Position control of quadrotor by embedded PID control with hardware in loop simulation

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2 authors:

Hamid Saeed Khan
Iqra University

Muhammad Bilal Kadri
Prince Sultan University

Position Control of Quadrotor by Embedded PID Control with Hardware in Loop Simulation

Hamid Saeed Khan*, Muhammad Bilal Kadri
Department of Electronics and Power Engineering, Pakistan Navy Engineering College, NUST, Islamabad, Pakistan*
College of Engineering, PAF-Karachi Institute of Economics and Technology, Karachi, Pakistan
Email: *hamidkhan_89@pnec.nust.edu.pk, bilal.kadri@pafkiet.edu.pk

Abstract—**Quadrotor is a MIMO non-linear system with complex dynamics. It is an open loop unstable system and it requires an efficient control scheme for a stable flight. This paper presents a discrete PID control scheme, which is able to move quadrotor to any point in 3-dimensional space. This paper also presents the implementation of this control scheme on programmable system-on-chip (PSOC) device and tests this controller hardware on quadrotor mathematical model with hardware-in-loop simulation. Simulation results have shown the effectiveness of control scheme and successful implementation on PSOC device.**

I. Introduction

Quadrotor is an unmanned aerial vehicle, capable of vertical take-off and landing. It is a non-linear dynamic system with open loop unstable nature and requires an efficient control scheme to fly properly. Quadrotor has four lift generating propellers. The position of quadrotor in 3-dimensional space can be controlled by varying angular velocities of these propellers.

This paper presents the quadrotor control by discrete PD, PI and PID controllers based control strategy. The discrete control strategy can be implemented on any embedded device like microprocessor or microcontroller. Here, the control strategy is implemented on programmable system on chip (PSOC) device [1]. This embedded PID controller hardware is tested on quadrotor mathematical model [2] with the usage of hardware-in-loop simulation technique.

In hardware-in-loop simulation, there is either controller implemented on an embedded device like microprocessor, microcontroller or FPGA with plant in simulation environment or there is actual plant hardware with control strategy in simulation environment.

Sometimes, the plant to be controlled is not available or too expensive to test the controller hardware. In this situation, HIL simulation is very helpful for testing the control performance of actual controller hardware in the absence of plant hardware. HIL simulation technique has been widely used in control systems. For e.g. in [3], hardware in simulation technique is used for online identification of squirrel cage induction motor with using ARMA model and recursive least square algorithm. It also performed online controller parameters tuning. HIL simulation is used for testing engine control system hardware with dynamic model of diesel engine in simulation environment [4]. HIL simulation is used for testing the actual controller hardware on automatic gearbox model of a passenger car [5]. In [6], HIL simulation is used for controlling permanent magnet synchronous motor drive model by controller on actual hardware. HIL simulation is used for designing pareto-optimal controller for actual electric motor speed control with multi objective optimization algorithm [7]. HIL simulation is used for online PID controller tuning and fuzzy logic controller designing of DC motor motion control platform by using multi objective evolutionary methods [8]. In [9], HIL simulation technique is used to control DC motor speed model by discrete PI controller implemented on 8051 microcontroller.

The quadrotor and its non-linear dynamic model are discussed in section II. Section III presents the discrete PID control of quadrotor. Section IV presents the hardware-in-loop simulation. HIL simulation results are shown in section V. The paper is concluded in section VI.

II. Quadrotor Dynamic Model

Quadrotor is a non-linear dynamic system with multiple inputs and multiple outputs.

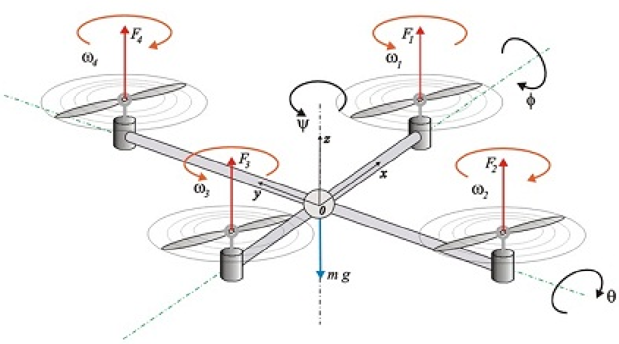

Fig. 1. Quadrotor[10]

As shown in Fig. 1 [10], quadrotor has four thrust generating propellers. Two propellers rotate clockwise and the other two rotates counter-clockwise. Quadrotor control is achieved by varying the angular velocities of these propellers (ω_1, ω_2, ω_3, ω_4).

The rotation angles of quadrotor are roll angle (ø), pitch angle (θ) and yaw angle (ψ) and the position of quadrotor in 3-dimensional space is represented by X distance (x), Y distance (y) and Z distance (z). The mathematical model [2] of quadrotor is:

$$
\begin{aligned}
\ddot{\phi} &= \dot{\theta}\dot{\psi}\frac{I_{yy}-I_{zz}}{I_{xx}} + \dot{\theta}\frac{J_r}{I_{xx}}\Upsilon + \frac{L}{I_{xx}}U_2 \\
\ddot{\theta} &= \dot{\phi}\dot{\psi}\frac{I_{zz}-I_{xx}}{I_{yy}} - \dot{\phi}\frac{J_r}{I_{yy}}\Upsilon + \frac{L}{I_{yy}}U_3 \\
\ddot{\psi} &= \dot{\theta}\dot{\phi}\frac{I_{xx}-I_{yy}}{I_{zz}} + \frac{1}{I_{zz}}U_4 \\
\ddot{x} &= \frac{(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)}{M}U_1 \\
\ddot{y} &= \frac{(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)}{M}U_1 \\
\ddot{z} &= -g + \frac{(\cos\phi\cos\theta)}{M}U_1
\end{aligned} \tag{1}
$$

U_1, U_2, U_3, U_4 and Υ are the control signals that are dependent on angular velocities of propellers (ω_1, ω_2, ω_3, ω_4).

The control signals are calculated as:

$$
\begin{aligned}
U_1 &= b\omega_1^2 + b\omega_2^2 + b\omega_3^2 + b\omega_4^2 \\
U_2 &= b\omega_4^2 - b\omega_2^2 \\
U_3 &= b\omega_3^2 - b\omega_1^2 \\
U_4 &= d(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \\
\Upsilon &= \omega_1 - \omega_2 + \omega_3 - \omega_4
\end{aligned} \tag{2}
$$

The control signal U_1 is related to total thrust of the quadrotor. U_2, U_3 are related to roll angle (ø) and pitch angle (θ) respectively. U_4 is related to yaw angle (ψ). Υ is the residual propeller angular speed.

Parameters used in quadrotor mathematical model are defined in table I.

TABLE I. PARAMETERS OF QUADROTOR MODEL

Parameter Symbol	Parameter Description
I_{xx}	x-axis inertia component
I_{yy}	y-axis inertia component
I_{zz}	z-axis inertia component
L	Length of the quadrotor arm
M	Mass of quadrotor
b	Thrust co-efficient
d	Drag co-efficient
J_r	Rotor inertia
g	Acceleration due to gravity

The parameter values used here are given in table II [2]:

TABLE II. QUADROTOR PARAMETER VALUES

Parameter	Value	Unit
M	0.8	Kg
L	0.3	m
J_r	6.01×10^{-5}	Kg m^2
I_{xx}	15.67×10^{-3}	Kg m^2
I_{yy}	15.67×10^{-3}	Kg m^2
I_{zz}	28.346×10^{-3}	Kg m^2
b	192.3208×10^{-7}	N s^2
d	4.003×10^{-7}	Nm s^2
g	9.81	m s^{-2}

The quadrotor dynamic model given by (1) and (2) is a general model, which represent quadrotor of any size. For simulation, parameter values given in table II are used, to make the quadrotor of a particular size and weight.

III. DISCRETE PID CONTROL

Position control (X distance, Y distance and Z distance) of quadrotor by discrete PD, PI and PID controllers based control scheme is presented here. As shown in Fig. 2, Z distance (height of quadrotor) is achieved by using nested loop of a discrete PD controller and a discrete PI controller. Discrete PD controller is used for Z distance (height) of quadrotor and discrete PI controller is used to regulate rate of change of Z distance w.r.t time i.e. velocity of quadrotor in z-axis. The control signal of Z distance PD controller becomes reference signal for Z velocity PI controller.

X distance and Y distance are achieved by using nested loops of two discrete PD controllers. The control signal of Y distance PD controller becomes the reference signal for roll angle PD controller. There is a gain block of -1 value, due to opposite relation between Y distance and roll angle i.e. if roll angle is positive, Y distance increase in negative and vice versa. The control signal of X distance PD controller becomes the reference signal for pitch angle PD controller. Yaw angle control is also achieved by using discrete PID controller.

r_1, r_2, r_3 and r_4 are the control signals generated by controllers and these signals form the final propeller angular velocity signals for quadrotor input with following relations.

$$
\begin{aligned}
\omega_1 &= r_1 - r_3 + r_4 \\
\omega_2 &= r_1 - r_2 - r_4 \\
\omega_3 &= r_1 + r_3 + r_4 \\
\omega_4 &= r_1 + r_2 - r_4
\end{aligned} \tag{3}
$$

r_1 is related to Z distance control of quadrotor. r_2, r_3 and r_4 are related to Y distance, X distance and yaw angle control respectively.

Discrete PD, PI and PID controller equations are achieved by applying Forward Euler's method [11] on continuous time controller equations.

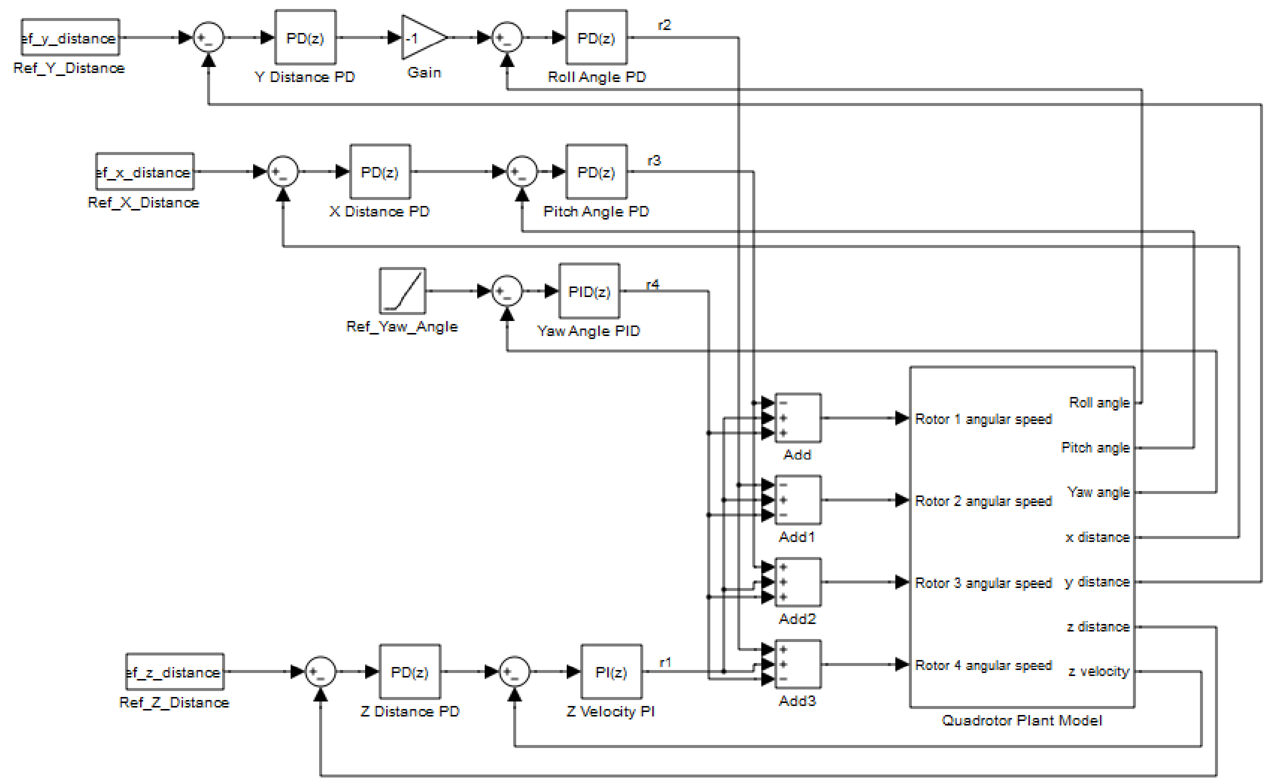

Fig. 2. Discrete PID Control of Quadotor

The discrete PID controller equation is:

$$u[k]=\begin{aligned}&(K_p+K_d\,\mathrm{N})\,\mathrm{e[k]}+(\mathrm{NT}_s\,K_p+K_i\,\mathrm{T}_s-\\&2K_d\,\mathrm{N}-2K_p)\,\mathrm{e[k-1]}+(K_p-K_p\,\mathrm{NT}_s\\&-K_i\,\mathrm{T}_s+K_i\,\mathrm{NT}_s^2+K_d\,\mathrm{N})\,\mathrm{e[k-2]}-\\&(\mathrm{NT}_s-2)\,\mathrm{u[k-1]}-(1-\mathrm{NT}_s)\,\mathrm{u[k-2]}\end{aligned}\tag{4}$$

The discrete PI controller equation is:

$$u[k]=K_p\,\mathrm{e[k]}+(K_i\,\mathrm{T}_s-K_p)\,\mathrm{e[k-1]}+\mathrm{u[k-1]}\tag{5}$$

The discrete PD controller equation is:

$$u[k]=\begin{aligned}&(K_p+K_d\,\mathrm{N})\,\mathrm{e[k]}+(\mathrm{NT}_s\,K_p-K_d\,\mathrm{N}\\&-K_p)\,\mathrm{e[k-1]}-(\mathrm{NT}_s-1)\,\mathrm{u[k-1]}\end{aligned}\tag{6}$$

The gains and other parameters used in controller equations are given in table III.

TABLE III. QUADROTOR CONTROLLER PARAMETERS

Controller	Parameters
Roll angle PD Controller	K_p=5, K_d=5, N=100, T_s=0.01sec
Pitch angle PD Controller	K_p=5, K_d=5, N=100, T_s=0.01sec
Yaw angle PID Controller	K_p= 0.5, K_d=2, K_i=0.01, N=100, T_s=0.01sec
Z velocity PI Controller	K_p= 5, K_i=5, T_s=0.01sec
Z distance PD Controller	K_p=20, K_d=20, N=100, T_s=0.01sec
Y distance PD Controller	K_p=0.01, K_d=0.05, N=100, T_s=0.01sec
X distance PD Controller	K_p=0.01, K_d=0.05, N=100, T_s=0.01sec

The Y-distance, X-distance and Z-distance results are given below. As shown in Fig. 2, the Y distance loop is link with roll angle loop and X distance loop is link with pitch angle loop. This relation can also be seen in Fig. 4 and 6, where roll angle and pitch angle becomes zero when Y distance and X distance becomes steady. Figure 3–7 clearly shows the effectiveness of controller. The Y distance, X distance and Z distance are achieved for their given references.

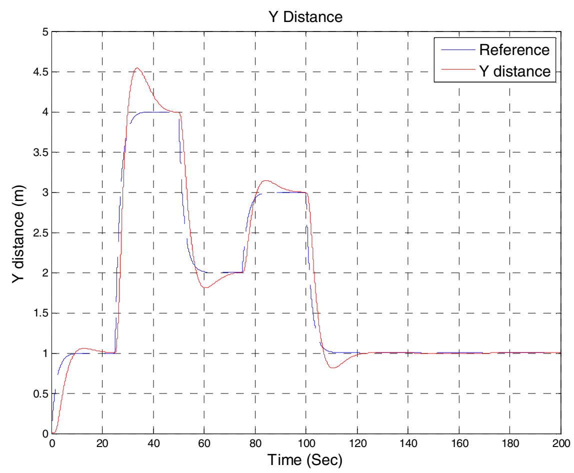

Fig. 3. Y distance control of quadrotor

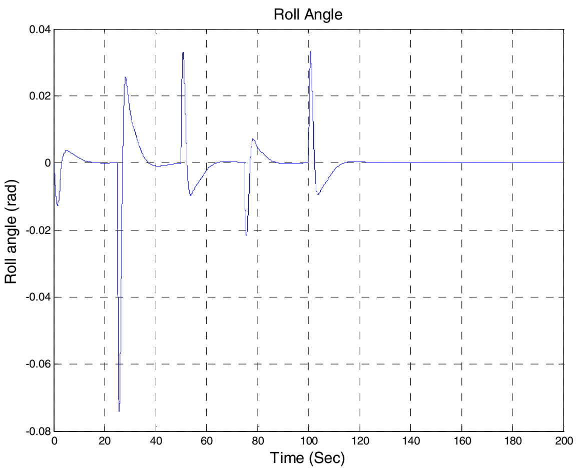

Fig. 4. Roll angle

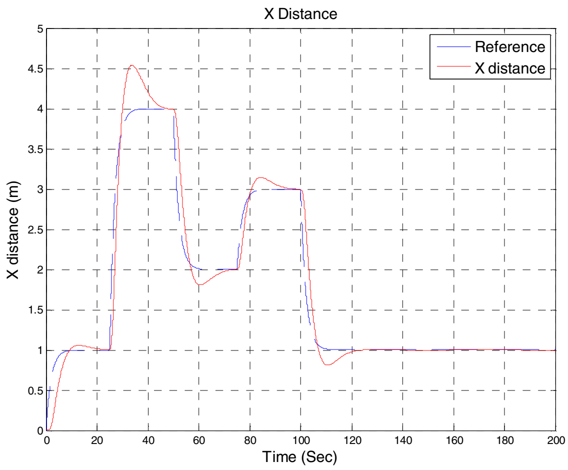

Fig. 5. X distance control of quadrotor

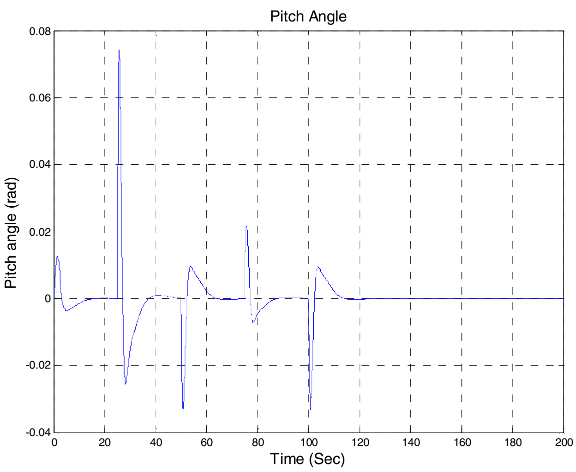

Fig. 6. Pitch angle

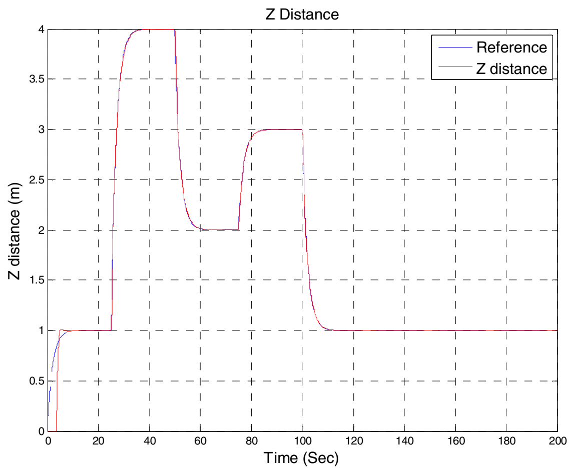

Fig. 7. Z distance control of quadrotor

This control strategy is able to move quadrotor to a given reference trajectory in 3-dimensional space as shown in Fig. 8 and 9.

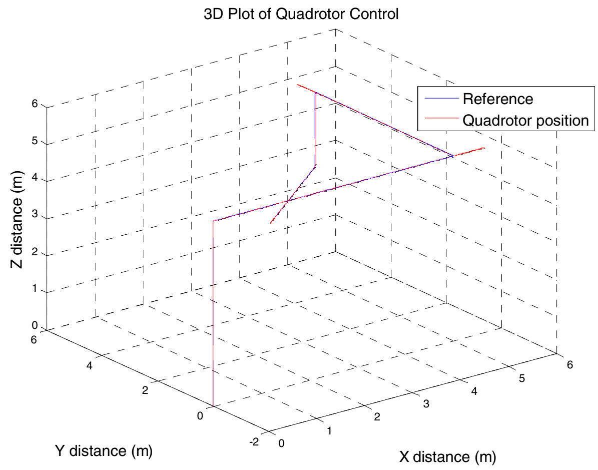

Fig. 8. 3D Plot of Quadrotor Control

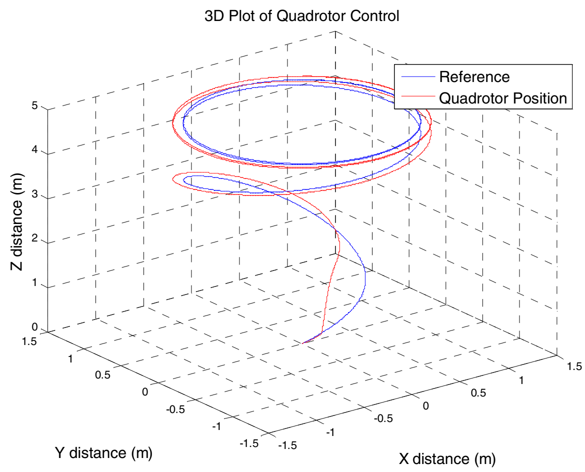

Fig. 9. 3D Plot of Quadrotor Control

IV. Hardware In Loop Simulation

The simulation strategy for hardware in loop simulation is shown in Fig. 10.

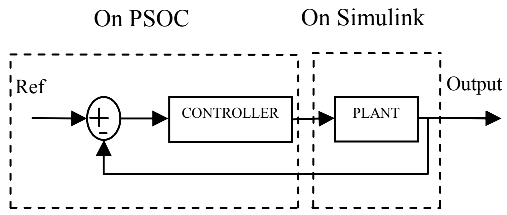

Fig. 10. HIL Simulation Technique

The control strategy presented in section III is implemented on PSOC [1] device by using C language. PSOC 5 is used in this work. PSOC 5 contains Cortex M3 ARM processor with analog and digital configurable blocks. These configurable blocks make this device different from traditional microcontrollers. HIL simulation is performed with serial communication between PSOC and Simulink. In this simulation, 9600 baud rate is used. The other baud rates can also be used. Quadrotor is a MIMO system and its control strategy is also a MIMO system. In HIL simulation, PSOC receives the roll angle, pitch angle, yaw angle, X distance, Y distance, Z distance and Z velocity and gives the calculated all four propellers speed signals.

The simulink blocks of HIL simulation are shown in Fig. 11. The "query instrument" and "to instrument" blocks are from the "Instrument control toolbox" of Matlab. The blocks are used for serial communication. The constants are used to make points calculation possible on PSOC board.

V. HIL Simulation Results

The X distance, Y distance and Z distance are achieved for their respective references and yaw angle is also achieved. The X distance, Y distance, Z distance and yaw angle results are given below:

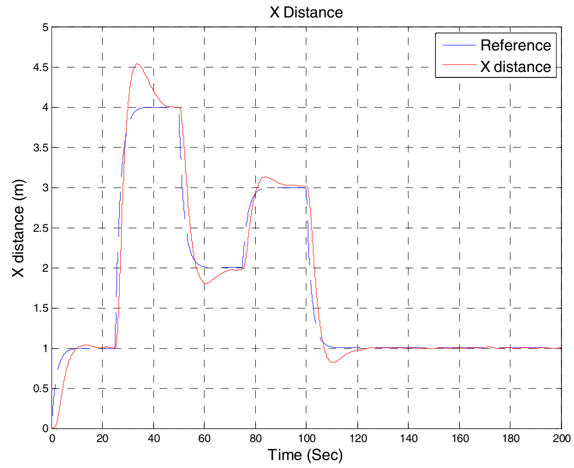

Fig. 12. X distance control of quadrotor by PSOC

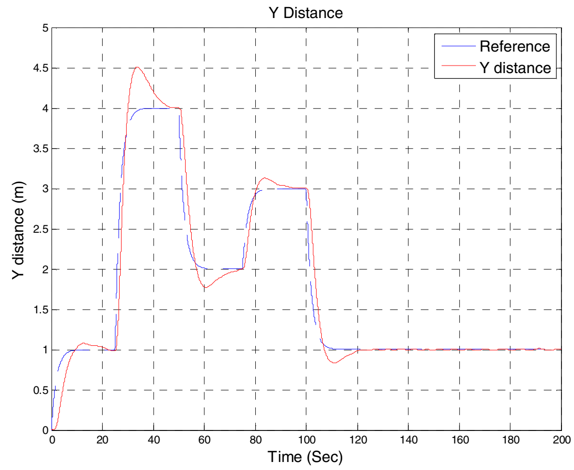

Fig. 13. Y distance control of quadrotor by PSOC

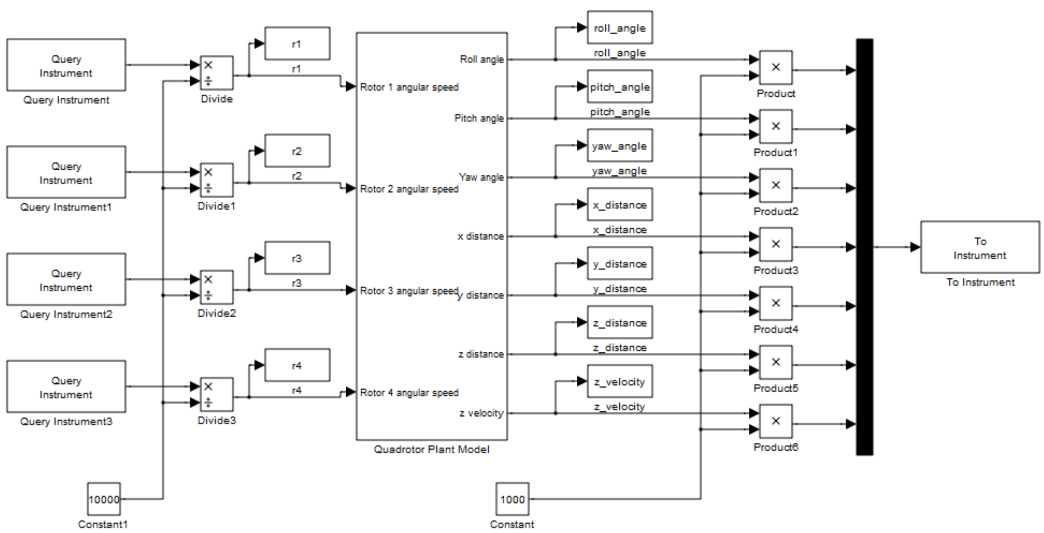

Fig. 11. Simulink Blocks of Quadrotor HIL Simulation

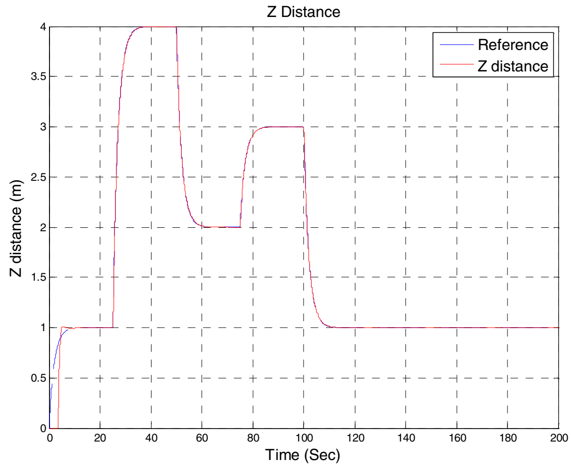

Fig. 14. Z distance control of quadrotor by PSOC

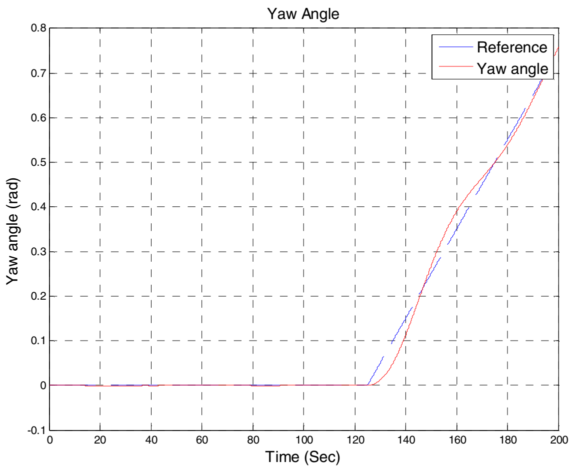

Fig. 15. Yaw angle control of quadrotor by PSOC

As shown in Fig. 12, 13, 14 and 15, the control strategy implemented on PSOC device is able to track the reference signals for X distance, Y distance, Z distance and yaw angle in hardware in the loop simulation. This control strategy implemented on PSOC is also able to move quadrotor to a given reference trajectory in 3-dimensional space as shown in Fig. 16 and 17. The similarity of results presented in section III and section V clearly shows the effectiveness and successful implementation of control strategy on PSOC.

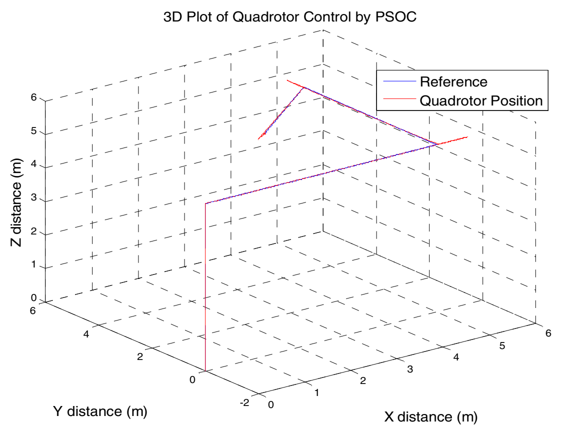

Fig. 16. 3D Plot of Quadrotor Control by PSOC

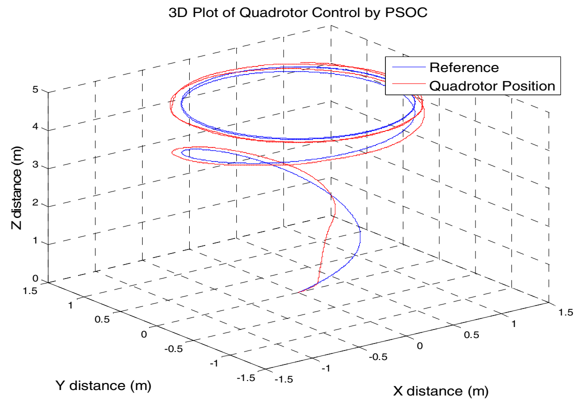

Fig. 17. 3D Plot of Quadrotor Control by PSOC

VI. CONCLUSION

Position control of quadrotor by discrete PID control scheme is presented. The control scheme is also implemented on PSOC device and runs this embedded controller on quadrotor model by using hardware in loop simulation technique. Results have clearly shown the effectiveness of the proposed control scheme and successful implementation of control scheme on PSOC. This also makes the PSOC device a good choice for control scheme implementation.

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