An Efficient Approach for Modeling and Control of a Quadrotor

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Abstract:

A quadrotor is a four-rotor aircraft capable of vertical take-off and landing, hovering, forward flight, and having great maneuverability. Its platform can be made in a small size make it convenient for indoor applications as well as for outdoor uses. In model there are four input forces that are essentially the thrust provided by each propeller attached to each motor with a fixed angle. The quadrotor is basically considered an unstable system because of the aerodynamic effects; consequently, a close-loop control system is required to achieve stability and autonomy. Such system must enable the quadrotor to reach the desired attitude as fast as possible without any steady state error. In this paper, an optimal controller is designed based on a Proportional Integral Derivative (PID) control method to obtain stability in flying the quadrotor. The dynamic model of this vehicle will be also explained by using Euler-Newton method. The mechanical design was performed along with the design of the controlling algorithm. Matlab Simulink was used to test and analyze the performance of the proposed control strategy. The experimental results on the quadrotor demonstrated the effectiveness of the methodology used.

الطريقة المثلى لنمذجة الطائرة الرباعية (الاكوادروتر) والسيطرة عليها

الخلاصة:

الاكوادروتر (quadrotor) هي طائرة بأربع محركات تتميز بقدرتها على الإقلاع والهبوط بصورة عامودية، وكذلك تتميز بقدرتها على المناورة بكفاءة عالية. يمكن تصنيع هذا النوع من الطائرات بأحجام صغيرة جدا مما جعلها ملائمة للتطبيقات الداخلية وكذلك للاستخدامات في الهواء الطلق. من اجل نمذجتها, يتم تمثيلها بأربع قوى تمثل المدخلات التي هي في الأساس القوة الدافعة التي تقدمها كل مروحة متصلة مع محرك دوار بزاوية ثابتة. تعتبر الاكوادروتر من الانظمة الغير مستقرة بسبب التأثيرات الهوائية اثناء الطيران. ونتيجة لذلك، لابد من توفر نظام سيطرة ومراقبة لتحقيق الاستقرار والتحكم الذاتي. هذا النظام يجب عليه تمكين الاكوادروتر بالوصول إلى الحالة المستقرة بأسرع وقت ممكن وبدون أي خطأ. في هذا البحث، تم تصميم نظام تحكم مثالي, بني على اساس (PID), للحصول على الاستقرار في عملية الطيران. سيتم شرح النموذج الديناميكي لهذه الطائرة أيضا باستخدام طريقة أويلر- نيوتن. تم تنفيذ التصميم الميكانيكي جنباً إلى جنب مع تصميم نظام السيطرة. تم استخدام برنامج المحاكاة في الماتلاب لاختبار وتحليل أداء الاستراتيجية المقترحة. أظهرت النتائج التجريبية على الطائرة متانة وفعالية الطريقة المستخدمة.

Keywords: Quadrotor, Modeling; PID Control; Vertical Take-off and Landing

1. Introduction

Unmanned aerial vehicles (UAVs) are playing an increasingly important role in many civil and military missions that are too hazardous for manned aircraft. Policing, firefighting, inspection of oil pipelines, surveying, aerial transportation, search and rescue tasks, disaster relief, indoor exploration and mapping can be mentioned as typical operations where UAVs are widely used. UAVs have many benefits over manned vehicles including the high maneuverability, decreased cost, longer endurance, minimized radar signatures, and lower hazard to crews [1]. Not surprisingly, UAVs are a common research area as attested by the growing attention received during the last years [2]. This is supported by the advances in computer and sensing technology, and the associated reduction in cost of such systems.

The maneuverability is required for many UAVs tasks; therefore, the helicopters possess advantages over classical fixed-wing aircrafts on surveillance and inspection missions because they can take-off and land in restricted area and can easily fly and hover above targets [3]. However, the dynamic model of helicopters exhibits the basic problems including under-actuation, strong coupling, multi input/ multi output and unknown nonlinearities [4]; therefore, they are extremely hard to be controlled, and "requiring advanced sensors and very fast on-board computation" [5]. In contrast, the UAV quadrotor helicopters offer the advantage of having extremely simple dynamic characteristics [6].

The great maneuverability, vertical take-off and landing, hovering capabilities and possible small size of quadrotor platform make it convenient for indoor uses as well as for outdoor purposes [7]. This flying robot has four propellers placed around a main body that can occur in one of two configurations, "plus" or "cross" shape. The rotational velocities of the four motors are independent; therefore, it is possible to control the attitude and altitude of the aircraft by the entire thrust of the four propellers whose direction alters according to the behavior of the quadrotor [6]. As such, the aircraft movement can be controlled; however, the quadrotor is unbalanced and it cannot hover in a full open-loop control scheme [8] because of uncertainties that associate with dynamic model [2]. Therefore, a close-loop controller is needed to attain stability and autonomy. The close-loop system must be constructed to be totally stable. Moreover, the desired location must be also rapidly reached without any "steady-state error". However, control of a nonlinear system, such as quadrotor, is an issue of both practical and theoretical interest [7].

There are many different techniques available to improve performance of UAV quadrotor through design and implementation of distinctive control systems that integrating restrictions related to sensors and actuators. The choice of an appropriate algorithm to be employed in a control scheme depends essentially on the intended use of the quadrotor [9]. PID (proportional integral derivative) Controller [2], Back-Stepping [10], and LQR (linear quadratic regulator) controller [11] can be cited among the most frequently used control mechanisms. In the following section a brief explanation of these mechanisms is provided.

Different Approaches of PID controller is proposed in [7] where the control objective is expressed as an "angular stabilization" of the quadrotor platform, and also as a tracking issue of selected "state variables". In that study three architectures of the PID technique have been considered in respect of "the optimal control signal" applied to the motors. The authors claimed that the conducted simulations and analysis showed the capability of the proposed PID systems to control the angles of the orientation and provide the promising requisites for practical uses. However, they did not implement their controllers with a realistic physical system. In the references [12, 13, 14], S.Bouabdallah et al. designed several controllers, including the PID controller, sliding-mode controller and back-stepping controller. W.Donget *et al.* in [15] criticized S.Bouabdallah et al. studies because those although the rigid body dynamics and many aerodynamic effects were considered by the authors; a complete dynamic model is still missing. S.Bouabdallah et al. [16] also compared the "PID and LQR" based on a dynamic model of a quadrotor. The authors in this study concluded that both controllers provide satisfactory feedback for a quadrotor's stabilization. H. Liu in [17] proposed an optimal controller that is designed based on LQR method for the desired tracking of the nominal linear system. The simulation and experimental results demonstrated the validity of the proposed control approach; however, the controller in that paper was only tested for the attitude control of the multi-rotor without consideration of the trajectory control.

As mentioned before the quadrotor inherits the characteristics in simple mechanical structure compared to the classical helicopter; however, there are still some concerns that stop it from being extensively employed in several of the suggested fields and applications. For instance, the "stabilization and guidance" of the quadrotor are difficult tasks because of its "nonlinear behavior", which means the traditional control techniques that use linear theory are not convenient. In this paper, a PID control strategy that is suitable for nonlinear systems is adapted and used to control the quadrotor.

Taking inspiration from the mentioned latter works, this paper describes the method of modeling and control of quadrotor. The performances of the controllers will be proposed theoretically and practically. The next sections explain the whole system developed. First, the quadrotor's mathematical model is explained. This is followed by explanation of the structure of the controller used. Then, the simulations supporting the objectives of the paper are presented. The system hardware architecture is then described and finally the experimental results are demonstrated.

2. System Modeling

The mathematical model of the quadrotor can be achieved by two different methods, the Lagran-gian equation and the Euler-Newton law [2]. The latter will be used in this paper because it is more comprehensible. The quadrotor can be generally modeled with four rotors in a cross shape configuration as shown in Figure 1. The front and rear actuators rotate in one direction while other two rotate in an opposite direction.

The thrust that is generated by each propeller represents one input force into the vehicle. By altering the rotor speed, one can change the lift force and generate movement. Consequently, the throttle motion is created by increasing or reducing the motor s' speed by the equivalent values. This provides a perpendicular force with respect to the quadrotor's frame which is raised up or lowered, accordingly. Pitch movement can be also attained by rising (or reducing) the rear motor's speed while decreasing (or increasing) the front motor's velocity. The roll motion is produced by raising (or reducing) the left rotor's speed while decreasing (or increasing) the right rotor's speed. The yaw movement can be gained by rising (or reducing) the front and rear motors' motion together while lessening (or increasing) the lateral motors' speed together. This should be performed while keeping the entire thrust constant [9].

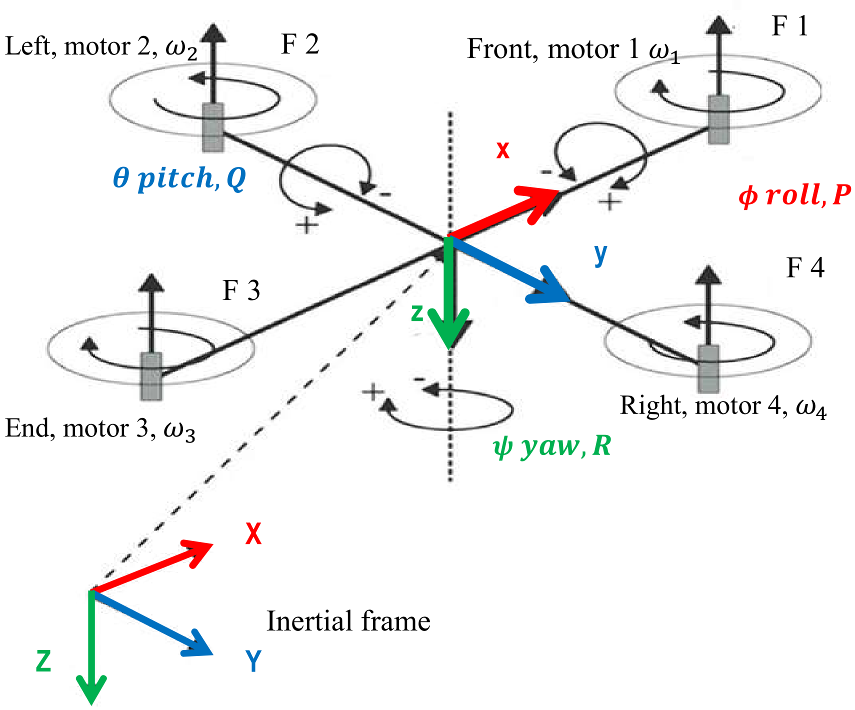


Fig. 1: The Configuration of quadrotor and relative coordinate systems

Two frames have to be defined in order to model the quadrotor dynamics as showed in Figure 1. The first is the inertial or the reference frame (Earth-fixed frame) (X, Y, Z) and the second is body-fixed frame (x, y, z). The translational and rotational motions of the quadrotors are characterized thanking to those frames. According to the aerospace rotation sequence, the orientation of the vehicle is defined by the "three Euler angles" as a revolving around the z-axis "yaw (ψ)" then a rotating about the y-axis "pitch (θ)" followed by a turning around the x-axis "roll (ϕ)".

The location of the aircraft in the "inertial frame" is specified by the rotation matrix R which transforms the motion of the quadrotor from the body frame to the reference frame [15], [18]

$$R_b^i = \begin{bmatrix} c(\theta)\,c(\psi) & (-\,c(\phi)\,s(\psi) + s(\phi)\,s(\theta)\,c(\psi)) & (s(\phi)s(\psi) + c(\phi)s(\theta)c(\psi)) \\ c(\theta)\,s(\psi) & (c(\phi)c(\psi) + s(\phi)s(\theta)s(\psi)) & (-s(\phi)c(\psi) + c(\phi)s(\theta)s(\psi)) \\ -s(\theta) & s(\phi)\,c(\theta) & c(\phi)\,c(\theta) \end{bmatrix} \quad (1)$$

Where s, c denote $\sin e\,c$ and $\cos ine$, respectively. The four revolving velocities ω_i of the motors characterize the "input variables" of the physical quadrotor; however, the transformation of the artificial input variables with respect to the mathematical model is appropriate, and it is taken from [2], [18] and modified to be

$$\begin{bmatrix} \Sigma T \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & lb & 0 & -lb \\ -lb & 0 & lb & 0 \\ -d & d & -d & d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \quad (2)$$

Where T is the "thrust force" supplied to the vehicle frame; τ_ϕ points to the force that creates the "roll torque"; τ_θ is the "pitch torque"; τ_ψ indicates the "yaw torque"; b is the thrust factor; d represents the drag factor, l is the arm's length from quadrotor's hub center to the motor; and ω_i is the "angular velocity of rotor i".

Notes that the thrust and drag factors depend on: the rotor's radius, the "cross sectional area of the propeller's rotation", and the air's density; and they can be determined by the static thrust test [18]. There is also one more set of forces that are resulting from gyroscopic precession, which is a phenomenon that occurs when the axis of rotation of a revolving body is changed. The gyroscopic forces depend on the rotating speed of the rotors ω_i, the inertia of rotating components of each motor (J_m), the rolling and pitching rates (P and Q). The gyroscopic torqueses that are generated by the motors for pitch and roll actions are determined as follow

$$\tau_{\phi_{gyro}} = J_m Q \left(\frac{\pi}{30}\right)(\omega_1 - \omega_2 + \omega_3 - \omega_4) \quad (3)$$
$$\tau_{\theta_{gyro}} = J_m P \left(\frac{\pi}{30}\right)(-\omega_1 + \omega_2 - \omega_3 + \omega_4)$$

Note that the π/30 term is to transfer from RPM to radians. If the gyroscopic torques are added into the appropriate terms in equation 2, the resulting are two matrices that are used for simulation purposes. The first is M matrix that describes the moments supplied to the quadrotor, and resulting from the aerodynamics, thrusts, and torques on the system

$$M = \begin{bmatrix} lb\omega_2^2 - lb\omega_4^2 + J_m Q\left(\frac{\pi}{30}\right)(\omega_1 - \omega_2 + \omega_3 - \omega_4) \\ -lb\omega_1^2 + lb\omega_3^2 + J_m P\left(\frac{\pi}{30}\right)(-\omega_1 + \omega_2 - \omega_3 + \omega_4) \\ -d(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \end{bmatrix} \quad (4)$$

The second is F matrix that indicates the forces act on the quadrotor from gravity and the thrust of the rotors

$$F = \begin{bmatrix} 0 \\ 0 \\ b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \end{bmatrix} \quad (5)$$

Now the first set of differential equations that describe the quadrotor's acceleration can be expressed as

$$\begin{bmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{bmatrix} = \left(\frac{1}{m}\right) F + g - \Omega\omega = \begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} \quad (6)$$

Where m denotes the entire mass of the vehicle; g represents the "acceleration of gravity"; Ω is a "cross-product matrix for rotational velocity"; and ω indicates the angular velocity around every axis in the "body frame" relative to the "inertial frame". When ϕ and θ are small, the Ω and ω matrices can be assumed to be

$$\Omega = \begin{bmatrix} 0 & -\dot{\psi} & \dot{\theta} \\ \dot{\psi} & 0 & -\dot{\phi} \\ -\dot{\theta} & \dot{\phi} & 0 \end{bmatrix} \quad \text{and} \quad \omega = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \quad (7)$$

Finally, the angular acceleration about every axis in the "body frame" relative to the "inertial frame" can be also expressed as

$$\dot{\omega} = (I)^{-1}[M - \Omega I \omega] = \begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix} \quad (8)$$

Where I is "inertia matrix that is a diagonal matrix with the inertias" I_{xx}, I_{yy} and I_{zz} on the main diagonal. Then evaluation of equations 4 to 8 yields the comprehensive mathematical model of the quadrotor in the following forms:

$$\ddot{X} = -[\cos(\phi)\sin(\theta)\cos(\psi) + \sin(\phi)\sin(\psi)]\frac{T}{m}$$

$$\ddot{Y} = -[\cos(\phi)\sin(\theta)\sin(\psi) - \sin(\phi)\cos(\psi)]\frac{T}{m}$$

$$\ddot{Z} = g - \cos(\phi)\cos(\theta)\frac{T}{m}$$

$$\ddot{\phi} = \frac{1}{I_{xx}}[\tau_\phi + \tau_{\phi_{gyro}} + (I_{yy} - I_{zz})\dot{\theta}\dot{\psi}]$$

$$\ddot{\theta} = \frac{1}{I_{yy}}[\tau_\theta + \tau_{\theta_{gyro}} + (I_{zz} - I_{xx})\dot{\phi}\dot{\psi}]$$

$$\ddot{\psi} = \frac{1}{I_{zz}}[\tau_\psi + (I_{xx} - I_{yy})\dot{\phi}\dot{\theta}] \quad (9)$$

Note that equations in (9) describe the entire dynamic model of the quadrotor by assuming that ϕ and θ are small; and disturbances and aerodynamics are negligible.

3. Controller Design

The purpose of deriving a mathematical model of the quadrotor is to assist in developing of a controller. The inputs to the system are the angular velocities of each rotor that can be controlled by the voltages across it [3]. The quadrotor is a six-degree of freedom system that is defined with twelve states [7]. Six out of twelve states determine the position (x, y, z) and the linear velocities of the quadrotor with respect to the "fixed reference frame". The other six states govern the attitude that includes the "Euler angles (ϕ, θ, ψ) and their angular rates about the body axes" [7]. The state and control vectors are defined as following:

$$\text{Outputs} = [x, y, z, \dot{x}, \dot{y}, \dot{z}, \phi, \theta, \psi, \dot{\phi}, \dot{\theta}, \dot{\psi}] \quad (10)$$

Based on the proposed dynamic models in equations (4), (5) and (9), the control system will be designed. The block diagram of this scheme, as shown in Figure 2, comprises of the attitude and position controllers. The identification of those subsystems is processed as follows.

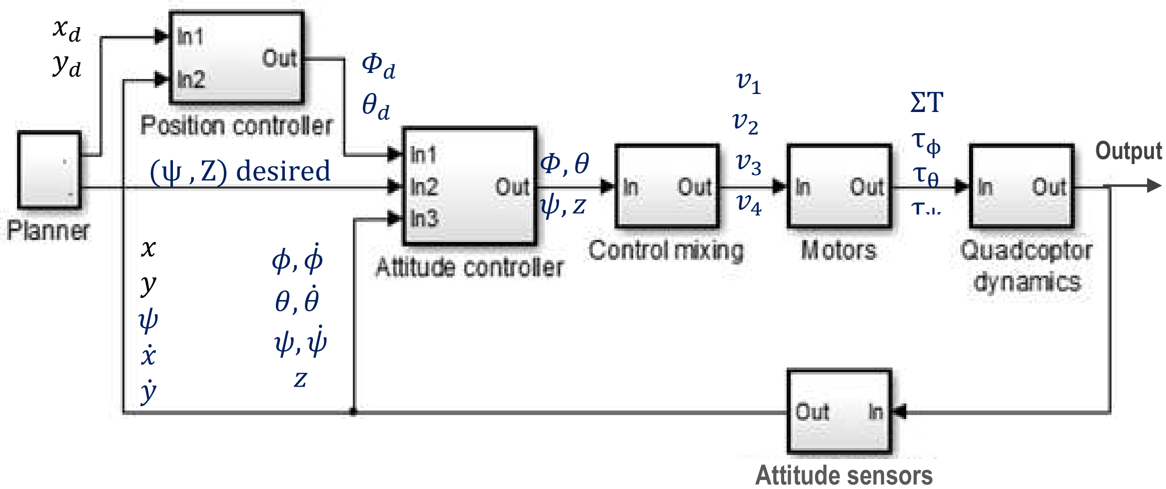


Fig. 2: The block diagram of control system

3.1 Attitude Controller

The attitude controller keeps the quadrotor's orientation within a desired value. Normally, the "pitch and roll angles" are required to be zero when the vehicle performs hovering flight [12]. This controller maintains the rates of revolution and orientations around (*x*, *y*, *z*) coordinates with an "accuracy of$\pm 2^{\circ}$". The controller determines the error $e(t)$ between the desired attitude and the state attitude of the quadrotor's frame. Proportional Integral Derivative (PID) controller (type B [7]) is adapted to control the vehicle. In control theory, the "ideal PID controller is in parallel configuration", and is described in the continuous time domain. The equation of type B PID controller is described as following:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt - K_d \frac{dy(t)}{dt} \quad (11)$$

Where K_p, K_i, K_d are proportional, integral and derivative gains, respectively. Figure 3 shows the block diagram of this controller. The attitude controller governs four components (ϕ, θ, ψ, z); thus, four PI-D controllers are needed to each variable. The corrected variable are then fed to the control mixing that provides the desired signal to each motor.

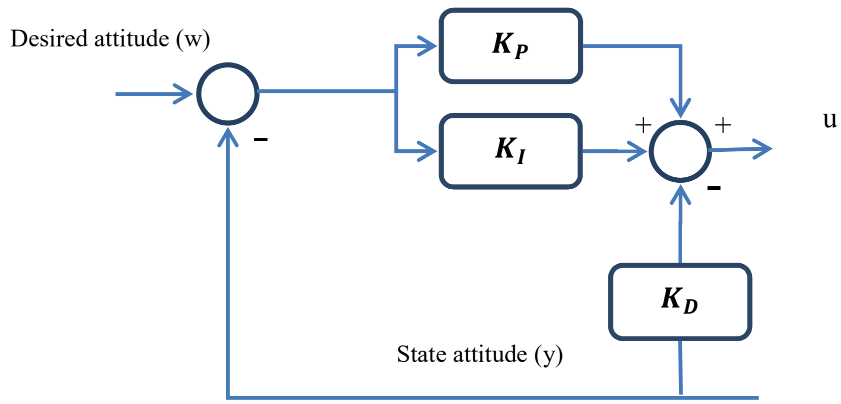


Fig. 3: PID Controller – type B [7]

3.2 Position Controller

The position controller maintains the quadrotor over the desired location that is defined by the specific "x-y horizontal position with respect to the starting point" [12]. Horizontal movement is attained by revolving the "thrust vector" towards the desired path of motion. This is performed by rolling or pitching the quadrotor in response to a deviation from the y_d or x_d references, respectively. Consequently, the position controller outputs the attitude references ϕ_d and θ_d as shown in Figure 2.

In position controller subsystem, the linear velocity is utilized as the state variable to be controlled, as this is what is adjusted by attitude. First, the error between the desired position and the state position of the body frame is determined; and then it is mapped to the desired velocity. In order to control the quadrotor, a Proportional Derivative (PD) controller that is frequently employed to control moving vehicles [19] is used (see Figure 4), with a component proportional to the error of the desired velocity and the observed velocity, and a component proportional to the derivative of the error. The output of the PD controller is then mapped to the desired attitude.

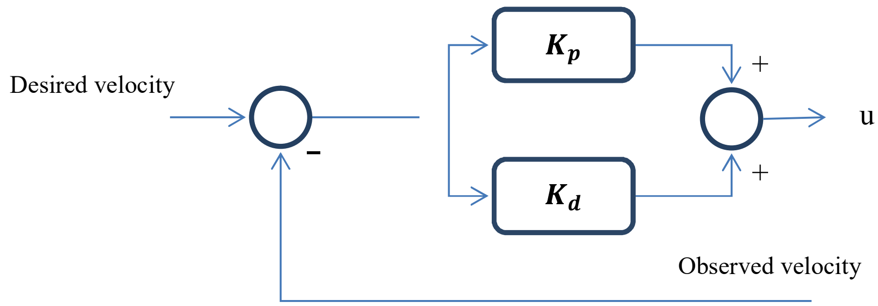


Fig 4: PD Controller

3.3 Motors

The dynamics model of the thrust system comprises of a DC motor and propeller [7]. As mentioned above, the inputs to the quadrotor are the angular velocities of each motor that can be controlled by the voltage. The DC motor's mathematical model is usually represented as in [15]

$$L\frac{d_i}{dt} + Ri + K_e\omega_m = v$$

$$J\frac{d\omega_m}{dt} = \tau - \tau_d \tag{12}$$

Where $\mathrm{L}, \mathrm{i}, \mathrm{R}$ denote the amount of inductance, current and resistance of the armature, respectively; $\mathrm{k_e}, \omega_\mathrm{m}$, v are the "back emf constant", motor's speed and armature voltage; and J, τ, τ_d denotes the motor's inertia, motor's torque and load's torque, respectively. The torque that is produced by the motor is converted by propeller to the thrust force [7]. The connection between the "angular velocities" of the rotors and the "thrust forces" is specified in Equation 2.

3.4 Attitude Sensors

This block includes all sensors that measure the actual quadrotor's states. This enables the user to characterize the real environment issues that can be faced during the implementation of a digital control system using a real microprocessor and sensors. This block enables the user to: 1) simulate the performances of the sensors that can be used, 2) explore the state of the estimation equations, and 3) see the effects of a filter that can be used.

4. The Quadrotor Configuration

When considering the hardware parameters, it is extremely important to configure the physical parameters of the quadrotor system, which mainly involves the mechanical and electronic schemes. The former comprises the chassis and movement tools, such as motors and propellers. The latter mostly consists of the main processor board, sensors and the motor-driver board, which controls and powers the motors. In this work, the main structure of the quadrotor that weighs 340g of weight contains a plus bar frame including four motors at each end. It has four 25cm long propellers where the distance between the quadrotor's hub center and the motor is 30cm. A battery of $1400\,mAh$ with a weight of $80g$ is used as the main power source. The quadrotor is equipped with a RF receiver, a microcontroller (Arduino Board [21]) for processing the sensory signals and performing the movement, four power boards to feed the motors and many sensors to offer a stable system. The microcontroller has Input/output interfaces to the servo, DC motors, sensors and other devices and uses Open source C library codes. The platform can support many types of sensors, which makes the quadrotor appropriate for many applications.

Figure 5 shows a general block diagram of the control system of the quadrotor. The objective (task) of the quadrotor can be coded in the Arduino's ROM (no external communication is required) or performed by the user through a "Remote Controller (RC)" equipped with a "RF transmitter" which sends the commands to a "RF receiver" that is attached on the quadrotor. In this work, the control codes that are needed to stabilize the quadrotor are directly implemented in the microcontroller. The sensor block comprises a magnetometer, gyroscope and compass that allow the quadrotor to compute the roll-pitch-yaw angles. Moreover, the sensor block also has a SONAR and IR module system to measure the height of the quadrotor from the ground and to provide information on the availability of the space around itself. The motors block comprises of the motors, propellers and motors' power boards. The DC motors with 3000 maximum rpm, which is controlled with electronic speed motor controllers, were used. The power boards are fundamental to deliver the voltage and current those are required by the motor.

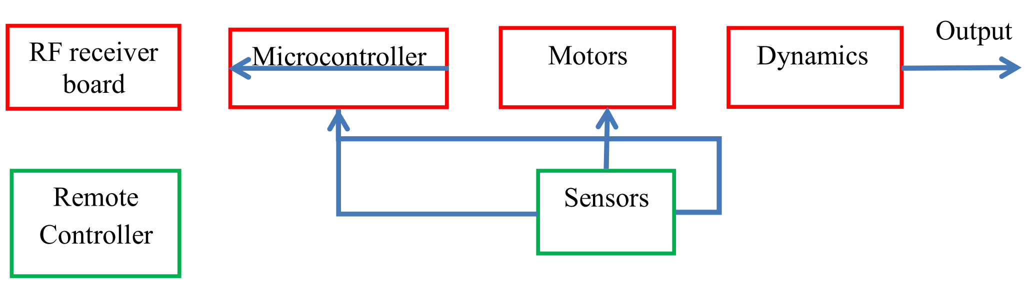


Fig 5: The general block diagram of the control system of the quadrotor

5. Experimental Results and Discussion

In order to assess the methodology used, both a real-quadrotor and simulation-based Matlab Simulink are used.

5.1 Simulation Results

A complete simulation of the mathematical model of the aircraft as well as the controllers was coded in "Matlab Simulink". The aim of this experiment was to investigate how well the controllers can stabilize the vehicle. It was also to highlight the tracking capabilities of the reported controller. For adjusting the PID controller gains Ziegler-Nichols method that is revised in [20] is adapted and used. Due to this method the PID gains are chosen to be, for example, $K_P = 2.3$, $K_I = 1.2$ and $K_D = 1.3$ in roll angle. Figures 6 to 8 show the response of the quadrotor for the "X-position, Y-position, Z-position", roll (phi-angle), pitch (theta-angle) and yaw (psi-angle). Here for each one, there is a value for an "initial (start) location and final position" in graph. There are also two plot lines for the reference (desired) values and the states (performances) of the quadrotor. For instance, Figure 6 shows an altitude reference (position desired) (red line) followed by the quadrotor's performance (blue line). The task was to climb to10 ft, hover, fly down to5 ft, hover and then land. The PID parameters were $K_P = 2.3,\ K_I = 1.2\ and\ \ K_D = 3.1$ in simulation. The slight deviation between the desired position and the performance lines in take-off and landing stages is congenital from actuators' dynamics. The take-off is performed in 2 s $(0 - 10\ ft)$ and landing in $1.6\ s$ $(5 - 0\ ft)$. It is adequate when compared with the results that are reported in [1] and [15]. Figures 7A and 7B show that the quadrotor tracks, with the available X and Y inputs, a desired trajectory. The PD gains were chosen to be ($K_P = 1$, $K_D = 0.5$) and ($K_P = 1.1$, $K_D = 0.4$) for X and Y controllers, respectively.

The attitude controller is directly related to the performance of the rotors; therefore its performance is of crucial importance. Figures 8A to 8C show the simulation results that are executed with a model that comprises actuators' dynamics and amplitude saturation. The objective was to stabilize the "orientation angles (roll (ϕ), pitch (θ) and yaw (ψ))" and keep them at zero. The PID gains for (ϕ, θ and ψ) were ($K_P = 2.3,\ K_I = 1.2,\ K_D = 1.3$), ($K_P = 2.3,\ K_I = 1.2,\ K_D = 1.3$) and ($K_P = 3.5,\ K_I = 1.2\ and\ \ K_D = 3$), respectively. As it can be realized from the plots, there is no a steady-state error remaining on the orientation angles as occurred with the reported LQ controller in [16]. The simulations results verified the capability of the designed control scheme to regulate the position and orientation of the quadrotor platform.

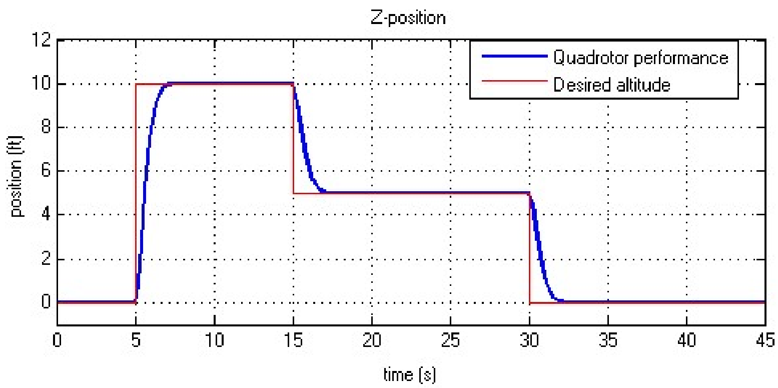
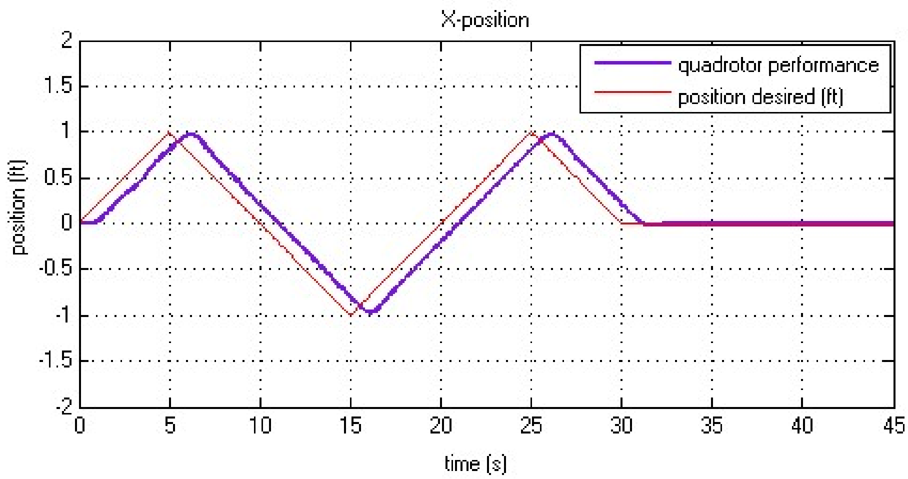
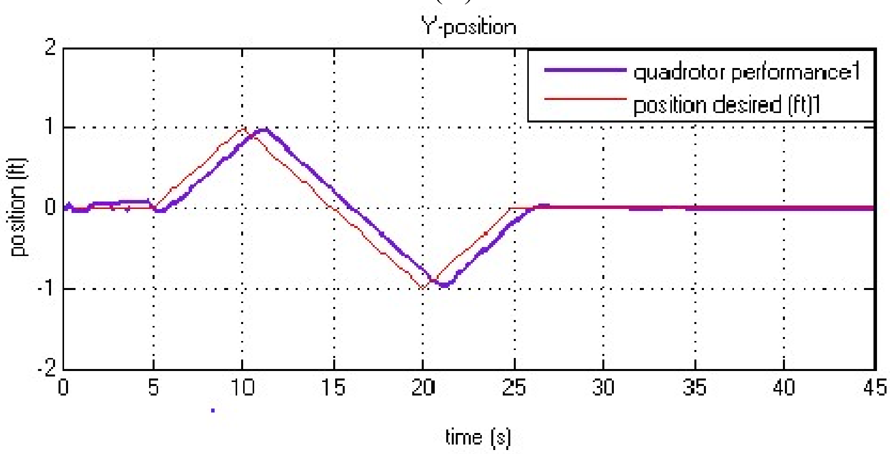


Fig. 6: Altitude control, take-off and landing in simulation

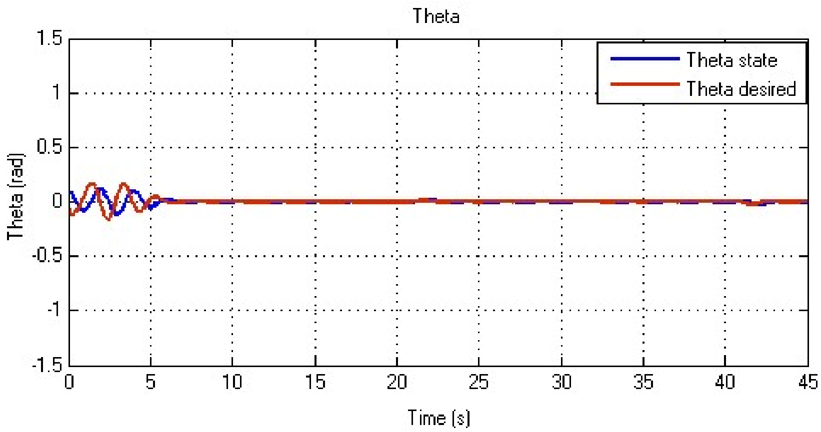


(A)

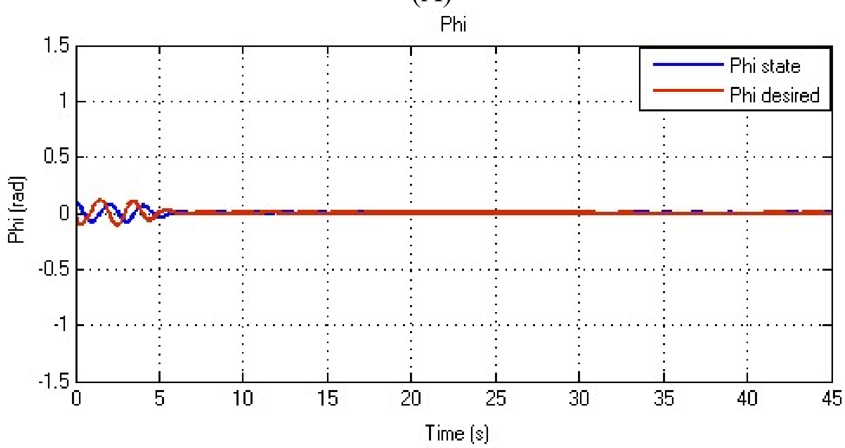


(B)

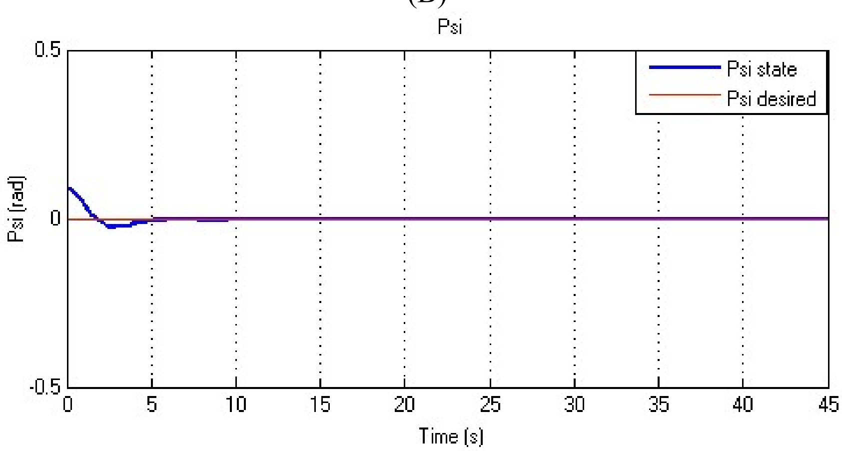
Fig. 7: Tracking of the predefined trajectory path; (A) X direction, and (B) Y direction



(A)



(B)



(C)

Fig. 8: PID attitude controller has to maintain roll (Theta), pitch (Phi) and yaw (Psi) angles to zero in flight, the controller should quickly bring the quadrotor back to equilibrium despite of the initial conditions

5.2 Experimental Results

Figure 9 shows a quadrotor that is used to test the functionality of the control system. All code was written using C languages and then tested with the quadrotor that is explained in previous section. The experiments were carried out to evaluate the control system. The experiments demonstrated that the quadrotor achieves stability and reaches the desired attitude without any steady state error. The experimental results on the quadrotor demonstrated the robustness and effectiveness of the proposed control strategy.

Fig. 9: The real-quadrotor experiment

6. Conclusion and Future Work

In this paper Euler-Newton approach has been applied for obtaining a simplified model of a quadrotor rotorcraft. The equations of motion were then driven by including major aerodynamic effects such as air friction as a linear drag force in all directions, blade element and momentum theory. The actuator's model was also identified. All equations were then used to create a simulator based on Matlab/Simulink in order to test and visualize quadrotor control mechanisms. Real experiments were carried out with the similar control parameters adjusted in simulation.

The paper proposes a control approach that allowed to design of the main controllers: attitude and position. The optimal controller was designed based on the PID control technique to attain the stability of the Quadrotor. "Ziegler-Nichols method" was used to modify the PID controller gains. The experimental results have shown that the vehicle is currently capable to "take-off, hover and land". As future work, it will be important to implement and develop some other intelligent controllers, such as a Fuzzy controller, to the quadrotor both in simulation and experiment. Then, these controllers will be compared to select the best controller in the real experiments. Moreover, it will be important to add a GPS that provides data about the global position that can be used to localize the quadrotor in its environment.

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