

TRAJECTORY TRACKING BASED ON ARM'S LENGTH VARIATION

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ABSTRACT

Recent growth in scientific technology, integrated actuators and data processing has made the improvement in Unmanned Aerial Vehicle (UAV), quadrotor; wholly possible. In this paper, a description of a novel controlling and modeling design of quadrotor based on the variation in the arm's length with fixing the motors speed. This design is performed by utilizing a stepper motor mounted inside the fixed arm in order to increasing or decreasing the sliding arm which leads to increasing or decreasing the total arms length according to the required movement. A PD controller is used to stabilize the system performance in altitude, attitude angle and position, a new mathematical model consequent the proposed design. For the optimal selection of the arm's length, a mathematical expression is designed. A MATLAB code is adopted for the simulation to study the stability of the quadrotor response according to the proposed design and its performance in the trajectory tracking.

Keywords: *Arm's length, PD controller, Quadrotor, Trajectory tracking, UAV*

1. INTRODUCTION

The first concept of quadrotor has been launched to presence from the last decade. In 1907, First Quadrotor helicopter built by Breguet-Richet and reported to have aviation into trip [1]. Recently, the quadrotor considered as an interactive model that belong to the Unmanned Aerial Vehicle (UAV) and has many features. These features represented by its relatively small size, low cost, and uncomplicated mechanical design. This makes it elected to utilize in many applications, such as search and rescue, inspection and fire forest monitoring.

Quadrotor consists of four motors placed at the end of a cross frame. Each motor hold a propeller which responsible for creating thrust force that is lifted the quadrotor and providing the specific angle to the whole quadrotor frame during maneuverability. The balance of quadrotor is achieved by providing equal momentum around its axes when each pair in the same axis rotates in the same direction. Since, the motor pair (M2, M4) in y-axis rotates clockwise (C.W) while the motor pair (M1, M3) in the x-axis rotates counter-clockwise (C.C.W). Therefore, increasing or decreasing the all

motors speed produce relative vertical lift force. Varying the M2 and the M4 motors speed conversely generates roll rotation. The pitch rotation is achieved by varying the M1 and the M3 motors speed conversely. Yaw rotation accomplished by varying in the counter torque between the motors pairs. Since, M1 and M2 decreasing their speed while M2 and M4 increasing their speed for (C. C. W) rotation and contrary to rotate (C. W)[2]. Regardless the four motors; quadrotor is under-actuated system.

Many methods have been proposed to control the stability of quadrotor. In [3] the authors focused on design and control the quadrotor using integral Backstepping controller in (position, attitude and altitude). According to the results the vision sensors and population group must be improved to be dependable. In [4] the altitude and yaw channel are controlled by using PD controller and backstepping based on PID used to control the attitude. In [5] 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 certain of mechanical parameter and simplification of the

controller. In [6], the position and altitude of quadrotor are controlled by using PID controller in condition of a wind gust and conclude that the controller worked effectively under this condition. In [7] 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. The slide mode controller is used in [8] to tackle the motor faults and treat the disturbance and system uncertainties problem. However, there is a position error with the increasing of the magnitude of the faults, which effects on the motion of the quadrotor. In [9], the authors are used the backstepping controller for attitude, altitude and used PD controller for position control. Feedback linearization is used in [10] to control the attitude, position controller and from position controller can control the yaw angle freely.

In this paper, a new mathematical and controlling system design which capable of controlling the stability of quadrotor in attitude movements is proposed based on the variation of arms' length. The proposed design depends on varying the length of arms instead of speed variation in motors. This design is implemented by using stepper motors placed inside each quadrotor's arm in order to decrease or increase the length of the arm as a result of the control requirements. A PD controller used to stabilize the system performance. New mathematical model is derived due to this proposed design; a mathematical expression is designed for the proper selection of the arm's length. Since the system is under actuated, the system divided into three subsystems which are altitude, attitude and position. The altitude and attitude subsystem can be controlled by one of the inputs while the position subsystem is dependently controlled by producing the desired attitude.

The proposed design exploits a new technique that depends on arm's length variation. This technique tends to fix the motors speeds at the speed which ensure the hovering case when the quadrotor reached the desired z-position. According to hover case, the quadrotor motors thrust capable of lifting the quadrotor body. Then, the quadrotor movement is performed by varying the length of the quadrotor's arm and fixing the motors speed. Consequently, the quadrotor is able to move and make the manoeuvrability to track the desired waypoint. As a result, a variable torque is generated with respect to the

arms length variation of the quadrotor, instead of the torque generated by varying the speed of motors in the conventional design. This design is proposed to decrease the computational complexity, where no additional combination of other controllers with PD controller which is a linear controller used to control nonlinear system. On other hand, the proposed technique tends to increase the motors lifetime since the speed is fixed during the flying path and implicitly the energy consumption reduced. The stability of the quadrotor performance enhanced.

This paper is arranged as, section 2 presents quadrotor arm design, section 3 refers to quadrotor proposed design, section 4 regarding the dynamic model of quadrotor, section 5 presents controller design approach in altitude, attitude and position, section 6 refers to results and discussion, finally, section 7 refers to the conclusion

2. QUADROTOR ARM DESIGN

According to the proposed design each arm consists of two parts, the fixed part which represents that part which fixed with frame of the quadrotor and the stepper motor fixed inside it, the stepper motor shaft rotates with constant speed. The fixed arm is a hollow arm. The second part is the sliding arm which sliding inside the fixed arm and it connects to the stepper motor by the terminal which still slide inside the fixed arm, when the motor and propeller fixed on the second terminal that remains outside the fixed arm as shown in the figure (1).

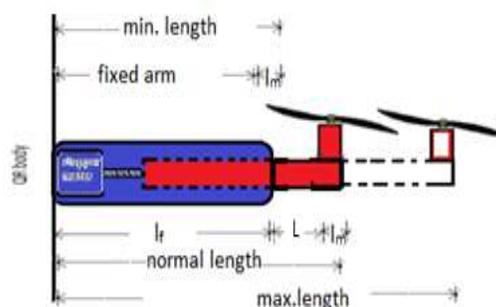


Figure (1): The Arm's Length Design

3. PROPOSED QUADROTOR DESIGN

Many researches have been developed for controlling the stability of the performance of the quadrotor depending on varying the angular velocities of motors [11]. In this paper a new approach performed based on varying the arm's

length of quadrotor and fixed the angular velocities to control the movement of this vehicle in roll, pitch and yaw movement, in order to control the position(x, y) of the quadrotor which depends on pitch and roll angles respectively as assumption of;

- The angular velocity of each motor fixed to be constant.
- The arm's lengths are varying according to the desired movement during the flight.
- The thrust coefficients for all motors are constant
- The quadrotor are supposed to be rigid body and symmetric
- The center of the mass and the origin of the body frame are coinciding.

Firstly after the quadrotor reached the desired altitude (hover case) motors speeds are calibrated to be constant and altering the arms' lengths of quadrotor and advance to the next movement. To accomplish pitch angle θ about y-axis, the length of arm (l_1) must be decreased and the length of arm (l_3) increases as shown in figure 2(a) and the other two arm's length will be fixed at a constant length which is called a normal arm as shown in figure (1). In context, increasing and decreasing the arms length are performed in the proposed design according to equations (1) and (2) that the maximum length will be (l_3) and minimum length will be (l_1)

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

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

Where l_f and l_m are the fixed arm and the diameter of the motor respectively, ($L + l_f + l_m$) represent the normal arm, L is specific length to ensure the permittivity in sliding arm movement, Δd the rate of change in the sliding arm. While for the roll angle ϕ about the x-axis, can be accomplished by decreased the arms length (l_2) and increased the arms length (l_4) relatively and the same as pitch angle for the other two arm's lengths as shown in figure 2(c). Finally, to accomplish yaw angle around the z-axis, this results from varying the counter torque between each pair of the propeller [1], that generate torque opposite the direction of propeller rotation. This can be done by increasing the arm length of motors pair (l_2, l_4) and decreasing the arms lengths of motors pair (l_1, l_3) in order to tilted the quadrotor in (C.C.W) direction as shown in figure 2(e) according to equations (1) and (2) the arms lengths (l_2, l_4) will be maximum length and the arms length (l_1, l_3) will be minimum length. Contrary, the quad rotor tilted in (C. W) by

increasing (l_1, l_3) and decreasing (l_2, l_4) as shown in figure 2(f).

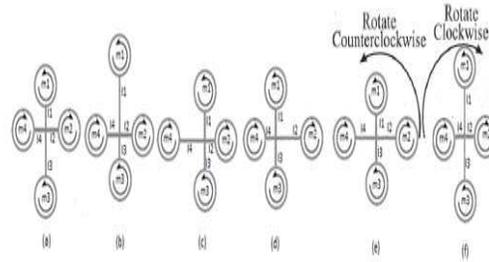


Figure (2): Quadrotor's Movements In Proposed Design

4. DYNAMIC MODEL OF THE QUADROTOR

Two frames are utilized to represent the quadrotor motion which is body frame and earth frame [12] as shown in figure (3).

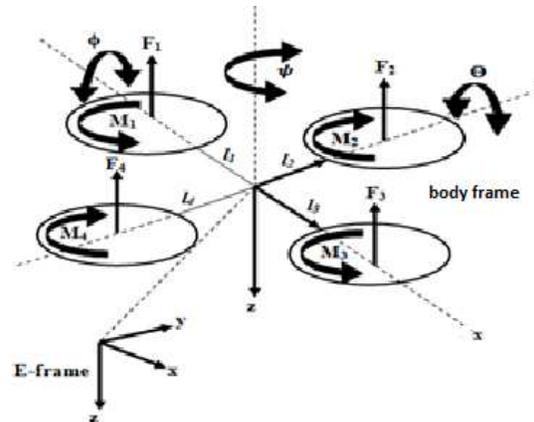


Figure (3): Architecture And Coordinates Of Quadrotor

A quadrotor consists of linear and angular position vectors related to the earth frame. Likewise, quadrotor consists of linear and angular velocity vectors related to the body frame. The position (x, y and z) and the orientation (ϕ, θ, ψ) of the quadrotor and the kinematics of the general 6-DOF of a rigid body[13] is defined as:

$$\dot{\eta} = J_{\Theta} v \quad (3)$$

Where $\dot{\eta}$ the general velocity vector related to earth frame, v represents the general velocity vector related to body frame and J_{Θ} is the generic transformation matrix from body frame to the earth frame which can be derived from Euler method which is defined in[14] as.

$$J_{\Theta} = \begin{bmatrix} E & 0_{3 \times 3} \\ 0_{3 \times 3} & \tau \end{bmatrix} \quad (4)$$

Where E, τ are the transformation and rotation matrices and the term $0_{3 \times 3}$ representing a 3×3 zero matrix, E defined according to [15].

$$E = \begin{bmatrix} c_{\theta}c_{\psi} & s_{\phi}s_{\theta}c_{\psi} - c_{\phi}s_{\psi} & s_{\phi}s_{\psi} + s_{\theta}c_{\phi}c_{\psi} \\ c_{\theta}s_{\psi} & s_{\phi}s_{\theta}s_{\psi} - c_{\phi}c_{\psi} & -s_{\phi}c_{\psi} + c_{\phi}s_{\theta}s_{\psi} \\ -s_{\theta} & s_{\phi}c_{\theta} & c_{\theta}c_{\phi} \end{bmatrix} \quad (5)$$

Where $c(\cdot)$ represents $\cos(\cdot)$ and $s(\cdot)$ represents $\sin(\cdot)$.

The dynamic model of the quadrotor based on Newton- Euler formula with respect to body frame will be expressed as in [7].

$$\left. \begin{aligned} F &= m \dot{v} + \omega \times mv \\ T &= I \dot{\omega} + \omega \times I \omega \end{aligned} \right\} \quad (6)$$

Where m and $I = \text{diag}(I_x, I_y, I_z)$ are the mass of quadrotor body and moment of inertia matrix respectively, F, T are the total aerodynamic force and moment effected on quadrotor motion which is mentioned in [7].

According to the proposed design since fixing the angular velocity, the thrust and drag forces are equaled for all motors ($f_1=f_2=f_3=f_4=f_i$) and ($D_1=D_2=D_3=D_4=D_i$) respectively. Varying the lengths of the arms generate variable torque around the axis that achieved the required rotation. Then, the quadrotor tilted toward the least torque in pitch and roll attitudes angles, yaw attitude angle tilted toward the largest torque as illustrated in section (3)

The total torque affected on the quadrotor rotation in [17] expressed in the proposed design as:

$$\begin{aligned} T_{total} &= (-1)^i \sum_{i=1}^4 Q_i z + (-1)^{i+1} \sum_{i=1}^4 R_i(xy) \\ &+ h \sum_{i=1}^4 D_i(-yx) + \{f_i(l_{m4} - l_{m2})\}_x + \\ &\{f_i(l_{m3} - l_{m1})\}_y + (-1)^i \sum_{i=1}^4 \{D_i l_i\}_z \end{aligned} \quad (7)$$

Where f_i and D_i represent the lift and drag forces respectively, acting on the quadrotor movements and defines in [4] as:

$$f_i = c_T \rho A r^2 \omega^2 \quad (8)$$

$$D_i = c_d \rho A r^2 \omega^2 \quad (9)$$

Where A represents the blade area, ρ represents the air density, r represents the radius of blade, ω represents the angular velocity of the propeller, and

C_T and C_d represent aerodynamic coefficients

Q and R represent the torque from each motor and the rolling moment which are expressed in [17] as;

$$Q_i = c_d \rho A r^2 \omega^2 r \quad (10)$$

$$R = C_R \rho A r^2 \omega^2 r \quad (11)$$

h represents the distance between propeller center and gravity center of quadrotor, l_{mi} represents the arm's length from the pivot center to the related motor as shown in fig (3).

The quadrotor dynamic model equations expressed in earth frame as in [1]:

$$\left. \begin{aligned} m \ddot{x} &= u_1 (\sin \phi \sin \psi + \cos \phi \sin \theta \cos \psi) - k_1 \dot{x} \\ m \ddot{y} &= u_1 (-\sin \phi \cos \psi + \cos \phi \sin \theta \cos \psi) - k_2 \dot{y} \\ m \ddot{z} &= u_1 (\cos \phi \cos \theta) - mg - k_3 \dot{z} \\ I_x \ddot{\phi} &= (I_y - I_z) \dot{\theta} \dot{\psi} + u_2 - k_4 \dot{\phi} \\ I_y \ddot{\theta} &= (I_z - I_x) \dot{\phi} \dot{\psi} + u_3 - k_5 \dot{\theta} \\ I_z \ddot{\psi} &= (I_x - I_y) \dot{\phi} \dot{\theta} + u_4 - k_6 \dot{\psi} \end{aligned} \right\} \quad (12)$$

Where k_i 's represent the frictions aerodynamic coefficients, and u_1, u_2, u_3 and u_4 represent the input to the system which defined as;

$$u_1 = f_1 + f_2 + f_3 + f_4 \quad (13)$$

$$u_2 = f_i (-l_2 + l_4) \quad (14)$$

$$u_3 = f_i (-l_1 + l_3) \quad (15)$$

$$u_4 = D_i (-l_1 - l_3 + l_2 + l_4) \quad (16)$$

Whereas the input to the system in conventional design are defined in [16] as

$$\left. \begin{aligned} u_1 &= f_1 + f_2 + f_3 + f_4 \\ u_2 &= l \cdot (-f_2 + f_4) \\ u_3 &= l \cdot (-f_1 + f_3) \\ u_4 &= -Q_1 + Q_2 - Q_3 + Q_4 \end{aligned} \right\} \quad (17)$$

Where $b = c_T \rho A r^2$ which is the thrust coefficient, $d = c_d \rho A r^2$ which is the drag coefficient.

5. CONTROLLER DESIGN APPROACH

In this paper, a PD control system is used for quadrotor stabilization performance. PD controller represents an effective linear controller which used to stabilize the nonlinear system [18]. This controller used to control the altitude, attitude and position of quadrotor. Figure (4) shows the block diagram of the control approach for quad rotor stabilization. In order to full control the quadrotor and track the trajectory, the vehicle follows three controllers in operation. Where, Take-off and landing to the desired point which is implemented using the altitude controller, the desired position (x, y) implemented using the position controller depending on the attitude controller which maintains the quadrotor in 3-D orientation. The output from the position controller is the desired angle to the attitude controller which facilitates to the position controller reaches its desired position in x and y axes without deviation

5.1 Altitude Controller Design

For quadrotor take-off case from the ground to the desired height, the altitude controller is employed. This mean must work on the z-axis equation of quadrotor and don't deal with other axes equation. From equation (12) select z axis equation and used PD controller as following:

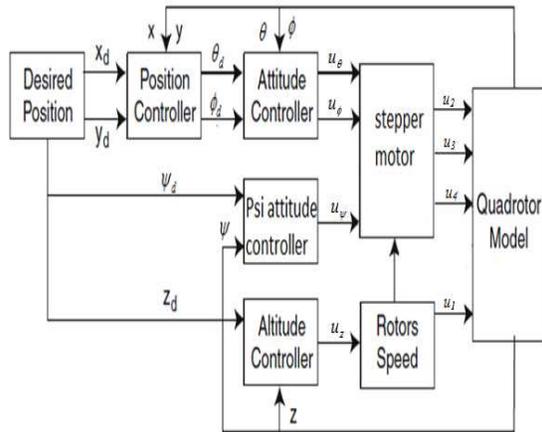


Figure (4): Block Diagram Of Quadrotor Full Control

$$m \ddot{z} = u_1 (\cos \theta \cos \phi) - mg \tag{18}$$

Since $\phi = \theta = 0$ for hovering and take-off condition [6] the error signal (e_z) is the difference between the desired altitude (z_d) and measured altitude (z) [19] as shown in equation (19)

$$e_z = z_d - z \tag{19}$$

The PD controller equation is shown below.

$$u_1 = k_p e_z + k_d \dot{e}_z \tag{20}$$

Where k_p and k_d are the proportional and derivative gains respectively. Then the closed loop system after adding the PD controller to the equation (18) will be as in equation (21).

$$m \ddot{z} = k_p e_z + k_d \dot{e}_z - mg \tag{21}$$

5.2 Attitude Controller Design

For this system a PD controller is used to stabilized the attitude angles (roll, pitch and yaw) which is directly controlled by (u_2 , u_3 and u_4) respectively. These represent the last three equations of equation (12) and after neglecting the gyroscopic effect as in [13].

$$\left. \begin{aligned} I_x \ddot{\phi} &= u_2 - k_4 \dot{\phi} \\ I_y \ddot{\theta} &= u_3 - k_5 \dot{\theta} \\ I_z \ddot{\psi} &= u_4 - k_6 \dot{\psi} \end{aligned} \right\} \tag{22}$$

The error signals (e_ϕ , e_θ and e_ψ) will the difference between the desired angles (ϕ_d , θ_d and ψ_d) and the measured angles (ϕ , θ and ψ) as in equation below:

$$\left. \begin{aligned} e_\phi &= \phi_d - \phi \\ e_\theta &= \theta_d - \theta \\ e_\psi &= \psi_d - \psi \end{aligned} \right\} \tag{23}$$

The equation of PD controller for roll attitude will be as in equation (24).

$$u_\phi = k_p e_\phi + k_d \dot{e}_\phi \tag{24}$$

In the same manner, the other attitude angles PD controller can be derived. The closed loop system after addition the effect of PD controller in equation (24) to equation (22) will be as in equation (25).

$$\ddot{\phi} = \frac{u_2}{I_x} u_\phi \tag{25}$$

For the other attitude angles (pitch and yaw) can be derived similarly to the mentioned above

5.3 Position Controller Design

A PD controller is used to control the horizontal motion. This motions accomplished by pitching or rolling the quadrotor by generates the pitch and roll angle from this controller which it will be the input to the attitude controller. The saturation function is used to control the boundary of these angles. Then, from equations (26) and (27) the desired acceleration (\ddot{x}, \ddot{y}) is calculated as in [9].

$$\ddot{x}_d = k_p e_x + k_d \dot{e}_x \tag{26}$$

$$\ddot{y}_d = k_p e_y + k_d \dot{e}_y \tag{27}$$

Where k_p and k_d are positive and constant proportional and derivative gains respectively. e_x and e_y are the error signal which expressed as in equation (28) and (29).

$$e_x = x_d - x \tag{28}$$

$$e_y = y_d - y \tag{29}$$

Where x_d, y_d the desired position and x, y are the measured position, by applied equations (26) and (27) into equation (12) for x and y position will obtain

$$\ddot{x}_d = -\frac{u_1}{m}(\sin \phi \sin \psi + \cos \phi \sin \theta \cos \psi) \tag{30}$$

$$\ddot{y}_d = \frac{u_1}{m}(\sin \phi \cos \psi - \cos \phi \sin \theta \sin \psi) \tag{31}$$

As assumption of hover case in position controller $\psi=0$ and θ and ϕ are small angles approximation. Then can calculate the desired pitch and roll angles from equations (30) and (31) respectively.

$$\theta_d = \sin^{-1}\left(\frac{u_1}{m} \ddot{x}_d\right) \tag{32}$$

$$\phi_d = \sin^{-1}\left(\frac{u_1}{m} \ddot{y}_d\right)$$

The θ_d and ϕ_d must be limited to a specific range, by using saturation function which is expressed below as.

$$sat(\theta_d) = \begin{cases} \theta_d & \theta > \theta_d \\ \theta & -\theta_d \leq \theta \leq \theta_d \\ -\theta_d & \theta < -\theta_d \end{cases} \tag{33}$$

6. RESULTS AND DISSECTION

In order to realize the efficiency of the proposed design adopted. MATLAB code simulation is performed. This section present the result of the altitude, attitude, position controller and trajectory tracking and the system parameter used as in table (1). As mentioned in section (2) and section (3) the arm's length designed as the fixed arm will be equal to 17.5cm and the maximum total arm's length will be equal to 30 cm and the minimum arm's length will be equal to 20 cm.

Table 1: The System Parameters

mass	2 kg	I_z	2.5 Ns ² /rad
Arm length	As in table 2	b	3.31*10 ⁻⁵
gravity	9.8 m/s ²	d	7.5*10 ⁻⁵
I_x	1.25 Ns ² /rad	$k_1=k_2=k_3$	0.010 Ns/m
I_y	1.25Ns ² /rad	$k_4=k_5=k_6$	0.12 Ns/m

Table 2: Arm's Length Variation According To Section 3

l_f (cm)	l_m (cm)	L (cm)	Δd	Max. length(cm)	Min. length(cm)
17.5	2.5	5	0.25	30	20

Figure (5) shows the desired flight shifting in (x, y and z) which are initiated with $x=y=z=0$ and $\phi=\theta=\psi=0$ rad, then the quadrotor follow the flight path as shown in figure (6). The trajectory tracked by the quadrotor is that it take-off from the point (0, 0, 0) to (0, 0, 10) then move to the point (5, 0, 10) and to the point (5, 5, 10) then lapped to the point (2, 5, 10) and to the point (2, 3, 10) then landing at point (2, 3,0).

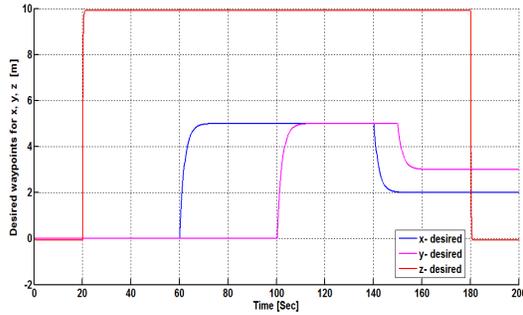


Figure (5): Desired Waypoint For X, Y, Z

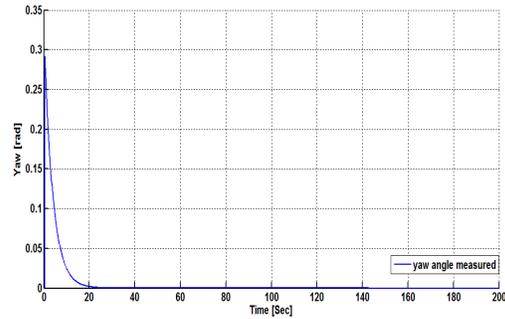


Figure (8): The measured Yaw angle

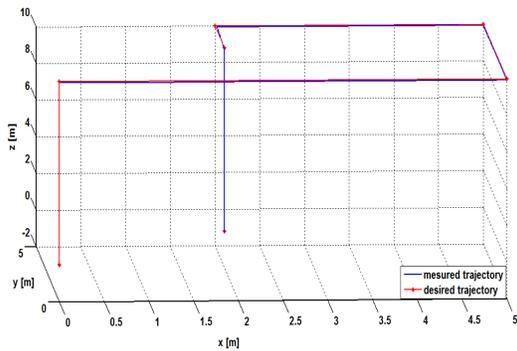


Figure (6): Quadrotor Trajectory Tracking

The measured altitude is shown in figure (7) while the yaw angle shown in figure (8) which illustrate that the proposed design works well with the yaw angle with no oscillation and reach the desired with the time equal to 18 sec. Figure (9) and figure (10) show the x-position and the pitch angle as the control input to the x direction which at 60 sec x-position move to point 5m and the pitch angle changes its state from 0 rad to the desired pitch angle which is -0.35 rad. There is little difference in the magnitude between the measured angle and the desired angle as shown in figure (10). After the x-position reaches the desired the pitch angle converges to zero and advanced to next step.

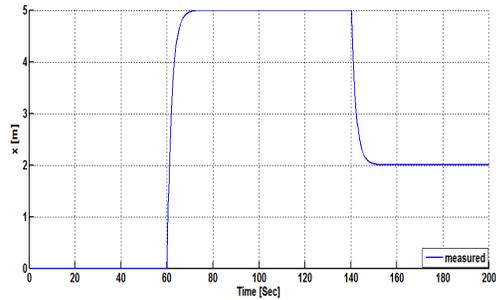


Figure (9): The measured X- position

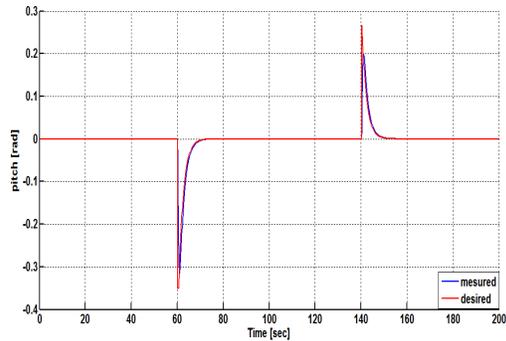


Figure (10): The Measured And Desired Pitch angle

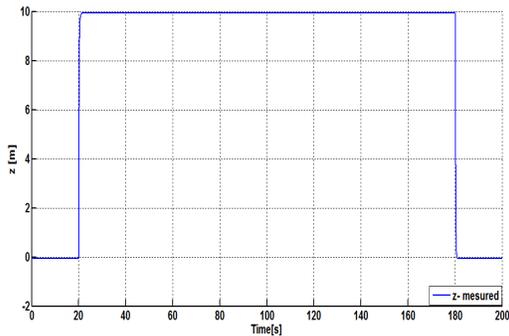


Figure (7): The Measured Altitude

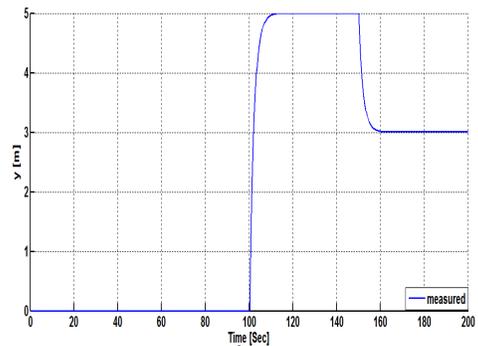


Figure (11): The Measured Y-Position

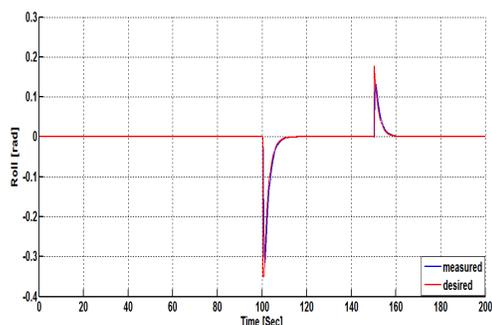


Figure (12): The Measured And Desired Roll Angle

Figure (11) and figure (12) show the y-position and its control input, the roll angle, which at 100 sec quadrotor moves to 5m in y-position and the roll angle responses to this change and followed the desired roll angle. Then, converge to zero in order to advance to the next point. From these results, the proposed design shows the stability in response and follow the desired accurately with good performance.

7. C ONCLUSION

In this paper, a new controlling method based on varying the arm's length is applied successfully to control the quadrotor movement. This method implemented based on PD controller for altitude, attitude and position controller due to this approach a mathematical model is developed and derived using Newton- Euler method. A mathematical expression is designed to identify the amount of increment and the decrement in arms' lengths. The simulation results show a perfect performance of the proposed design in tracking the desired path. The proposed design with PD controller proves the capability for controlling the orientation angles and develops the stability of autonomous vehicle.

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