Design and Control of Miniature Quad Rotor for Indoor Applications

[1]Abdul Ghani Aarbi [2]Bilal Fazal Khan
Department of Electrical Engineering
Institute of Space Technology
Islamabad, Pakistan
[1]silveraarbi@live.com
[2]bilalfazalkhan@yahoo.com

Abstract*— From the last couple of years there is an enormous development in the field of UAVs (Unmanned Aerial Vehicles). UAVs have wide variety of applications ranging from entertainment, commercial use to military requirements. Now a days UAVs are used for aerial imaging and videography, search and rescue, monitoring and security, spying, indoor and outdoor surveillance, traffic monitoring etc. [1]–[4] There are basically two major types of Unmanned Aerial Vehicles, first is one having Conventional Takeoff and Landing (CTOL) also known as fixed wing aircrafts, while second is having Vertical Takeoff and Landing (VTOL). [5] UAVs with Conventional Takeoff and Landing requires runway for takeoff as well as for landing. For this reason, CTOL type of UAVs does not have feasibility for indoor applications. As far as indoor applications are concerned the other major problem with CTOL type UAVs is that it does not have hovering capabilities. But CTOL type UAVs have other benefits like low power requirements and high speed, are name few. For the mentioned reasons the UAVs with vertical takeoff and landing are widely used for complex environments where runway is not available for UAV or hovering capability is required. UAVs with vertical takeoff and landing capabilities is also utilized widely in indoor applications. Apart from vertical takeoff and landing it also provide benefit of hovering and aggressive movements. [6] There are various configurations of VTOL type UAVs. In this experimental studies, we will be focusing on designing and control of VTOL type UAV having miniature sized quad rotor based design, with modest PID based control system.

Index Terms*—Indoor UAVs, quadrotor, quadcopter, miniature size, indoor surveillance, indoor applications, multi rotor, PID control, vertical takeoff and landing (VTOL).

I. Introduction

Recent development in the field of MEMS (Micro Electro Mechanical Systems) devices opened the possibility of micro size IMUs (inertial measurement unit). These micro sized IMUs are utilized for the micro size indoor UAVs. [4], [7] as discussed above, it is clear that UAV with VTOL capabilities have great importance in indoor applications. In comparison with single rotor based conventional coaxial type helicopter, Multi-rotor based system have various advantages. I.e. mechanism and mechanical construction of multi-rotor based system is simpler than the conventional coaxial type helicopters, the rotor of multi-rotor type aircraft can be covered with frame which makes it much safer for indoor applications as compared to coaxial type helicopter. [5], [8] Tri-rotor type design gives more maneuverability and battery timings then quad-rotors but less payload and less stability. Hex-rotor or Octo-rotor design gives more stability and payload then quad-rotor but lesser maneuverability and battery timings. Also quad-rotor design and mechanism is simpler than other multi-rotor based systems. [5], [9] That is the reason multi-rotor based design with four rotor known as Quad rotor or Quad Copter is developed for this experimental studies.

In this experiment miniature quad-rotor is approximately palm sized with Live Video Transmission camera for FPV (First Person View) on receiver side. The live video can be recorded on receiving side or images can be capture for image processing or for further use.

The quad-rotor is nonlinear system with multiple input and output parameters. There are linear as well as nonlinear control techniques are made for control of quad-rotor system. Some of the common and most utilized techniques for controlling quad-rotors are PD Control, PID Control, LQ Control, Adaptive Robust Control (ARC), Back stepping Control, Hybrid Back stepping Control, Robust inernal-loop compensator (RIC) Control, Robust Controller, etc. [10]–[19]

II. Flying Mechanism

Quad-rotors have six degree of freedom, three of which are x, y, z position in Cartesian coordinates while other three are roll, pitch, and yaw. Input parameter of quad-rotor system are forward and backward movement, left right movement, up and down movement, and yaw control. While the output of these inputs is basically speed control of four rotors. Quad-rotor systems have four identical rotors from which two opposite side rotors rotates in clockwise direction while other two opposite side rotors rotates in counter clockwise direction. [20] There are basically two configurations of quad-rotors, first is in '+' configuration and second one is in 'x' configuration.[6]

The Thrust is controlled by simultaneously increasing or decreasing speed of all rotors as illustrated in figure (1.a). The reason behind two clockwise and two anti-clockwise movements of rotors is to eliminate unnecessary yaw, as well as make yaw movements possible when desired. Yaw movement is made by simultaneously increasing speed of pair moving in one direction and simultaneously decreasing speed of pair moving in opposite direction, concept of yaw movement is illustrated in Figure (1.b). The Roll of mechanism is controlled by maintaining same speed of forward and backward rotors, but increasing the speed of left or right rotor while decreasing the speed of counterpart, concept of roll is illustrated in figure (1.c). The Pitch is controlled maintaining same speed of left and right rotors, but increasing the speed of forward or backward rotor while decreasing the speed of counterpart, concept of pitch is illustrated in figure (1.d).

Note that by mentioned four controls (thrust, yaw, roll and pitch) all the 6 DOF movements (x, y, z position, roll, pitch, and yaw) of the quad-rotor UAV are controlled.

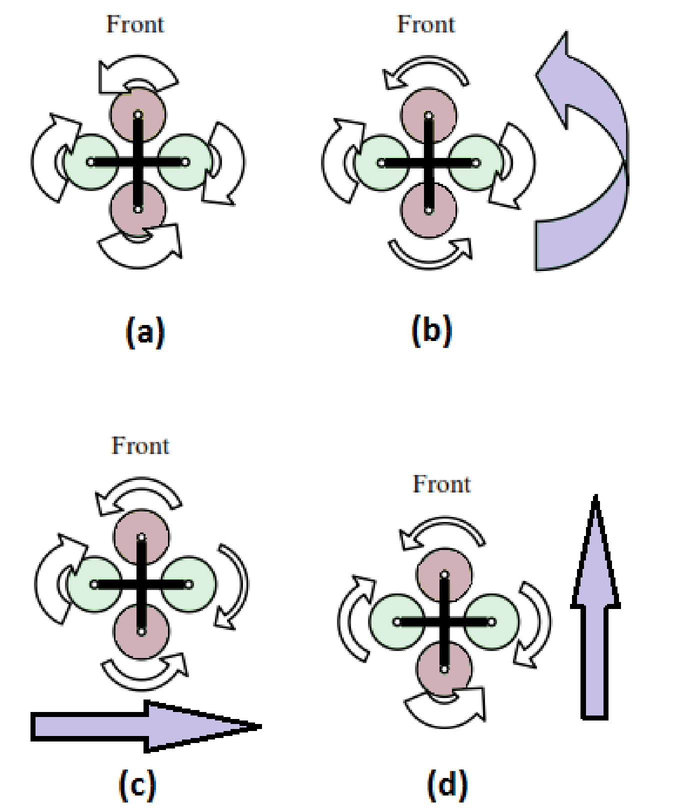

Fig. 1. Top view of Quad-rotor. (a) Thrust showing upward movement. (b) Yaw movement in counter clockwise direction. (c) Roll movement to right. (d) Pitch movement forward.

III. System Details

A. Mechanical Structure

Mechanical frame of the system is made-up of Carbon Fiber for its rigidness and light weight.

Fig. 2. Motors with Propellers

The high speed brushed DC motors are attached with aluminum based boom which is light in weight and rigid in nature. Motors with propellers are shown in figure (2).

B. Electronic Circuit

Micro MWC flight controller board is used, which is having Atmel based 8bit microcontroller ATMEGA328P, uses MEMS based accelerometer/gyroscope MPU6050, have built in 4 channel DSM2 receiver as well as four 2 ampere brushed Electronic Speed Controller (ESCs), supports UART for FTDI communication. The design of this flight controller is based upon open source project MultiWii. [21] Flight controller is show in figure (3). The DSM2 based transmitter is used which is compatible with this flight controller. TX5805 low power, small size Camera with built in 5.8GHz video transmitter is used for First Person View (FPV) video link. At the receiving end 5.8GHz AV receiver is used for showing FPV.

Fig. 3. Micro Flight Controller Board

IV. Quad-Rotor Flight Dynamics

The aim of this paper is to develop a dynamic model for quad rotor as realistic as possible as modeling a vehicle such as quad rotor is not an easy task due to the nature of its complex structure.

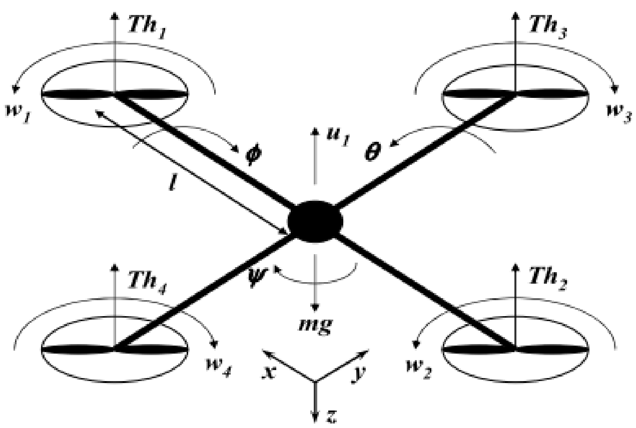

Fig. 4. The quad-rotor schematic.

The thrust is generated by the four rotors placed at fixed angles on the quad rotor known as input forces for the system as shown in the figure.4 . the sum of thrust generated by each rotor is known as collective input represented by (Ul). There are four input forces and six output states (θ, Ψ, Φ, x, y, z) representing pitch, roll, yaw and the motion in Cartesian coordinates respectively. The desired pitch angle is achieved by increasing (reducing) the speed of rear-faced rotor while reducing (increasing) the speed of front-faced rotor. The desired roll angle is achieved by increasing (reducing) the speed of right-faced rotor while reducing (increasing) the speed of left-faced rotor. The desired yaw angle is achieved by increasing (reducing) the speed of front and rear-faced rotors at the same time while reducing (increasing) the speed of lateral rotors at the same time.

The transition matrix R defines the transformation of quad rotor model from earth to a fixed point in space, which is obtained by a mathematical design obtained by a direction cosine matrix,

$$R_{xyz} = \begin{pmatrix} C\Phi C\theta & C\Phi S\theta S\Psi - S\Phi C\Psi & C\Phi S\theta C\Psi + S\Phi S\Psi \\ C\Phi S\theta & S\Phi S\theta S\Psi + C\Phi C\Psi & S\Phi S\theta C\Psi - C\Phi S\Psi \\ -S\theta & C\theta S\Psi & C\theta C\Psi \end{pmatrix} \quad (1)$$

Where

- S( ) = Sin( ) , C( ) = Cos( ).
- R: represents the transition matrix.
- Φ: roll angle.
- θ: pitch angle.
- Ψ: yaw angle.

The equations of motion for the quad rotor are obtained by the force and moment balance which is given as follow [22]

$$\left.\begin{aligned} \ddot{x} &= Ul\,(\mathrm{Cos}\Phi \mathrm{Sin}\theta \mathrm{Cos}\Psi + \mathrm{Sin}\Phi \mathrm{Sin}\Psi) - K1\,\dot{x}/m \\ \ddot{y} &= Ul\,(\mathrm{Sin}\Phi \mathrm{Sin}\Psi \mathrm{Cos}\Psi - \mathrm{Cos}\Phi \mathrm{Sin}\Psi) - K2\,\dot{y}/m \\ \ddot{z} &= Ul\,(\mathrm{Cos}\Phi \mathrm{Cos}\Psi) - g - K3\,\dot{z}/m \end{aligned}\right\} \quad (2)$$

Where:
x: Forward position
y: Lateral position
z: Vertical position
Ki: Drag coefficients

As drag coefficients are negligible at low speed there we assume the drag force to be zero [4].

Each of the input to controller changes certain parameters in the quad rotor model, U1 here represents the z-axis (altitude), U2 affects the angle roll rotation, U3 affects the angle of pitch and U4 is responsible for controlling yaw during flight.

Therefore defining the inputs to be:

$$\left.\begin{aligned} U1 &= (Th1+Th2+Th3+Th4)\,/m \\ U2 &= l\,(-Th1-Th2+Th3+Th4)\,/I1 \\ U3 &= l\,(-Th1+Th2+Th3-Th4)\,/I2 \\ U4 &= C\,(Th1+Th2+Th3+Th4)\,/I3 \end{aligned}\right\} \quad (3)$$

Where:
U1: Vertical thrust
U2: Moment generated by pitch angle
U3: Moment generated by yaw angle
U4: Moment generated by roll angle
Thi: Thrust generated
Ii: Moment of inertia
C: Moment scaling factor

The following quad rotor model is an under actuated system having four inputs and six output states (θ, Ψ, Φ, x, y, z), where (x, y, z) are three positions and (θ, Φ, Ψ) are three Euler angles representing pitch, roll and yaw respectively. In order to move the quad rotor to an arbitrary position a possible combination of outputs x, y, z and Φ have been used keeping other angles stable. The desired roll angle 'Φ_d' and desired yaw angle 'Ψ_d' can be extracted as:

$$\left.\begin{aligned} \Phi_d &= \tan^{-1}(y_d-y/x_d-x) \\ \Psi_d &= \tan^{-1}(z_d-z/\sqrt{[(x_d-x)^2+(y_d-y)^2]}) \end{aligned}\right\} \quad (4)$$

V. PID CONTROL DESIGN

The proportional integral and derivate control is implemented where higher precision and control is required such as quad rotors in order to minimize the error chances and make the platform stable by nullifying the effects of errors. The structure of PID is of the form represented by [23]:

$$u(t) = K_p\,[e(t)+1/Ti\,{}_0\!\int^t e(f(f)+ T_d\,de(t)/dt] \quad (5)$$

Where u(t) is the input to the system, error signal is defined as:

$$e(t) = r_{ref}(t) - y_{out}(t) \quad (6)$$

where r_{ref} (t) is the reference signal and y_{out} (t) is output signal of the system.

Controller selection for the quad rotor depends upon the control mode adopted by a quad rotor [22], control mode can be mode-based control and can be non-mode based control. For the mode-based controller it requires the controllers independently for each state acquire by the quad rotor and one master controller for controlling all the independent controllers. While non-mode based control requires one central controller managing all the states of the quad rotor.

For z-axis (altitude) and yaw angle 'Ψ' stabilization,

$$\begin{pmatrix} z'' \\ \Phi'' \end{pmatrix} = \begin{pmatrix} u_1 \mathrm{Cos}\,\Phi\, \mathrm{Cos}\,\Psi - g \\ u_4 \end{pmatrix} + \begin{pmatrix} -K_3\,\dot{z}/m \\ -K_6\,\Phi'/I_3 \end{pmatrix} \quad (7)$$

For x, y positions with roll 'Φ' and pitch 'θ' angles.

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \end{pmatrix} = \begin{pmatrix} u_1 \mathrm{Cos}\,\Phi & u_1 \mathrm{Sin}\,\Phi \\ u_1 \mathrm{Sin}\,\Phi & -u_1 \mathrm{Cos}\,\Phi \end{pmatrix} \begin{pmatrix} \mathrm{Sin}\,\theta\,\mathrm{Cos} \\ \mathrm{Sin}\,\Psi \end{pmatrix} + \begin{pmatrix} -K_3\,\dot{x}/m \\ -K_2\,\dot{y}/m \end{pmatrix} \quad (8)$$

And

$$\begin{pmatrix} \theta'' \\ \Psi'' \end{pmatrix} = \begin{pmatrix} u_2 \\ u_3 \end{pmatrix} + \begin{pmatrix} -IK_4\,\theta'/I1 \\ -IK_5\,\Psi'/I2 \end{pmatrix} \quad (9)$$

At low speed the drag coefficients are considered to be small disturbances for the system, therefore the drag terms are ignored. For achieving desired position PID controller is implemented in the system with having u_1, u_2, u_3, u_4 as inputs and Φ, θ, Ψ, Z_d as outputs.

VI. RESULTS

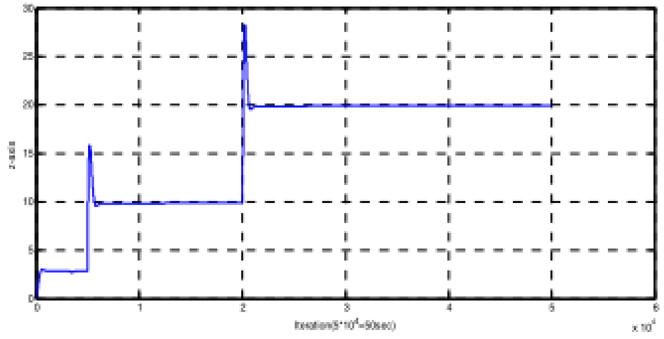

Fig. 5. z-axis moving to desired z-point.

The proposed PID control algorithm has been implemented to the micro sized quad rotor by adjusting gains for the pitch, roll and yaw angles. Fig.5 represents the (altitude) z-axis moving to the desired z-position containing some transient overshoot. Fig.6 shows the roll 'Φ' angle after 3 seconds to start moving to the desired point. Fig.7 representing the yaw 'Ψ' angle after 5 seconds towards the position desired. Fig.8 shows the pitch 'θ' angle towards achieving the position desired.

The results shows that the proposed PID control algorithm best suits to stabilize the quad rotor system to attain desired position under control. The reason for implementing the PID control algorithm in the quad rotor system is to control the z (altitude), as the other parameters are associated to the changes in the z (altitude).

The overshoot in the altitude response was removed, the transient response of the system gets faster by the implementation of proposed PID control algorithm for micro sized quad-rotor system.

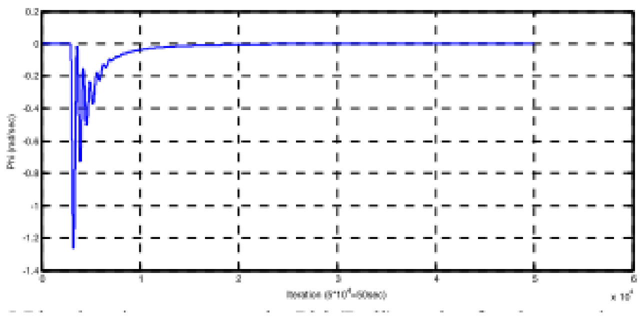

Fig. 6. Represents Roll-angle to desired point.

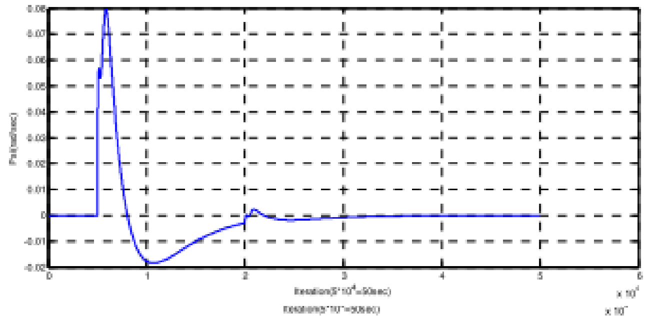

Fig. 7. Represents Yaw-angle to desired point.

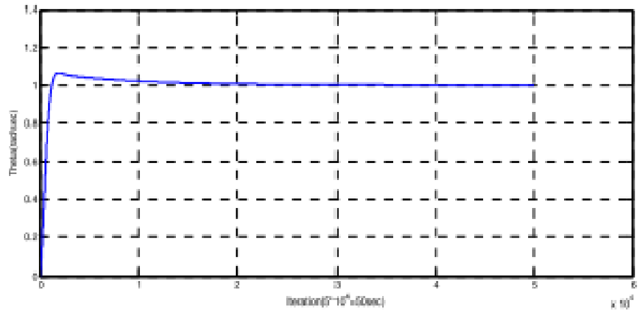

Fig. 8. Represents Pitch-angle to desired point.

VII. CONCLUSION

The aim of this paper was to present the design and control of miniature quad rotor for indoor applications. Starting with some basic concept of different type of UAVs we moved towards working of quad rotors. The PID based control system was used for better controlling. The control mechanism was minimized so that it can be efficiently implemented on 8bit processor. The design was practically implemented with FPV camera system so that it can be used for indoor surveillance. Graphs are presented which shows the PID controller response for desired roll, yaw and pitch.

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