of the motor. This technique allows the motors to exert more torque on the propellers even though they draw much less current. The holder for the gearbox is made from polytetrafluoroethylene while the motor mount uses hard aluminum plate.

Figure 5. Gearbox and Motor Mount.

B. Electronic System

As shown in Fig. 6, the electronics consist of a PIC16F876 microcontroller with several devices: an external power supply, a 7805 DC voltage regulator, an inertial measurement unit (IMU), drivers, and motors. The schematic diagram for the electrical circuit is shown in Fig. 7. As can be seen, this figure details the circuit used to interface the sensors and send their signals to the PIC16F876 microcontroller, as well as the circuit used to amplify the PWM outputs in order to drive the motors.

As a primary component, an IMU board with a high-precision ADXL203 accelerometer and an ADXRS613 rate sensor from the Spark Fun Company is used. ADXL203 is high precision, low power and has complete dual axis accelerometers used as a tilt sensor. It has a range of +/- 1.7g with a sensitivity of 1000mV/g. The ADXRS613 is a complete angular rate sensor. Fig. 8 shows the IMU and the printed circuit board with the IMU installed at the center of the board.
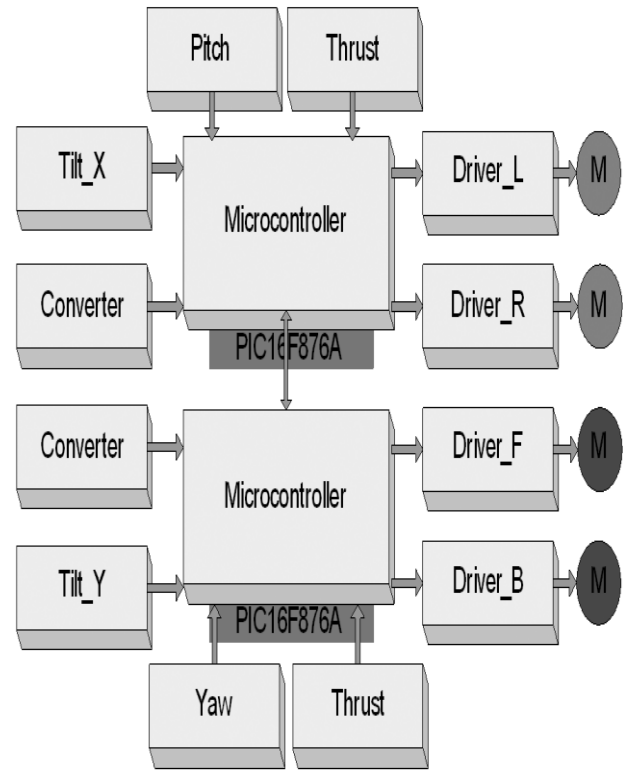

Figure 6. Block Diagram for Electronic Control System.
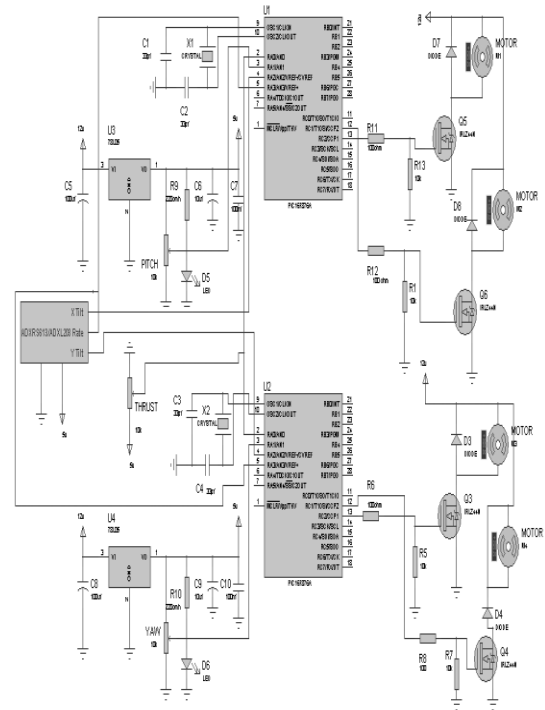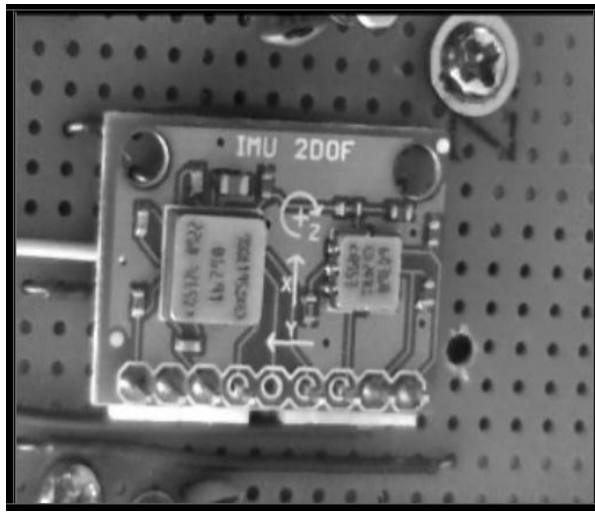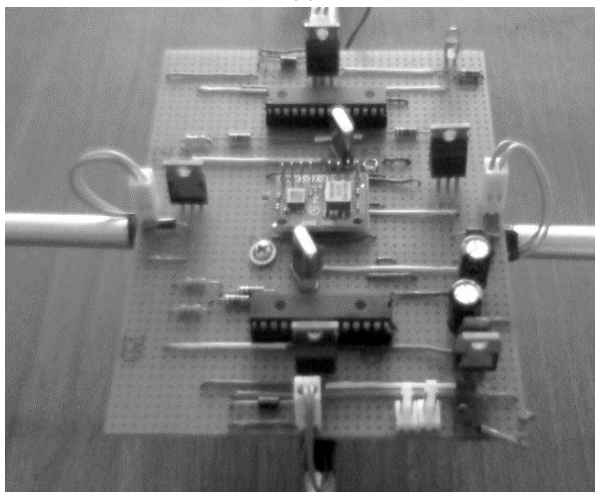

Figure 7. Circuit Diagram for System.

(a)

(b)

Figure 8. (a) IMU, (b) Printed Circuit Board with the IMU at the Center.

V. SIMULATION AND IMPLEMENTATION RESULTS

Our research included two stages. The first was performed using Matlab to evaluate the performance with a mathematical approach, and the second was carried out on the quadrotor platform in order to evaluate the behavior of the quadrotor structure and the electronic system. We experimented with various propellers designs to determine the dimensions which would provide the most lift. We also used four commercial propellers for comparison. Fig. 9 shows the maximum amount of thrust versus the pulse width modulation input for different rotor propellers. Two different propellers were designed for this study, and a commercial one was tested with various airfoils, diameters, and pitches. The first one was manufactured as shown in Fig. 4, from aluminum sheets with a thickness of 1mm while the second one had a thickness of 1.5mm. All propellers

were 31.8cm in length from tip to tip. The results show that the thickness of the material and the angle of attack have a strong effect on the thrust produced by the propeller. In addition, they show that the 1mm propeller outperformed the others in terms of the total thrust produced. As a result, this propeller, as seen in Fig. 10, is the propeller used for our quadrotor which has a PTEF hub, 0.8 mm aluminum tube for arms and a Mabuchi motor.
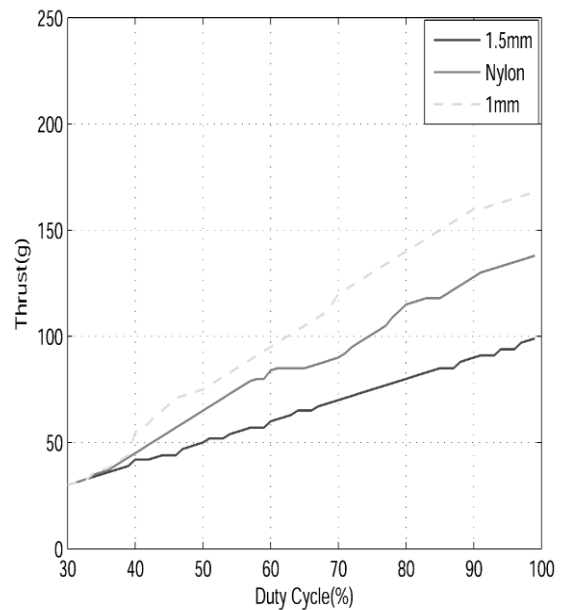

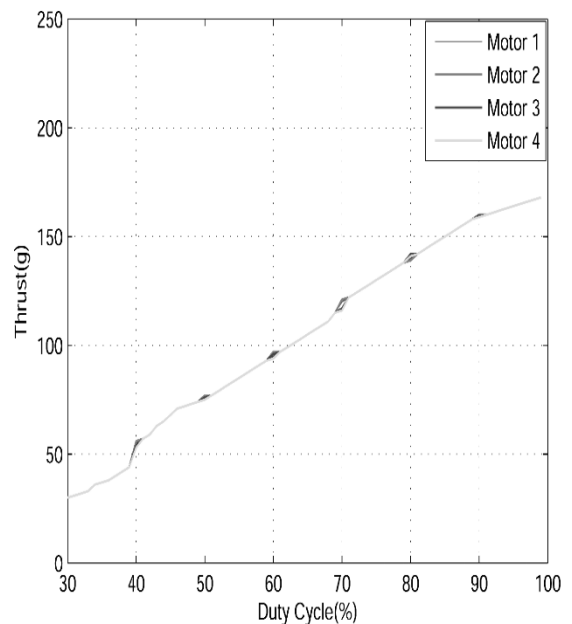Figure 9. Thrust vs. PWM for Various Propellers.

Figure 10. Rotors Thrust Curve Using the 1mm Propeller.

The experiments show that the accelerometer is sensitive to vibrations produced by the rotors and the frame. As shown in Fig. 11, the reading from the tilt sensor was 2.4 volt while the reading from the angular rate sensor was 2.54 volt. The output is fixed and will not change since the rotors are all off, but when the motors are running at only half power, an extreme amount of noise is produced. This noise is due primarily to the vibrations of the frame. As shown in Fig. 12, the voltage input for each propeller was varied between 0 and 11V, and the voltage required to make the UAV hover was 7.5V on each rotor. As shown in the same figure, the noise worsens when full power is applied using a nylon hub. The PTEF hub is able to reduce the noise, but it does not eliminate it completely. The addition of a second-order butterworth filter is able to reduce the noise. With this modification, the PTEF reduces the noise to such an extent that it appears that there is no noise at all.
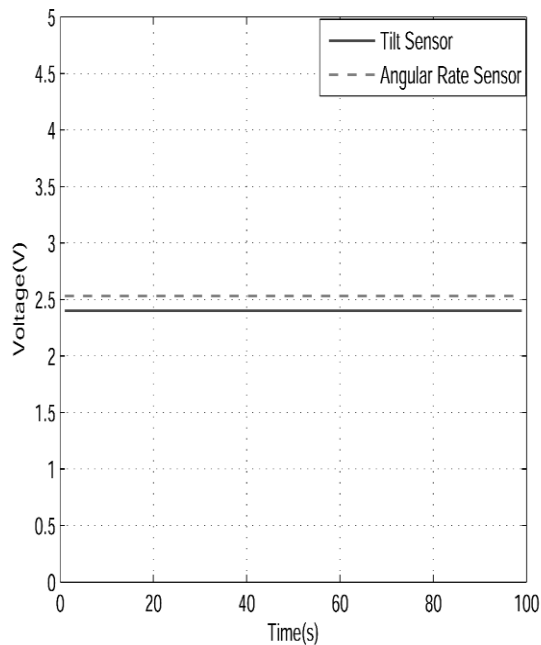

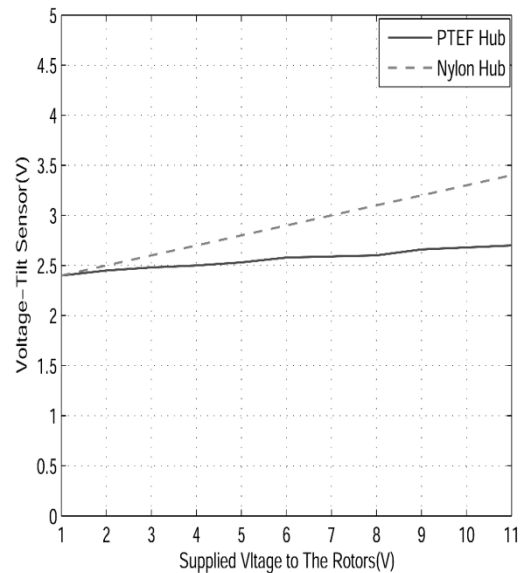Figure 11. Sensors Output with all Motors Off.

Figure 12. Sensors Output with all Motors On.

VI. CONCLUSION AND FUTURE WORK

In this research, a quadrotor was designed using inexpensive commercially available components. A new material was used for the first time to minimize rotor vibration. This has proven to be much more effective than the materials used by other commercial quadrotors. In addition, a custom-designed circuit board and software have been developed to interface those components with a PIC16F876 microcontroller. Several experiments were conducted to test this material and a proportional control law was successfully implemented on the system. The quadrotor has been successfully tested and flown by an external power supply. The results presented in this paper demonstrate that the material used in the construction of the vehicle brought about several useful aerodynamic effects. We suggest that future work to investigate the result of using the same material to build the arms of the vehicle would be useful.

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