Evaluation the Performance of a New Quadrotor Model Based on the Arm's Length Variation

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Abstract

The field of UAV has exceptional level of growth; in addition it is predictable to be one of the most prevalent fields of development and research in future. The unmanned aerial vehicle (UAV)- quadrotor widely used as a service robotic in several fields. This paper presents a new design of this miniature aerial vehicle in altitude and attitude movements, based on varying the arm's length of quadrotor instead of varying the speed of motors to obtain a rotation around each axes. The length of arms varying are achieved by fixing a stepper motor in each arm of quadrotor to increase or decrease the length of these arms according to controller command for attitude movement. The controller commands are accomplished by designing a PID controller with specific parameters to maintain the stability of the quadrotor in the flight path. A MATLAB software code used to evaluate the simulation results and demonstrate the ability of the proposed design to perform a mission.

Keywords: arm's length; PID controller; quadrotor, trajectory tracking, UAV.

1. Introduction

The autonomous miniature aerial vehicle has attracted the interest of researchers and represents a challenge in the world of Unmanned Aerial Vehicle (UAV) from few years ago. One of the UAV is the quadrotor, which has an endless list of applications in civil, military and commercial. Therefore, the quadrotor included the tasks of search rescue, fire monitoring in the forest, the inspection in contaminated with nuclear radiation areas, where human pilot not desirable to be there. The quadrotor is underactuated nonlinear system [1]. It has exceptional advantage over helicopter and other multi-rotor aerial vehicle according to its simple mechanical arrangement, weight, size, minimum cost and without any risk to human life [2], and it has the ability to payload. Major disadvantage in quadrotor is the consumption of energy [1] this means the lower endurance for life time.

The conventional quadrotor structure comprises of four motors which are arranged such that two motors rotate counter clockwise in frontal and rear, and other two motors in the lateral rotate clockwise. This arrangement of motors achieves stability in hover and the total momentum of the system equiponderant [3]. Many methods have been proposed to develop the quad rotor model and validation. In [4], the structure of quadrotor was comprised of four propellers, three of them were horizontally placed to control the roll and pitch whereas the fourth was vertically placed to control the yaw rotation. . But the authors conclude that the dynamic model was difficult to derive and cannot get the accurate model. In [5], a new design for quadrotor was presented by tilting propellers to solve the problem of under- actuated system. In which the normally fixed propellers are permitted to tend about the body axes of quadrotor.

Another papers adopted the controller design to achieve the stability of quadrotor. In [1] the altitude and yaw channel are controlled by using PD controller and backstepping based on PID are used to control the attitude. In [6] the PID controller is used for developing the stability of pitch, roll, yaw and altitude of the vehicle. Unfortunately, the system contains some transient overshoot because of disturbance and some other reasons like some certain of mechanical parameter and simplification of the controller. . In [7], the position and altitude of quadrotor are controlled by using PID controller in the condition of wind gust and conclude that the controller worked effectively under this condition. In [8], the PID based on feedback linearization combined with block control technique are used for controlling the position of quadrotor. This technique mathematically complex may have some fault in the mathematical model leads to a fault in the design, and the performance of the system is slow.

In this paper, a new model for quadrotor attitude is proposed based on varying the length of arms to generate variable torque without altering the motors' speed. This torque has the ability to rotate the attitude angles of quadrotor to the desired orientations and keeping quadrotor balance. Varying the arms' length have been done by using stepper motor in each arm to increase or decrease the length of arm depending on controller command. The PID controller is used to control the altitude, attitude, and position movements for stabilization requirement of quadrotor.

The rest of the paper is arranged as, section 2 shows the conventional quadrotor design, section 3 the proposed quadrotor design, section 4 presents the dynamic model of quadrotor, section 5 presents the control strategy which include the altitude, attitude, and position controller algorithm, section 6 included the simulation results and finally, section 7 included the conclusion.

2. Conventional Quadrotor Design

The conventional quadrotor consist of four motors fixed on the end of a cross frame and motors speed are controlled to produce a lift force [3]. Quadrotor is under-actuated nonlinear system with four input forces and six output motions. Each motor produces torque and force, the collection of all motors are produced the main thrust, the pitch torque, the roll torque and the yaw torques. The force generated from each motor f_i is proportional to the square of the angular velocity ω^2, such that $f_i=k(\omega_i)^2$, where $k > 0$ and constant.

Finally, the front motor (m_1) and the rear motor (m_3) rotate counter clockwise (C.C.W). The right motor (m_2) and the left (m_4)are rotated clockwise (C.W). This arrangement in motors' rotation is to maintain balance [2]. The transitional and rotational movements of conventional quadrotor are illustrated clearly in [9].

3. Proposed Quadrotor Design

The quadrotor faces many problems, the main problem is the consumption energy during flight and maneuverability due to varying the speed of four motor. Where, at least the speed of one motor must be increased to perform rotational movements, this mean lower endurance time. Herein, for roll rotational movement about the x-axis, the arms length related to lateral motors; one of them most be increased and another must be decreases as shown in Fig.1(c) and (d). The other two motors in frontal and rear must be fixed at the same length while the speed of four motors will be fixed. In the same manner, to achieve the pitch rotational movement about the y-axis, but the arms' lengths related to frontal and rear motors must be varying, whereas the arms lengths related to lateral motors must be fixed as shown in Fig.1 (a) and (b).

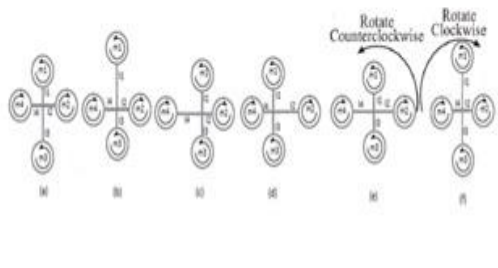

Fig. 1. Quadrotor's motion due to the proposed design

The yaw rotational movement achieved by increasing the arm's length of two motors and decreasing the arm's length of two other motors with fixed the speed of the four motors. When the propeller rotate (C.W) then it is generates a torque in (C.C.W). The quadrotor rotates in the direction of the greater torque as shown in Fig.1(e). This approach done by using stepper motor fixed in each arm which produces stepping rotation, the arm's length varying due to the stepping rotate of the stepper motors, when the stepper motor rotate (C.C.W) the arm's length increased and when the stepper motor rotate (C.W) the arm's length decreased [10].

The stepper motor fixed inside the fixed arm at a specific distance, the sliding arm is connected with the rotate shaft of the stepper motor. Therefore, when the stepper motor controlled to produce step rotate in C.W the sliding arm is sliding out of the fixed arm to increase the quadrotor total arm, if the stepper motor shaft rotate C.C.W the sliding arm is sliding inside the fixed arm and the total arm length will decrease.

Consequently, the increasing and decreasing in the arms length implemented according to the Eq.(1) and Eq.(2). The arms that increased will have maximum length and the arms that decreased will have the minimum length as illustrated in [10]

$$(l_f + l_m + L) + \Delta d.\ (l_f + l_m) = \text{maximum length} \quad (1)$$

$$(l_f + l_m + L) - \Delta d.\ (l_f + l_m) = \text{minimum length} \quad (2)$$

Where l_f is the fixed arm, l_m is the diameter of the motor, ($L + l_f + l_m$) represent the normal arm, L is specific length to ensure the freely movement in sliding arm, Δd the rate of change in the sliding arm

4. Dynamic Model of Quadrotor

The motion of any rigid body in space can be represented by rotational and translational motions [3]. Quadrotor is nonlinear system with (6_DOF) and only four inputs which are motor speed, 3-translational and 3-rotational motion as shown in Fig 2.

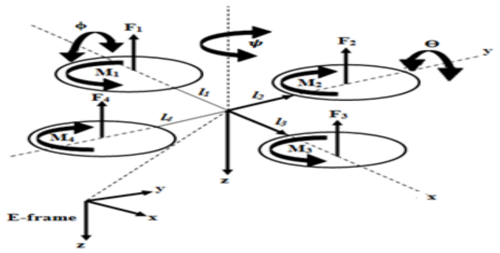

Fig. 2. Quadrotor coordination

The thrust force and control torque which acting on the quadrotor body is generated by the propellers rotation. The dynamic equations of quadrotor in the body frame are extracted from Newton- Euler form as in [8].

$$\begin{aligned}
m\ddot{x} &= u_1(\sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi) - k_1\dot{x} \\
m\ddot{y} &= u_1(-\sin\phi\cos\psi + \cos\phi\sin\theta\cos\psi) - k_2\dot{y} \\
m\ddot{z} &= u_1(\cos\phi\cos\theta) - mg - k_3\dot{z} \\
I_x\ddot{\phi} &= (I_y - I_z)\dot{\theta}\dot{\psi} + u_2 - k_4\dot{\phi} \\
I_y\ddot{\theta} &= (I_z - I_x)\dot{\phi}\dot{\psi} + u_3 - k_5\dot{\theta} \\
I_z\ddot{\psi} &= (I_x - I_y)\dot{\phi}\dot{\theta} + u_4 - k_6\dot{\psi}
\end{aligned} \quad (3)$$

Where m represents the body mass of quadrotor, I=diag(I_x, I_y, I_z) represents the moment of inertia, , x represents the linear position, the input vectors to the conventional quadrotor are defined as in [7]

$$\left.\begin{aligned}
u_1 &= b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \\
u_2 &= b.l(\omega_3^2 - \omega_1^2) \\
u_3 &= b.l(\omega_4^2 - \omega_2^2) \\
u_4 &= d(\omega_2^2 + \omega_4^2 - \omega_1^2 - \omega_3^2)
\end{aligned}\right\} \quad (4)$$

Where u_1, u_2, u_3, and u_4 are representing the input vectors to the quadrotor system, b represents the thrust coefficient, d represents the drag coefficient. According to the assumptions are mentioned in [11].

The quadrotor proposed design depends on varying the arms' lengths of motors and fixing the angular velocity. Therefore, the same thrust and drag coefficients from all motors are obtained; this means ($b_1=b_2=b_3=b_4$), ($d_1=d_2=d_3=d_4$). The change in the arms length produces variable torque around the aircraft center of mass. Thus, the induced torque is oriented the quadroto**r** to the desired attitude even the rotors speed are fixed to be constant. The total torques influential on the conventional quadrotor rotation are expressed as in [12] whereas in the proposed design will be derived as in [10]. Then the input vectors will be expressed as:

$$\left.\begin{aligned} u_1 &= b(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2) \\ u_2 &= b.\omega^2(-l_2+l_4) \\ u_3 &= b.\omega^2(-l_1+l_3) \\ u_4 &= d.\omega^2(-l_1-l_3+l_2+l_4) \end{aligned}\right\} \qquad (5)$$

Where l_i represents the arms length related to each motor.

5. Control Strategy

The quadrotor requires a stable and robust controller during the maneuverability and flight path [7]. In this paper a PID controller is applied in altitude, attitude and position.

The parameters of PID are adjusted to a specific value to reach steady state system. The equation of PID defined mathematically [7] as

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \qquad (6)$$

where k_p, k_i, k_d are the proportional, integral, and the derivative gain respectively [6], e(t) is the error signal which is the difference between the desired value and the measured value

5.1. *Altitude controller algorithm*

The quadrotor must be at desired value from the ground to maintain this distance the altitude controller is used [7]. Therefore, the quadrotor lift force must be greater than its weight and the earth's gravity to keep the quadrotor at hovering and take-off. This can be done by working on quadrotor z-axis from Eq.(3) and made x and y axis constant.

$$\ddot{z} = g - (\cos\theta\cos\phi)\frac{u_1}{m} \qquad (7)$$

In the above equation, θ and ϕ must be 0 for hovering [13] and by solving the differential equation to obtain the value of z. The error signal in altitude is $e_z = z_{ref} - z$, where, z_{ref} is the desired and z is measured output this applied in Eq. (6) to obtain the PID controller equation.

5.2. *Attitude controller Algorithm*

Quadrotor attitude controlled the angles of orientation pitch, roll, and yaw. In this paper we present only the yaw angle and only choose yaw differential equation from Eq. (3).

$$\ddot{\psi} = \frac{u_4}{I_z} - \frac{k_6}{I_z}\dot{\psi} \qquad (8)$$

By solving the differential equation can obtain ψ as the output value, so the control design for the error signal will be: $e_\psi = \psi_{ref} - \psi$ Where ψ_{ref} the desired value and ψ is the measured output signal. This applied in Eq.(6) to get the PID controller equation. At the same manner, other attitude angle (e.g Roll and itch) can be derived.

5.3 Position controller algorithm

This controller responsible for movement in x and y-axis, this movement achieved by rolling or pitching the quadrotor, the x and y equation are considered from Eq. (3) to achieve these movements.

$$\left.\begin{aligned} \ddot{x} &= -\frac{u_1}{m}(\sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \ddot{y} &= \frac{u_1}{m}(\sin\phi\cos\psi - \cos\phi\sin\theta\sin\psi) \end{aligned}\right\} \qquad (9)$$

Assume a small angle for pitching and rolling [11]. The error signal to position controller will be

$$\begin{aligned} e_x &= x_d - x \\ e_y &= y_d - y \end{aligned} \qquad (10)$$

Then, apply Eq. (10) in Eq. (6) to get the controller input which applied in Eq. (9)

6. Simulation results

The physical parameter used in simulated the result are the same used in [6]: m = 2 kg, g = 9:81 m/s2, Ix = Iy= 1:25 Ns^2/rad , Iz= 2:5 Ns^2/rad, $K_1 = K_2 = K_3$ = 0:01, Ns/m, $K_4 = K_5 = K_6$ =0:012 Ns/rad. While the chosen of the appropriate arms length as in table 1.

Table.1 Arm's length variation parameter

l_f	l_m	L (cm)	Δd	Maximum length(cm)	Minimum

(cm)	(cm)				length(cm)
17.5	2.5	5	0.25	30	20

The result shown in Fig.3 presents the performance of quadrotor and demonstrates the trajectory tracking. The path tracking include the take-off and landing of quadrotor and the way point that the quadrotor tracked are illustrated in the Fig.3.

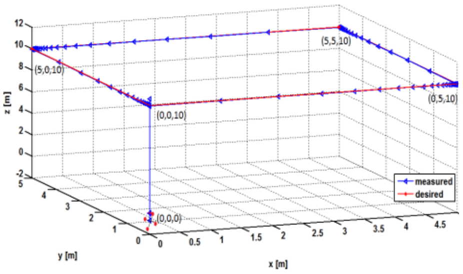

Fig.3. The path followed by quadrotor

Fig. 4 illustrated the altitude and hovering position by applying PID controller while Fig. 5 and Fig. 6 illustrated the x-position and the pitch angle respectively, when the quadrotor oriented to the desired x-position, the pitch angle change its state due to this orientation. In the same manner, Fig. 7 illustrated the y-position and Fig. 8 demonstrated the roll angle which changes its state due to y-position.

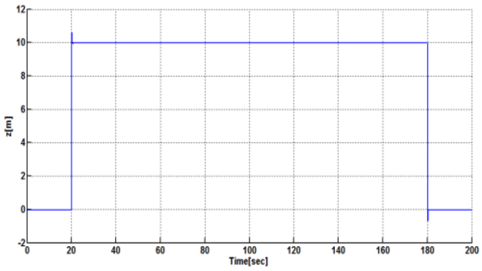

Fig.4. the z-position

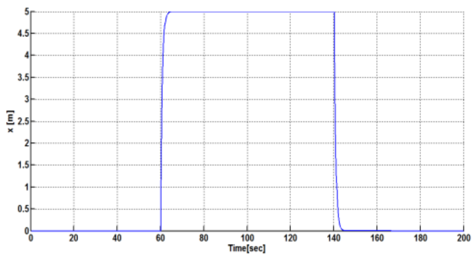

Fig.5. The x-axis position

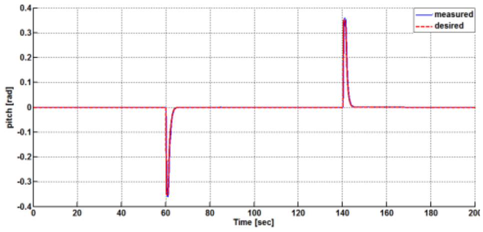

Fig. 6. The pitch angle

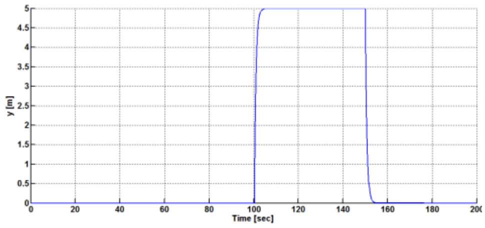

Fig. 7. The y-position

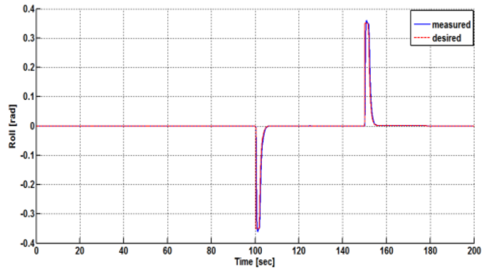

Fig. 8. The roll angle

7. Conclusion

In this paper, a new design of quadrotor is proposed depends on varying the arms length instead of varying the motors speed for performing the maneuverability. The PID controller is used in altitude, attitude, and position movements to control the stability of the system. The mathematical model of the proposed design is modeled. The simulation results evaluated the effectiveness of the proposed design with control strategy to improve the system performance.

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