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Methodology for Identifying Quadrotor Parameters, Attitude Estimation and Control

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***Abstract*— This paper describes a methodology to identify all the parameters of a quadrotor system including the structure parameters and rotor assembly parameters. A CAD model is developed using SOLIDWORKS to calculate the mass moment of inertia and all the missing geometrical parameters. A three simple test rigs are built and used to identify the relationship between the motor input Pulse Width Modulation (PWM) signal and the angular velocity, the thrust force, and drag moment of the rotors. A simple algorithm is implemented to an inertial measurement unit (IMU) for estimating the attitude and altitude of the quadrotor. Experimental set up is built to verify and test the accuracy of these proposed techniques. A controller is designed based on the feedback linearization method such that the quadrotor attitude can be stabilized. Finally, the experimental results show the effectiveness of the proposed techniques and the controller design.**

Keywords-quadrotor; parameter identification; inertial measurement unit; feedback linearization; thrust and drag moment identification

I. INTRODUCTION

Quadrotor is one of the unmanned aerial vehicles (UAVs) that possess certain essential characteristics. Their potential is highlighted in search, surveillance and rescue applications. Characteristics that provides a clear advantage over other UAVs is their Vertical Take Off and Landing (VTOL), hovering capability, ability to make slow precise movements, impressive maneuverability, traversing through an environment with many obstacles, and landing in small areas [1, 2, 3, 4, 5]. Quadrotor model based control is mainly depending on the dynamic behavior and the parameters of quadrotor. Researchers have studied the quadrotor's dynamics and presented models based on Newton-Euler and Lagrangian methods [3, 6]. However, the parameters of the quadrotor's dynamic model are essential for robust control. Consequently, parameters identification for quadrotor is inevitable. The general idea behind identification is to discover the physical system properties by observing quadrotor inputs and outputs.

Quadrotor research topic involves many areas such as structure parameters identification, rotor assembly identification, estimation algorithms of the unmeasured system states using an IMU, control synthesis and new design and application of quadrotor [7, 8]. Quadrotor structure identification is used to define the terms of mass, mass moment of inertia, and the rotor inertia. Two methods for structure identification are commonly used [3, 4, 9, 10, 11]. First one calculates these parameters using the principal equations for the mass moment of inertia, but this method is too difficult and not accurate for complex shapes. The second method utilizes online measurements with the identification algorithms to estimate these parameters. These algorithms require high computational.

Rotor assembly suffers from the lack of data. Few manufacturers support the research with the technical data for the quadrotor system [1, 4, 5, 12]. The other way is to measure the rotor assembly parameters by using wind tunnel identification [13]. This method needs complicated measurements with special instruments. Researchers in [12, 14, 15, 16, 17] present the estimation of the attitude and altitude using IMUs. They present algorithms that need a high computational time, so this cannot be implemented onboard microcontroller units. A simple algorithm is presented in [18] to estimate the roll, and pitch angle only.

In this research a method is proposed to identify all the quadrotor's structure parameters with simple and more accurate method. For the rotor parameters, a method is introduced that can be implemented easily without any extra instrumentations or manufacturer's data. Finally for the measurements, a low-cost small-size IMU is used. An algorithm is executed onboard to estimate the attitude and altitude of the quadrotor. Our proposed method is tested and verified experimentally. Moreover, a controller is designed based on feedback linearization technique that utilizes the identified parameters in order to stabilize the attitude of the quadrotor.

The paper is organized as following: Section II presents the quadrotor dynamic model. Section III presents the quadrotor structure and the estimation of its parameters. Section IV presents an experimental method for determining thrust and drag coefficients. Section V presents an IMU sensor fusion and simple algorithm for estimating the attitude and altitude for the quadrotor. Section VI presents controller design that used to verify the identified parameters. Finally conclusion remarks are shown in Section VII.

II. DYNAMIC MODELING

The quadrotor dynamic model is presented in this section to emphasis the importance of the quadrotor parameters identification and to be used as a basis for the control synthesis presented latter. Fig.1 presents the corresponding torque, force, and angular velocity of each propeller. There are some assumptions for the dynamic model. First the quadrotor structure is symmetrical and rigid. Second the

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propeller has a fixed pitch angle. Finally the center of mass (CM) is coincident with the geometrical center (GC). To accomplish the dynamic model of the quadrotor; two frames have to be defined. The first one; body Frame {B}, OB – $x_B y_B z_B$ whose origin is coincident with the center of mass (CM). Second is the earth frame {E}, O_I –xyz, where position and orientation of the body frame is described with respect to it. Let's define the rotation matrix R_I^B which expresses the transformation from the inertial frame to the body frame [1, 4, 6, 9].

$$R_I^B = \begin{bmatrix} C(\psi)C(\theta) & S(\psi)C(\theta) & -S(\theta) \\ -S(\psi)C(\phi) + C(\psi)S(\theta)S(\phi) & C(\psi)C(\phi) + S(\psi)S(\theta)S(\phi) & C(\theta)S(\phi) \\ S(\psi)S(\phi) + C(\psi)S(\theta)C(\phi) & -C(\psi)S(\phi) + S(\psi)S(\theta)C(\phi) & C(\theta)C(\phi) \end{bmatrix} \quad (1)$$

Where $C(\phi)$ denotes $Cos(\phi)$, and $S(\phi)$ denotes $Sin(\phi)$. Also ϕ, θ, and ψ are roll, pitch and yaw angles respectively. These angles indicate the rotation about x, y and z of the fixed frame.

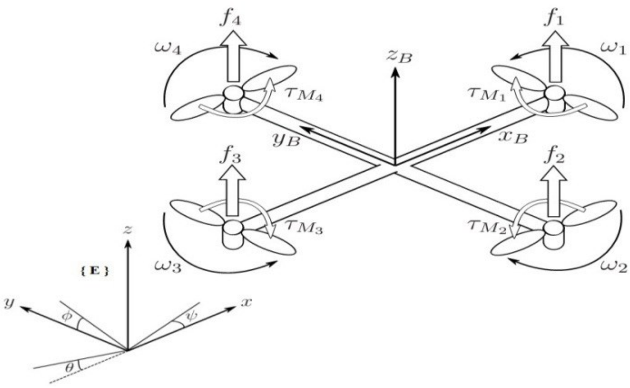


Figure 1. Schematic of Quadrotor System

From Fig.1, the angular velocity of rotor i, denoted with ω_i, creates a thrust force f_i and drag moment τ_{Mi}. Based on the momentum theory, both thrust force and drag moment are proportional to the square of the angular speed of the propeller. The consumed power of rotor i, P_i, is the drag moment times the angular velocity as stated in the following equations.

$$f_i = k_t \omega_i{}^2 \quad (2)$$
$$\tau_{Mi} = k_d \omega_i{}^2 \quad (3)$$
$$P_i = \tau_{Mi}\omega_i \quad (4)$$

Where k_t and k_d are the thrust force and drag moment coefficients respectively. The aggregation of rotor thrust forces, T, is directed along the z-axis of the body frame. Moments that applied to the quadrotor's body are denoted as τ_ϕ, τ_θ and τ_ψ. These moments are the rolling, pitching, yawing moment about x-, y-, and z-axis of the body frame respectively. The equation of motion of the quadrotor is obtained using Newton-Euler formalism. The linear acceleration is expressed in the inertial frame.

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} C(\psi)\,S(\theta)\,C(\phi) + S(\psi)S(\phi) \\ S(\psi)S(\theta)C(\phi) - C(\psi)S(\phi) \\ C(\phi)\,C(\theta) \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \dot{\theta}\dot{\psi}(I_y - I_z)/I_x \\ \dot{\phi}\dot{\psi}(I_z - I_x)/I_y \\ \dot{\phi}\dot{\theta}(I_x - I_y)/I_z \end{bmatrix} - I_r \begin{bmatrix} \dot{\theta}/I_x \\ \dot{\phi}/I_y \\ 0 \end{bmatrix} \overline{\Omega} + \begin{bmatrix} \tau_\phi/I_x \\ \tau_\theta/I_y \\ \tau_\psi/I_z \end{bmatrix} \quad (6)$$

Where, $\overline{\Omega} = \omega_1 - \omega_2 + \omega_3 - \omega_4$ (7)

ϕ, θ, and ψ are assumed small angles in the derivation of equation (6). From the previous equations of motion four control inputs u_t, u_ϕ, u_θ and u_ψ are responsible for achieving the quadrotor movements. These control signals are defined as follows:

$$u_t = k_t(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \quad (8)$$
$$u_\phi = lk_t(-\omega_2^2 + \omega_4^2) \quad (9)$$
$$u_\theta = lk_t(-\omega_1^2 + \omega_3^2) \quad (10)$$
$$u_\psi = k_d(-\omega_1^2 + \omega_2^2 - \omega_3^2 + \omega_4^2) \quad (11)$$

Where, l is the distance between the center of rotor and the center of mass. A lot of parameters presented in the previous equations are anonymous. They will be identified in the next sections.

III. Quadrotor Structure Parameters

A CAD model, as shown in Fig.2, is developed using SOLIDWORKS by modeling all the parts of the quadrotor. The modeled parts are motors, electronic parts, battery and the aluminum frames, which are assembled together. The rotor arms are manufactured from aluminum sheet 1 mm thickness. These arms are engraved to lighten the total weight and decrease the resistance of aerodynamics during flying. All these holes complicate the calculations of the mass moment of inertia using the principal laws. So, the mass moments of inertia of the quadrotor structure and rotors are extracted directly from the CAD model in our methodology.

The inertia matrix obtained from the CAD model is diagonal and positive definite. Table.1 presents the mass moment of inertia about x-, y- and z-axis of the body frame, total mass, the mass moment of inertia of the rotor I_r and center distance l between the rotor axis and the quadrotor center.

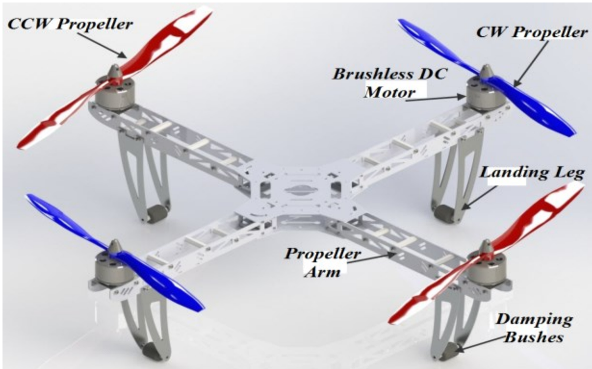


Figure 2. Quadrotor CAD Model

TABLE I. Quadrotor Parameters

Parameter	Value	Unit
I_x	13.215 X 10^{-3}	$kg.m^2$
I_y	12.522 X 10^{-3}	$kg.m^2$
I_z	23.527 X 10^{-3}	$kg.m^2$
I_r	33.216 X 10^{-6}	$kg.m^2$
l	223.5 X 10^{-3}	m
M	0.952	Kg

IV. Rotor Assembly Identification

The rotor assembly (ESC, motor, and propeller) is the most important part which delivers the lifting force that permits the quadrotor to fly. This assembly is consists of an electronic speed controller (ESC), brushless DC motor and propeller EPP1045 type that has two blades. To identify the rotor assembly, it is needed to find the relationship between input and output of each motor. Motor voltage is the input of the rotor assembly. However, Pulse Width Modulation (PWM) is used as input for its simplicity and it can be directly programmed using Microcontroller. Outputs of propeller-motor assembly are angular velocity, thrust force and drag moment. In this section two experiments are presented to identify the relationships between PWM input signal, and the outputs.

A. Angular Speed Identification

The problem is that no direct relationship between the motor input signal and the propeller angular speed exists. The input signal is PWM which is generated precisely using Arduino Mega 2560 Microcontroller Unit (MCU). PMW signal in this case has a limited boundary from 1000 to 2000. Motors have no response in case of PWM values smaller than the lower limit. On the other hand, a saturation phenomenon occurs for values larger than the upper limit of PWM. An optical tachometer device is required to measure the output angular velocity of the propeller in order to establish a direct relationship between PWM, and the angular velocity. This instrument is expensive.

A solution for this problem is developed by using a simple microphone placed 2 cm over the tip of the propeller to work as a rudimentary tachometer. Fig.3 shows a clamping vice used to clamp the quadrotor during the test as well as other components used for the identification test. Microphone holder is used to ensure that the position over the propeller tip is high enough to avoid hitting by the propeller.

The concept of using microphone as a rudimentary tachometer is simple to understand. At each time the propeller pass under the microphone the air between the propeller and microphone is sucked downward. In this case the microphone records the suction pulses. The most interesting is the microphone readings which can be captured in real time using MATLAB. This data is processed to obtain the number of pulse-pairs per unit time which indicate the angular velocity accurately. The experiments are made as follows. First, the readings are captured after 30 seconds from starting the motor rotation, which make the motor reach to the steady state condition. Then suction pulses are recorded for 5 seconds. This process is repeated three times for each PWM signal. Finally; these values are averaged to determine the angular velocity for each motor at different input PWM.

The rotor angular speed is calculated by measuring the period time between each passage of the propeller blades T_p:

$$\omega = \frac{\pi}{T_p} \tag{12}$$

Fig.4 shows a sample signal from the propeller sound. It can be noticed that each two pulses can indicate a complete turn for the propeller. One can notice from Fig. 4 that the ratio between noise and pressure signal is very low. So, it is possible to identify the sound pressure waves clearly due to the rotation of the propeller. The input/output data is gathered for one motor. This data is used to determine the relationship between PWM, and rotor's angular speed. Continuing with the rotor assembly identification; all the rotors' obtained data are plotted in Fig. 5. It was found from the fitting that there is a linear relationship between the PWM, u, and the squared angular velocity as shown in (13). It was observed from Fig. 5 that the four rotors are not identical in their angular velocities at the same value of PWM.

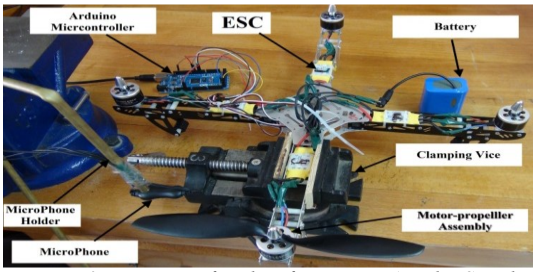


Figure 3. Test Rig for identifying Rotor Angular Speed

$$\omega_i^2 = a_i u_i + b_i \tag{13}$$

After finishing the identification; constants for the four motors are obtained. Table II presents the values of these constants which satisfy the linear relationship (13). It is easy now to obtain precise values for angular velocity to help in building a robust controller.

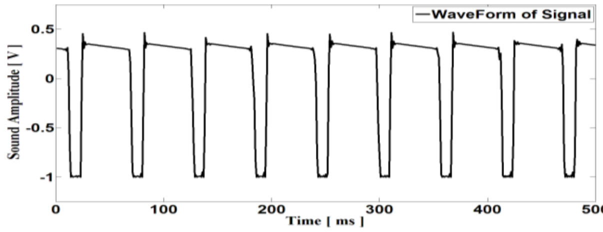


Figure 4. *Propeller Sound Signal*

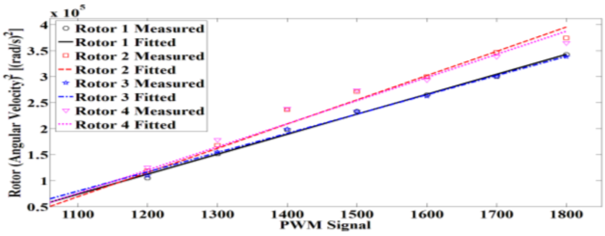


Figure 5. Relationship Between motor PWM and rotor angular velocity

TABLE II. CURVE FITTING PARAMETERS

Parameter	*Rotor 1*	*Rotor 2*	*Rotor 3*	*Rotor 4*
a	*420.5*	*466*	*411.4*	*445*
b	*-4.06*e+5*	*-4.43*e+5*	*-3.92*e+5*	*-4.13*e+5*

B. Thrust force and Drag Moment Identifications

In this section a new test rig is developed to measure the thrust force and drag moment simultaneously. The test rig consists of a lever arm of 50 cm length and 25X25X1 mm hollow square cross section. The arm is pivoted at its center point by steel pin of 10 mm diameter. Rotor is mounted on one end of the lever arm using 4 screw bolts, M2.5. On the other end, electronic balance is mounted under the lever arm. This lever mechanism is clamped from the pivot pin to a clamping vice to prevent it from flying.

The concept of this lever mechanism is that the propeller rotation produces a vertical upward thrust force. This force tends to rotate the lever arm about its pivot pin, and hence generates an equivalent downward force at the other end of the arm. This force can be measured using an electronic balance. The thrust force at certain motor speed is equal to the difference between the balance reading at this motor speed and the balance reading at zero motor speed. On the same time the drawn current and voltage are measured as shown in

Fig. 6. The consumed power by the motor is then calculated, and from (1) the drag moment is determined.

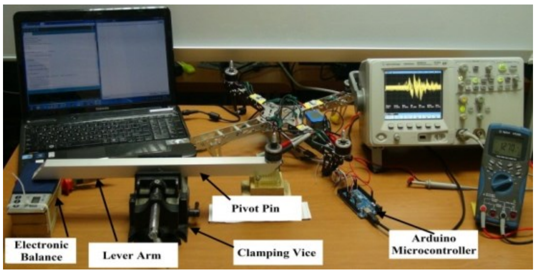


Figure 6. Test Rig for Identifying Thrust Force and Drag Moment

The tests are carried out by varying the PWM from 1060 µs to 1800 μs, to obtain the measurements of thrust, drawn current and voltage. Gathering data for all motors is made by repeating the previous procedures. This data is plotted then fitted. It is observed that there are linear relationships between PWM and both thrust force and drag moment as shown in Fig. 7 and Fig. 8 respectively. TABLE III presents the values of the constants in equations (14, 15) which express these linear relationships.

$$f_i = c_i u_i + d_i \tag{14}$$

$$\tau_{mi} = e_i u_i + \mathrm{h}_i \tag{15}$$

It can be noticed from Fig.7, and Fig.8 that the motors are not identical, and having variance in the thrust forces, and the drag moments.

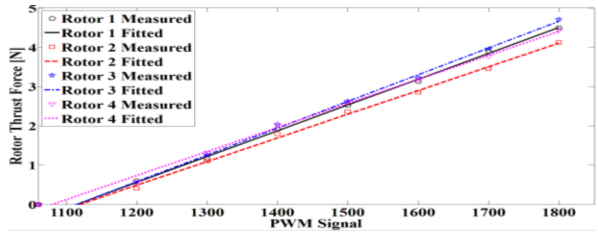


Figure 7. Relationship between motor PWM and rotor thrust force

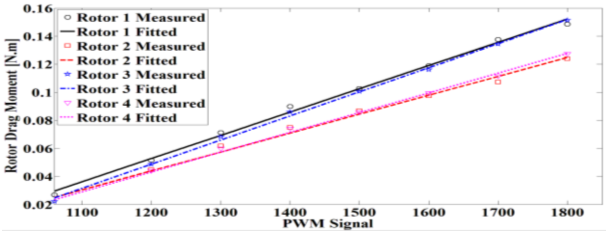


Figure 8. Relationship between the motor PWM and rotor drag moment

TABLE III. CURVE FITTING PARAMETERS

Parameter	*Rotor1*	*Rotor 2*	*Rotor 3*	*Rotor 4*
c	*0.6566*	*0.6029*	*0.6805*	*0.6119*
d	*-731.4*	*-674.4*	*-758.3*	*-660.5*
e	*0.0001658*	*0.0001348*	*0.000172*	*0.000141*
h	*-0.1462*	*-0.1178*	*-0.1577*	*-0.126*

Transformation from the motors signals u_1, u_2, u_3, and u_4 to system thrust and moments u_t, u_ϕ, u_θ, and u_ψ is derived by substituting in (2, 3) by (14, 15). It is as follow:

$$u_t = c_1 u_1 + c_2 u_2 + c_3 u_3 + c_4 u_4 + d_1 + d_2 + d_3 + d_4 \tag{16}$$

$$u_\phi = l c_4 u_4 - l c_2 u_2 + (l d_4 - l d_2) \tag{17}$$

$$u_\theta = l c_3 u_3 - l c_1 u_1 + (l d_3 - l d_1) \tag{18}$$

$$u_\psi = -e_1 u_1 + e_2 u_2 - e_3 u_3 + e_4 u_4 - h_1 + h_2 - h_3 + h_4 \tag{19}$$

From the last equation (21), it is now clear after the identification the direct relationship between the motors input signal, and the quadrotor input thrust and moments. The previous equations make the rotor control and its implementation into an embedded system easier which helps in achieving robustness. Finally all the quadrotor parameters are estimated, and they will be tested in Section VI.

$$\underbrace{\begin{bmatrix} u_t \\ u_\phi \\ u_\theta \\ u_\psi \end{bmatrix}}_{U} = \underbrace{\begin{bmatrix} c_1 & c_2 & c_3 & c_4 \\ 0 & -lc_2 & 0 & lc_4 \\ -lc_1 & 0 & lc_3 & 0 \\ -e_1 & e_2 & -e_3 & e_4 \end{bmatrix}}_{G} \underbrace{\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}}_{u_i} + \underbrace{\begin{bmatrix} d_1 + d_2 + d_3 + d_4 \\ ld_4 - ld_2 \\ ld_3 - ld_1 \\ -h_1 + h_2 - h_3 + h_4 \end{bmatrix}}_{A} \tag{20}$$

$$[u_i] = G^{-1}\{[U] - [A]\} \tag{21}$$

V. IMU SENSOR FUSION

Sensor fusion is a term used to combine the data of different types of sensors to enhance the accuracy of the measurements, and decrease the level of noise as much as possible. A Multiwii ZMR board type is used as an IMU which consists of high quality MEMS sensors. The board containing a three axes gyroscope (ITG3205), a three axes accelerometer (BMA180), a three axes magnetometer (HMC5883L), and embedded pressure sensor (BMP085). All these sensors are connected to ATMEGA 328P microcontroller on the same board as shown in Fig. 9. This microcontroller handles all the readings from all sensors through an I^2C bus. IMU sensor fusion is to combine all the sensors readings to estimate the orientation of the quadrotor namely roll, pitch, and yaw angles as well as their rate. Multiwii ZMR board in connected via serial port to Arduino Mega2560 MCU, which has the main control algorithm.

The main objective is to estimate the Euler angles of the quadrotor, in order to use these angles as feedback signals for quadrotor attitude stabilization. These angles cannot be estimated using a single sensor, because each sensor has its own problem. The disadvantage of accelerometer is mechanical vibration, whereas drift in gyroscope. Direction cosine matrix (DCM) complimentary filter algorithm is used to estimate the quadrotor attitude [19, 20]. DCM is used to transform from the body frame to the earth frame. Then a complimentary filter is used to estimate the roll, and pitch angles based on the gyroscope and accelerometer data which are fused together. The usage of gyroscope is to make fine tuning for the DCM matrix which is returned by the accelerometer. Another complementary filter is used to estimate the yaw angle by fusing the gyroscope and magnetometer data as shown in Fig. 10. Gyroscope is used with magnetometer to enhance the yaw angle determination relative to the earth's magnetic north. Finally the altitude is estimated using the pressure sensor.

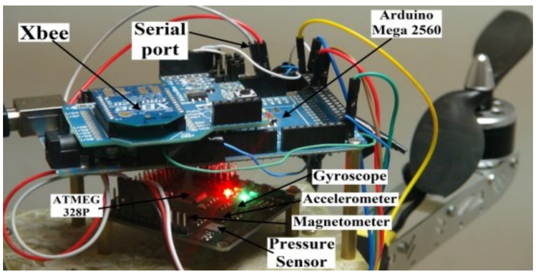


Figure 9. IMU, and Arduino board connection

VI. Testing and Results

After identifying all the quadrotor parameters and constructing the attitude estimation algorithm, their verification and testing are desired. So, this section describes a control system design based on the technique of feedback linearization which is used to test the attitude stabilization of the quadrotor using the identified parameters. Feedback linearization [21] is used to transform the nonlinear system dynamics into a linear system. The control laws are chosen so that we can obtain a good tracking performance. The controllers' laws for the attitude namely roll, pitch, and yaw angles are stated as follows:

$$u_\phi = I_x\, U_\phi \;-\; \dot{\theta}\dot{\psi}(I_y \;-\; I_z) \;+\; I_r\, \dot{\theta}\, \Omega \tag{22}$$

$$U_\phi = \ddot{\phi}_d + K_{p\phi}e_\phi + K_{d\phi}\dot{e}_\phi + K_{i\phi}\int_0^t e_\phi dt \tag{23}$$

$$u_\theta = \; I_y\, U_\theta \;\; - \; \dot{\phi}\dot{\psi}(I_z \;-\; I_x) \;-\; I_r\, \dot{\phi}\, \Omega \tag{24}$$

$$U_\theta = \ddot{\theta}_d + K_{p\theta}e_\theta + K_{d\theta}\dot{e}_\theta + K_{i\theta}\int_0^t e_\theta dt \tag{25}$$

$$u_\psi = I_z\, U_\psi \;\; \text{-}\, \dot{\phi}\dot{\theta}\,(I_x \text{ -} I_y) \tag{26}$$

$$U_\psi = \ddot{\psi}_d + K_{p\psi}e_\psi + K_{d\psi}\dot{e}_\psi + K_{i\psi}\int_0^t e_\psi dt \tag{27}$$

Where K_p, K_d and K_i are the proportional, differential and integral gains respectively. These gains are tuned manually to obtain a satisfied controller performance. Table IV presents the used controller gains.

TABLE IV. Controller Gains

Parameter	K_p	K_i	K_d
Roll	*100*	*10*	*1*
Pitch	*85*	*10*	*1*
Yaw	*0.01*	*250*	*260*

Two different test rigs are constructed to check the identified parameters of the quadrotor and attitude estimation. Fig.11 presents the rig which is used to perform stabilizing control of roll, and pitch angles. This rig is a wooden bracket used to support the quadrotor. It contains two holes to mount two cylindrical supports. Then the quadrotor is fixed to these supports. These supports allow the rotation about x-axis or y-axis. The controller which presented in (23), (25), and (27) has been implemented. These controllers are executed on Arduino Mega 2560 MCU, with a sampling time of 1.8ms. Arduino Mega 2560 is connected to MATLB in order to record the measured data from the test rig.

Fig. 12 presents roll, and pitch controllers' responses. These controllers achieve the stability of the quadrotor, and rotate the quadrotor successfully to the desired roll and pitch angles. For the roll angle a small oscillation happens that ranges from 0.5^o to -0.5^o as shown in Fig. 12a. This oscillation is satisfactory in the flying and it can be reduced by fine tuning of the controller parameters. Fig. 12b shows the response of the quadrotor to the pitch angle controller. One can notice that a very small oscillation occurs. The range of this oscillation is between 0.2^o and -0.1^o. It is accepted for flying and hovering.

The second test rig is designed to control the yaw angle. This rig consists of two cylindrical tubes. One of them is fixed to the ground using clamping vice. The other one is fixed to the quadrotor. A ball bearing is fitted between these two tubes to facilitate the rotational motion about z-axis as shown in Fig. 13. The experimental result for the yaw angle is presented in Fig.14. In this figure, one can see that the controller achieves the stability of the yaw angle although the system starts from large initial conditions.

Finally the experiments show that the quadrotor identified parameters are accurate in such way that the feedback linearization algorithm stabilizes the quadrotor in an efficient manner.

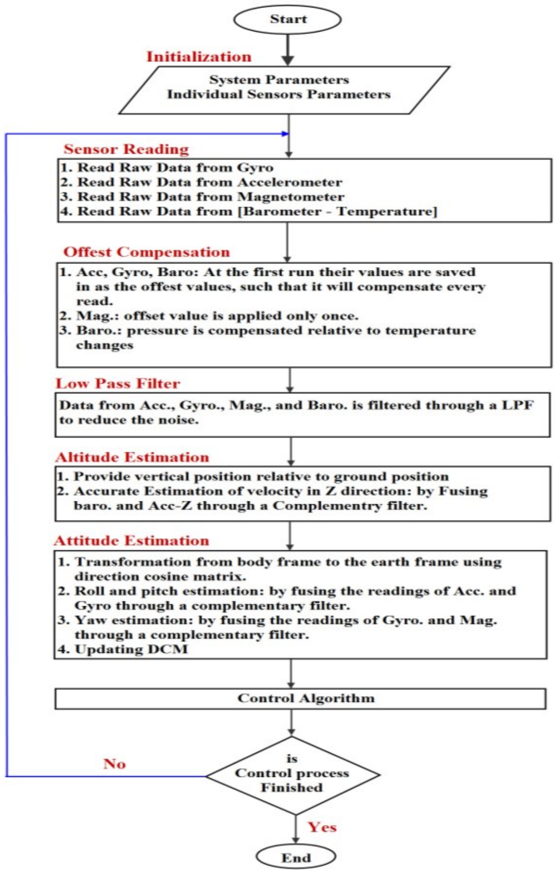


Figure 10. Flowchart for estimating attitude of quadrotor

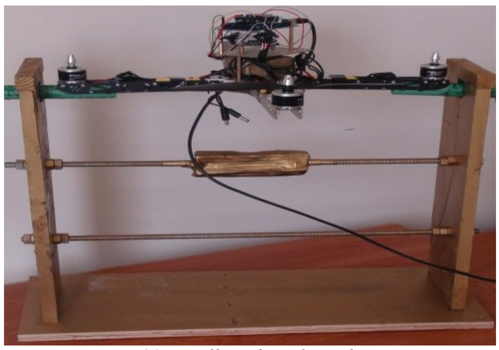
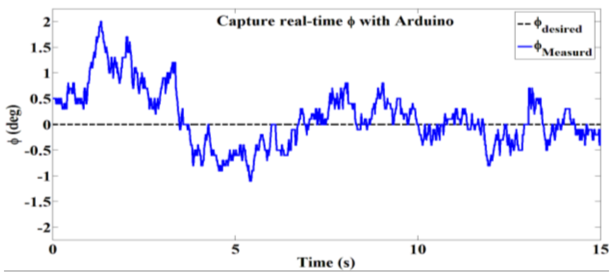
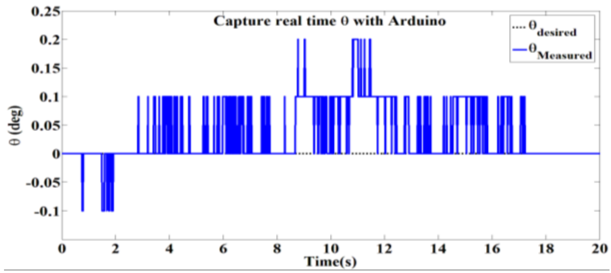


Figure 11. Roll, and pitch angle test rig



(a)



(b)

Figure 12. (a) Experimental response of roll controller, (b) Experimental response of pitch controller

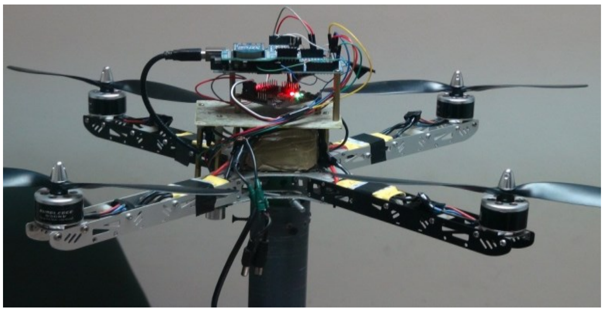


Figure 13. Yaw angle test rig

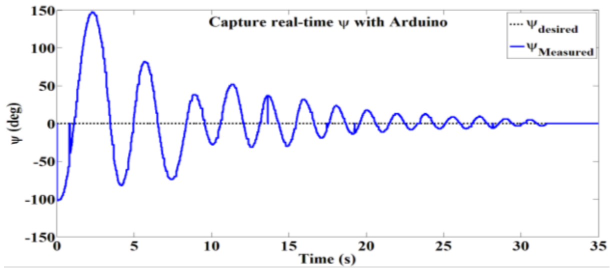


Figure 14. Experimental response of yaw controller

VII. CONCLUSIONS

In this paper a complete methodology for identifying the quadrotor parameters is presented in details. Quadrotor dynamic model is described. A CAD model was developed to calculate the mass moment of inertia in an accurate way. Direct relationships between PWM and each of the angular speed, thrust force, and drag moment of the rotors are identified. A new relationship that directly linking the quadrotor control input (forces and moments) with the motor control PWM signal is achieved and tested. A DCM complementary filter is used to estimate the attitude of the quadrotor based on the IMU measurements. Controller is designed based on the feedback linearization technique to test the identified parameters and the attitude estimation. Finally, the result of the experiments shows a satisfied accuracy of the proposed techniques of the identified structure parameters, the identified rotor assembly parameters, the used IMU with attitude estimation algorithm, and the control design for quadrotor attitude stabilization.

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