AENSI Journals
Australian Journal of Basic and Applied Sciences
ISSN:1991-8178

Journal home page: www.ajbasweb.com

Pilot in the Loop Simulation for Quadrotor Flight Experiment

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ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form 24 January 2014
Accepted 29 January 2014
Available online 5 April 2014

Key words:
pilot in the loop; real time window target; flight simulator; UAV; quadrotor

ABSTRACT

The purpose of this research is to develop an experimental test bed for pilot in the loop (PIL) simulation of quadrotor dynamics. The simulator set-up includes two CPUs working in sync, a radio control transmitter, a DAQ card, a microcontroller, four brushless DC motors, and sensors for attitude, acceleration and altitude measurements. This paper shows simulation results of decentralized PD compensators applied in three attitude directions and the vertical axis. These results validate the stable performance of decentralized PD controllers and at the same time reveal that the simulation runs in real time as shown by the zero values of the missed ticks parameter at all time in MATLAB/Simulink environment. The simulator provides a very closed to reality flight situation that a pilot can experience; thus the simulator is very useful for researchers to understand the character of the quadrotor system being developed and for pilots to complete a mission using the quadrotor system.

To Cite This Article: Joga Dharma Setiawan, Mochammad Ariyanto, Agus Mukhtar, Munadi, Pilot in the Loop Simulation for Quadrotor Flight Experiment. ***Aust. J. Basic & Appl. Sci.,*** *8(4): 485-494, 2014*

INTRODUCTION

Quad rotor is one of the most active research topic in rotary wing unmanned aerial vehicles (UAVs) due to its mechanical design simplicity and human interaction safe characteristic (Mellinger, D., *et al*., 2011) and (Pounds, P., *et al*., 2011). However extra care in design and construction processes must be taken as the quad rotor at many times is loaded with expensive electronic equipment. This study proposes a real-time flight simulator as one of the tools used for designing quadrotor systems. The benefits of the simulator are to reduce risk of accident, design development time, cost, and the number of flight test.

Konkuk University (Putro, I.E., *et al*., 2010) has developed real-time simulation of quadrotor. The real-time simulation was done in MATLAB/Simulink using xPC Target in which two host PCs and two PC targets were used. However the development of real-time simulation of quadrotor to be used for flight simulator has not been done yet. The closest flight simulator that has been developed is flight simulator for a small scale helicopter and fixed wing. Georgia Institute of Technology (Munzinger, C., 1998) and (Johnson, E.N., 2002) has developed a real-time flight simulator for a small scale helicopter. The flight simulator tools can provide real-time display of all flight data, including plotting, logging and modifying flight data. In reference (Jung, D. and Tsiotras, P., 2007), a realistic simulation based on MATLAB/Simulink with flight-gear for fixed wing UAV has been developed. The real-time simulator is equipped with hardware in the loop. Similarly, a real-time simulation has been conducted using LabVIEW software (Benrejeb, W. and Boubaker, O., 2012) for an inverted pendulum model.Control Systems and Robotics Lab, Diponegoro University, has developed a quadrotor equipped with a gripper for aerial object interaction/aerial grasping, as shown in Fig. 1 (Setiawan, J.D.,*et al*., 2012). This paper deals with the development of real-time flight simulator and experiment of PIL simulation. In this research, PIL simulation is developed using hardware and software arrangement as shown in Fig. 1.The objective of this research is to develop an experimental test bed for PIL simulation of quadrotor dynamics. The PIL can be used for facilitating pilot training purpose and basic understanding of quadrotor flight dynamic. Proportional Derivative (PD) compensator is used to control the attitude and altitude of quadrotor.

A six degrees of freedom (6-DOF) nonlinear model of quadrotor dynamics is developed in MATLAB/Simulink environment. The PD compensator is utilized to control altitude and attitude at hover flight. PD compensator is capable of controlling the attitude of quadrotor as in (Wu, Y., 2009; Bresciani, T.,2008; Bouabdallah, S., 2007).

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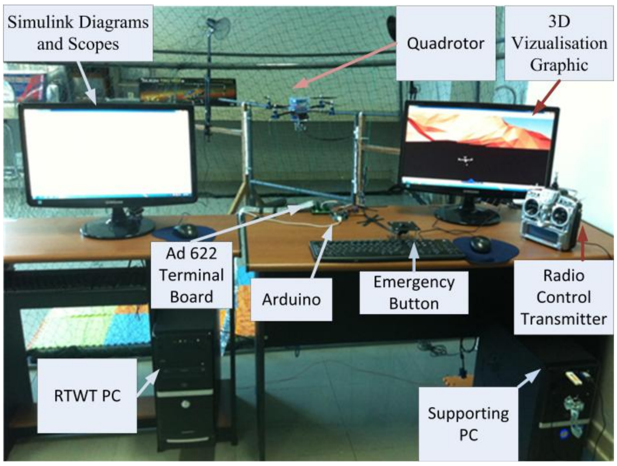

Fig. 1: Quadrotor prototype equipped with gripper and experimental test bed for pilot in the loop simulation

2. Quadrotor Dynamics and Control:

2.1.Quadrotor Dynamics:

The quadrotor consists of a rigid cross frame equipped with four brushless DC motors as shown in Fig. 2. The front and the rear propellers rotate in clockwise while the right and the left propellers rotate in counter clockwise. The vertical motion is achieved by increasing or decreasing the total thrust of quadrotor while maintaining an equal individual thrust [U_1] during going up and going down respectively.

The roll motion is accomplished by increasing (or decreasing) the left propeller speed and by decreasing (or increasing) the right propeller speed [U_2]. It leads to the torque which makes the quadrotor turn in the x_{body} axis. The total vertical thrust is maintained at the same trust as in hovering, such that this command only leads to roll angle acceleration and makes the quadrotor move to the right or left.

The pitch motion is accomplished by increasing (or decreasing) the front propeller speed and by decreasing (or increasing) the rear propeller speed [U_3]. It leads to the torque which makes the quadrotor turn in the y_{body} axis. The total vertical thrust is maintained at the same trust as in hovering, such that this command only leads to the pitch angle acceleration and makes the quadrotor move forward or backward.

The yaw motion is accomplished by increasing (or decreasing) the front and the rear propeller speed and by decreasing (or increasing) the left and the right propeller speed [U_4]. It leads to the torque which makes the quadrotor turn in the z_{body} axis. Again, the total vertical thrust is maintained at the same trust as in hovering, such that this command only leads to the acceleration of yaw angle (Bresciani, T., 2008).

This work assumes that:

- The quadrotor frame structure is rigid and symmetrical.
- The center of mass and the center of geometry coincide.
- The propellers are rigid.
- Thrust is linear with duty cycle/PWM input; four brushless DC motors have high bandwidth response such that the actuator dynamic modeling is not needed.
- The four brushless DC motors have the same properties

Two frames as shown in Fig. 2 can be considered as earth inertial fixed frame (E-frame) and body-fixed frame (B-frame). Using the first Euler axioma and Newton's second law, the dynamics of a generic 6-DOF of rigid body can be written as follows.

$$\begin{bmatrix} mI_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & I \end{bmatrix}\begin{bmatrix} \dot{V}^B \\ \dot{\omega}^B \end{bmatrix}+\begin{bmatrix} \omega^B \times \left(mV^B\right) \\ \omega^B \times \left(I\omega^B\right) \end{bmatrix}=\begin{bmatrix} F^B \\ \tau^B \end{bmatrix} \tag{1}$$

where m is the mass of the body, $I_{3\times3}$ is a 3 by 3 diagonal inertia matrix, $\dot{V}^B$ is the linear acceleration vector with respect to the body fixed frame, $\dot{\omega}^B$ is the angular acceleration vector with respect to the earth inertial frame, F^B is the force vector from the quadrotor with respect to the body fixed frame and τ_B is the torque vector from quadrotor with respect to the body fixed frame.

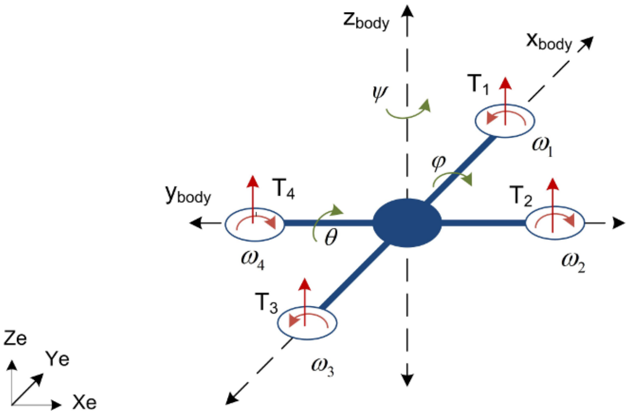

Fig. 2: Quadrotor coordinate and thrust forces

Equation of motion of quadrotor is influenced by 2 contributors. The first contributor is the gravitational vector. The second contributor takes account of the forces and torques directly produced by the main movement inputs, u_i where i= 1 to 4. Eq. (2) represents the quadrotor dynamics with respect to the body fixed coordinate of quadrotor.

$$\begin{aligned}\dot{u} &= (vr - wq) + g\sin\theta\\ \dot{v} &= (wp - ur) - g\cos\theta\sin\phi\\ \dot{w} &= (uq - vp) - g\cos\theta\cos\phi + \frac{U_1}{m}\\ \dot{p} &= \frac{I_{YY} - I_{ZZ}}{I_{XX}}qr + \frac{U_2}{I_{XX}}\\ \dot{q} &= \frac{I_{ZZ} - I_{XX}}{I_{YY}}pr + \frac{U_3}{I_{YY}}\\ \dot{r} &= \frac{I_{XX} - I_{YY}}{I_{ZZ}}pq + \frac{U_4}{I_{ZZ}}\end{aligned} \tag{2}$$

The control of quadrotor in earth inertial fixed frame can be determined using Eq.(3),

$$\begin{aligned}\ddot{X} &= (\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi)\frac{U_1}{m}\\ \ddot{Y} &= (-\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi)\frac{U_1}{m}\\ \ddot{Z} &= -g + \cos\theta\cos\phi\frac{U_1}{m}\\ \dot{p} &= \frac{I_{YY} - I_{ZZ}}{I_{XX}}qr + \frac{U_2}{I_{XX}}\\ \dot{q} &= \frac{I_{ZZ} - I_{XX}}{I_{YY}}pr + \frac{U_3}{I_{YY}}\\ \dot{r} &= \frac{I_{XX} - I_{YY}}{I_{ZZ}}pq + \frac{U_4}{I_{ZZ}}\end{aligned} \tag{3}$$

The kinematics of Euler angle can be calculated using equation as follows

$$\begin{aligned}\dot{\phi} &= p + (q\sin\phi + r\cos\phi)\tan\theta\\ \dot{\theta} &= q\cos\phi - r\sin\phi\\ \dot{\psi} &= (q\sin\phi + r\cos\phi)\sec\theta\end{aligned} \tag{4}$$

while the equations of quadrotor input (U_i) generated by thrust and moment caused by four motors and propellers are given inEq. (5).

$$\begin{aligned}U_1 &= \sum_{i=1}^{4} F_i\\ U_2 &= l(F_4 - F_2)\\ U_3 &= l(F_3 - F_1)\\ U_4 &= M_1 + M_3 - M_2 - M_4\end{aligned} \tag{5}$$

in which F_i is motors and propellers thrust and M_i is moment caused by motors and propellers.

$$\begin{aligned}F_i &= a_i v_i + b_i\\ M_i &= c_i v_i + d_i\end{aligned} \tag{6}$$

wherei= 1 to 4 indicates the front, right, rear and left motors, *a* is the thrust coefficient (N/duty), *b* is the thrust constant (N), *c* is the moment coefficient (N.m/duty), and *d* is the moment constant (N.m). The quadrotor parameters and values can be seen in table 1.

Table 1: Quadrotor parameters and values

Parameter		Description
m	1.8 kg	Quadrotor mass
I_{xx}	0.0397 kg m^2	Rolling moment of inertia
I_{yy}	0.0397 kg m^2	Pitching moment of inertia
I_{zz}	0.0594 kg m^2	Yawing moment of inertia
l	0.285 m	Horizontal distance of each propeller center to CoG

2.2.PD Compensator:

PD compensator design is used to stabilize the quadrotor at hover flight condition, as shown in Fig. 3. the PD compensator is used for four subsystems; roll, pitch, yaw, and throttle for altitude.

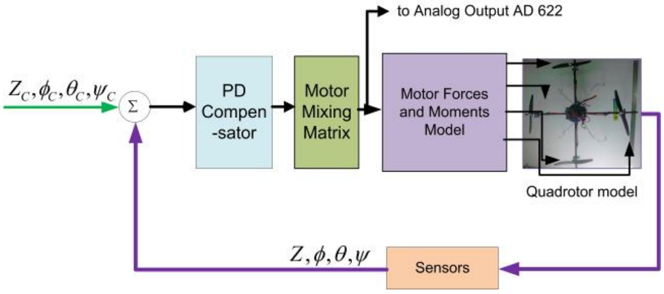

Fig. 3: Basic structure of PD compensator system in real-time flight simulator for quadrotor

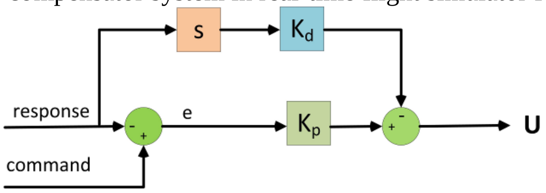

Fig. 4: Enhanced PD compensator in real-time flight simulator

As shown in Fig. 4, the response, command, and actuator control input U can be summarized in Eq. (7)

$$\begin{aligned}&\text{response} = [Z\ \phi\ \theta\ \psi\ ]^T\\&\text{command} = [Z_c \phi_c \theta_c \psi_c]^T\\&\text{actuatorcontrolinput} = [U_{\text{altitude}}\ U_\phi\ U_\theta\ U_\psi]^T\end{aligned} \tag{7}$$

The duty cycle/PWM inputs can be calculated using the motor mixing matrix in Eq. (8), then the resulting duty cycle signals converted to their corresponding voltage and sent to AD 622 DAQ board. The voltage output from AD 622 DAQ board is converted to PWM signal using Arduino Uno microcontroller to drive the four brushless DC motors in real quadrotor as shown on Fig. 5.

$$\begin{bmatrix} dt_1 \\ dt_2 \\ dt_3 \\ dt_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 & 1 \\ 1 & -1 & 0 & -1 \\ 1 & 0 & 1 & 1 \\ 1 & -1 & 0 & -1 \end{bmatrix} \begin{bmatrix} U_{altitude} \\ U_\phi \\ U_\theta \\ U_\psi \end{bmatrix} + \begin{bmatrix} dt_{1nom} \\ dt_{2nom} \\ dt_{3nom} \\ dt_{4nom} \end{bmatrix} \tag{8}$$

3. Hardware and Set-up

In this research, Real Time Windows target (RTWT) with MATLAB/Simulink is used to make the quadrotor flight simulator run in real time. It is important, because the real behavior of the model can be understood from this simulation prior to applying it to the hardware. Whether the model behaves well or not can be checked and if there is something wrong, it can be immediately corrected.

This research uses two computers in which one of them is used as Real Time Windows Target for running Simulink simulation program, generating Voltage output to drive brushless DC motor in real time environment and also displaying curve plots. Another PC is used as the supporting computer in order to display 3D visualization graphics or popularly known as virtual reality view. The pilot in the loop simulation set-up of the hardware is shown in Fig. 5. Specifications of those computers are as follows:

- Real Time Windows Target PC: Intel® Core i3 CPU 3.2 GHz, 2.00 GB of RAM

- Supporting PC: Intel® Core i3 CPU 3.2 GHz, 4.00 GB of RAM

It was observed that graphic presentation of the 3D virtual reality view experienced significant time delay of around 2 seconds if the RAM size in VGA Card of the supporting PC was only 2GB. As the RAM size increased to 4GB, this time delay could not be noticed by the pilot anymore. The sensor data is acquired using Humusoft AD 622 DAQ Card. In this research, LAN/Ethernet connection is used to link the two PCs. This connection was chosen because, according to MATLAB Help, LAN connection is capable of transferring data faster than the other connection, Serial RS-232. Simulation program running in real time environment in Real Time Windows Target PC can be seen in Fig. 6. The communication between two computers is achieved by utilizing the packet input output data in RTWT.

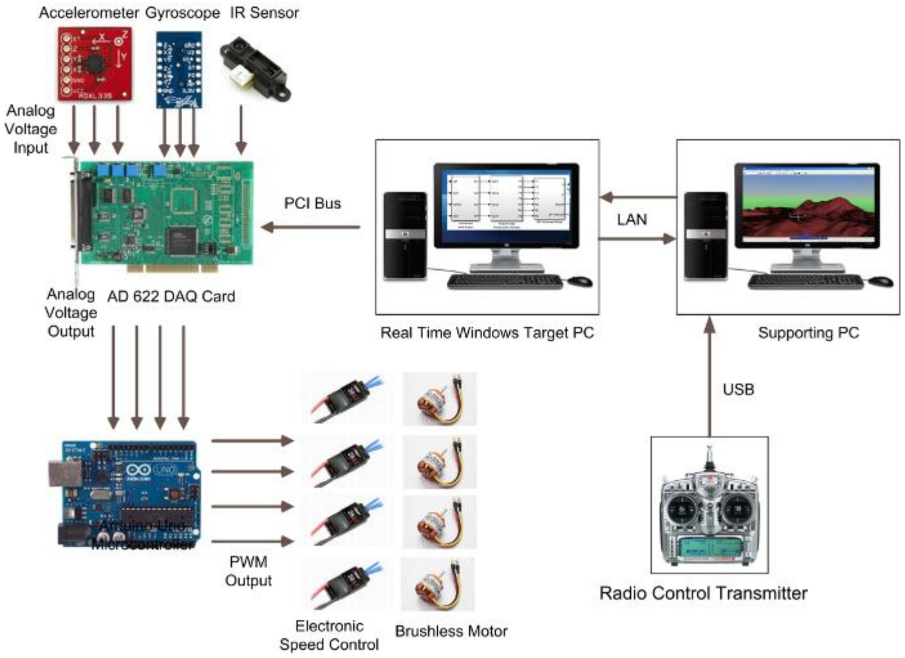

Fig. 5: Pilot in the loop simulation set-up of the hardware

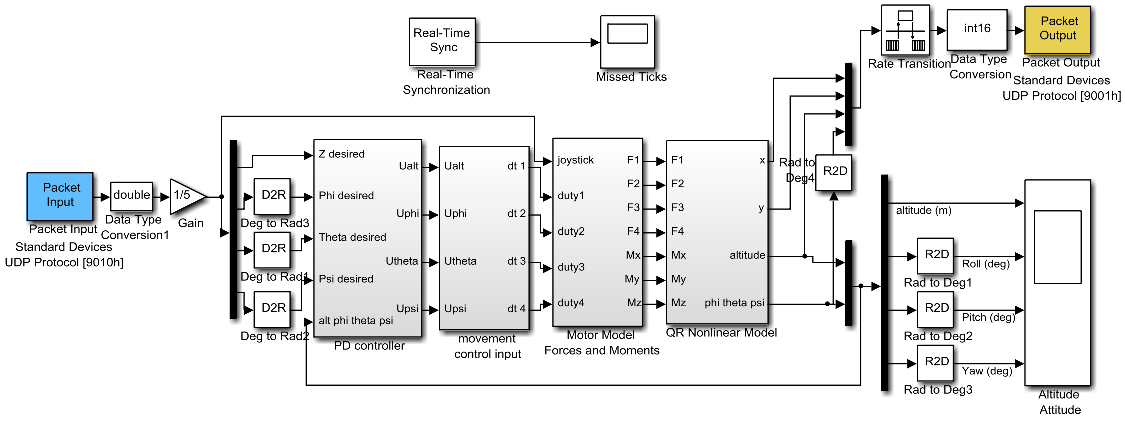

Fig. 6: Plant and controller model of quadrotor in Real Time Windows Target PC

4. Real-Time Flight Simulator

The plant and controller model is shown in Fig. 6 whereas the input model which is run at the supporting computer is shown in Fig. 7.

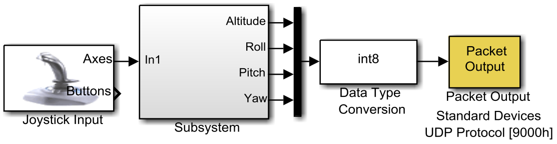

Fig. 7: Input model of quadrotor system

The command signal from the radio control transmitter is read using the joystick input block as shown in Fig. 7. The command signal data type is converted to int8 and then sent to the plant and controller model which is run in the RTWT PC shown in Fig. 6 such that simulation can proceed in real time. A scope in RTWT PC is to used monitor the real time values of the altitude and attitude. The output signals from the plant and controller model are sent to virtual reality model which is run in the supporting computer. The process of converting the data type to int 8 was necessary to reduce data size sent to the RTWT computer such that it can shorten the data transfer process time via UDP protocol using LAN connection.

Virtual reality model in Fig. 8 enables 3D visualization of the simulation as shown in Fig. 9.

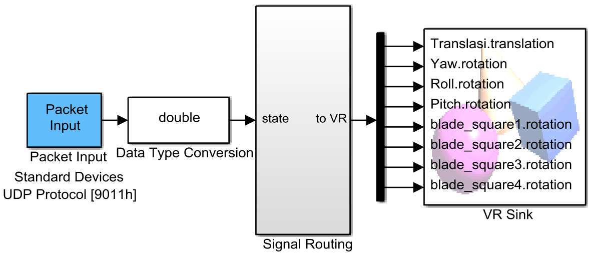

Fig. 8: Virtual reality model of quadrotor system

In the virtual reality model, the data is sent by the host PC through the UDP protocol using LAN connection. After the data is received in type int8, the data is modified to double type in the supporting PC such that it can be used for 3D visualization as presented in Fig. 9.

The next step after the RTWT computer and the supporting computer have been configured is to connect MATLAB/Simulink to the Humusoft AD662 DAQ board as shown in Fig. 5. Four channels of the analog output of the DAQ board are connected to an Arduino board in order to generate PWM signals that are used to drive the electronic speed controllers for the four brushless DC motors. To avoid over voltage instructed to DAQ board, the signal in each channel is limited using the saturation block as shown in Fig. 10.

This new system arrangement, having the components from the Humusoft AD 662 DAQ Card up to the brushless motors shown in Fig. 5 avoid the use of another PC as sound generator presented in [8]. In this case, the sound generated by the angular speed variation of brushless motors together with the induced aerodynamic noise of propellers can provide a more realistic feeling to the pilot.

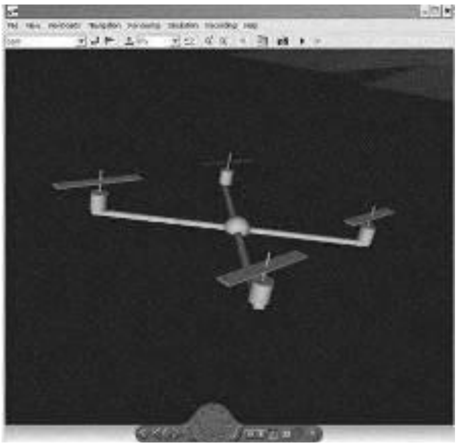

Fig. 9: 3D visualization of quadrotor attitude and position in the simulation

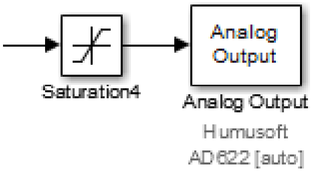

Fig. 10: Connectivity of quadrotor model with Humusoft AD 622 DAQ board

The pilot command is recognized through a radio control transmitter, connected to the supporting PC via USB port, it consists of 4 channel inputs for throttle to maintain altitude, yaw angle, roll angle and pitch angle.

After building the real-time simulator, verification for the simulation model was performed by testing the dynamic in three flight directions: longitudinal, lateral and vertical. These tests are also to observe control system performance. These pilot in the loop tests were performed by varying the angle of two radio control stick inputs: the left stick is for the throttle and yaw inputs while the right stick is for pitch and roll inputs. The angle of the throttle stick as shown in Fig. 11 means a command for the quadrotor altitude. When the throttle stick angle is positioned to 27^0, the quadrotor altitude of 2 m above the land is steadily reached.

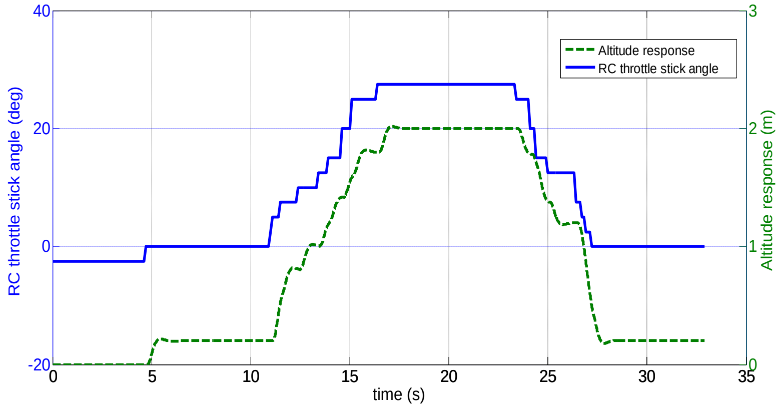

Fig. 11: Test for altitude response and its RC throttle stick input

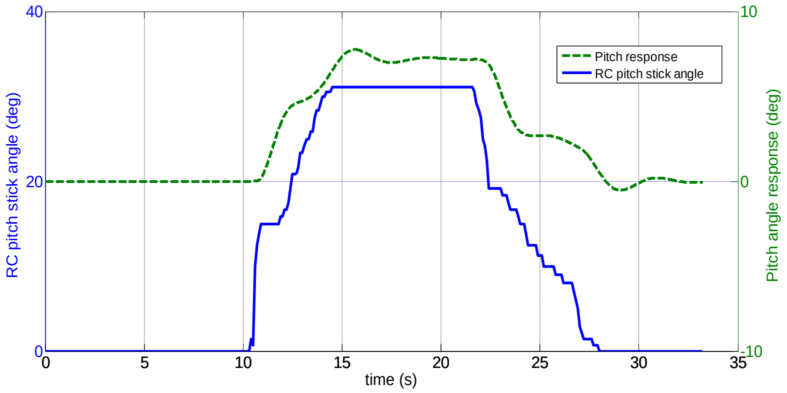

Fig. 12: Test for pitch angle response and its RC pitch stick input

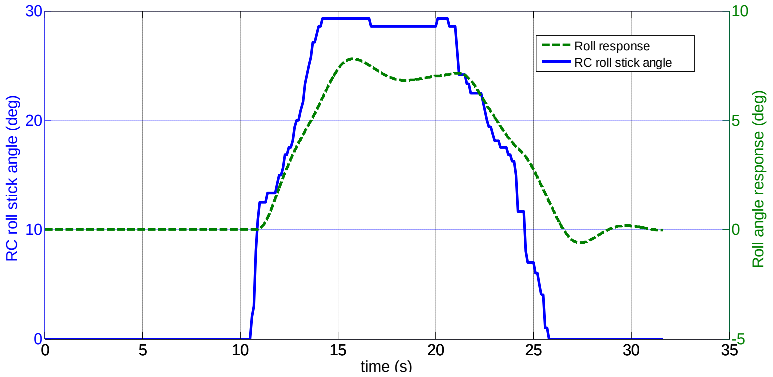

Fig. 13: Test for roll angle response and its RC roll stick input

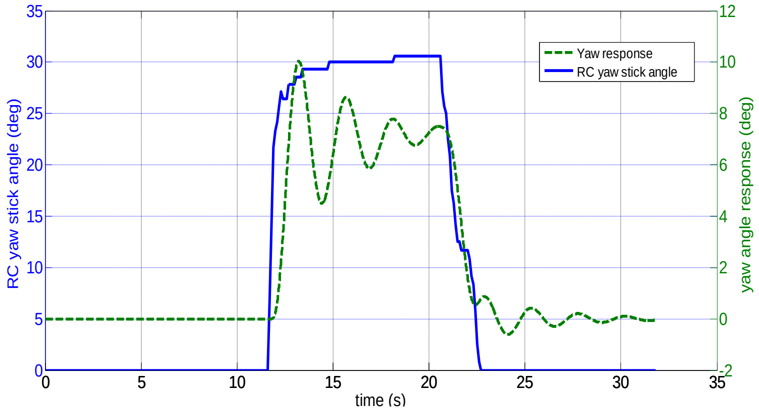

Fig. 14: Test for yaw angle response and its RC yaw stick input

Fig. 12 shows the pitch stick angle as the commandfor the pitch angle and the response is the quadrotorpitch angle. Fig.13 presents the quadrotor roll responseto the roll stick angle of 27^0. The quadrotor yaw angleresponse to the commanded yaw stick angle is shownin Fig. 14. The operating range of roll, pitch, and yawstick angles is ± 65^0 correlating with the quadrotorcommand signal range of ± 20^0 in roll, pitch, and yawangles. Significant oscillations can be observed in theyaw angle response in Fig. 14 while only slightoscillations are seen in the pitch and roll responses inFigs. 12 and 14.This phenomena is possible since thePD compensator was designed based on the SISOlinear model while the simulation utilizes the completenonlinear model and applies a relatively large stepinput. Additional tuning of PD gains is needed forbetter performance in the complete nonlinear model.

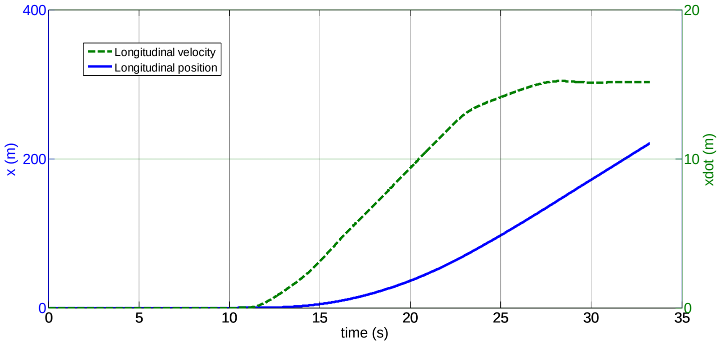

Fig. 15: Longitudinal position and velocity resulted from pitch stick input

In the x direction, the position and velocity responses with respect of the inertial frame are shown in Fig. 15. The quadrotor moves in the positive x direction due to the RC pitch stick angle command shown in Fig. 12. Similarly, the quadrotor motion in negative y direction together with its velocity is shown in Fig. 16. This is due to the RC roll stick angle command shown in Fig.13. The altitude and vertical velocity responses of the quadrotor due the RC throttle stick angle command shown in Fig. 11 are presented in Fig. 17. As the throttle angle increases the quadrotor moves to higher altitude.

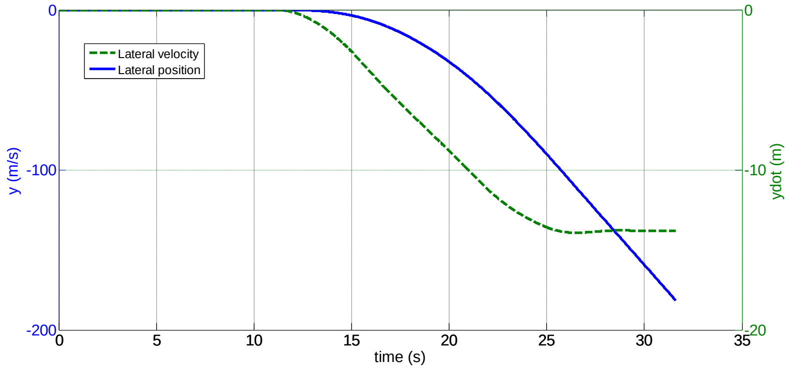

Fig. 16: Lateral position and velocity resulted from roll stick input

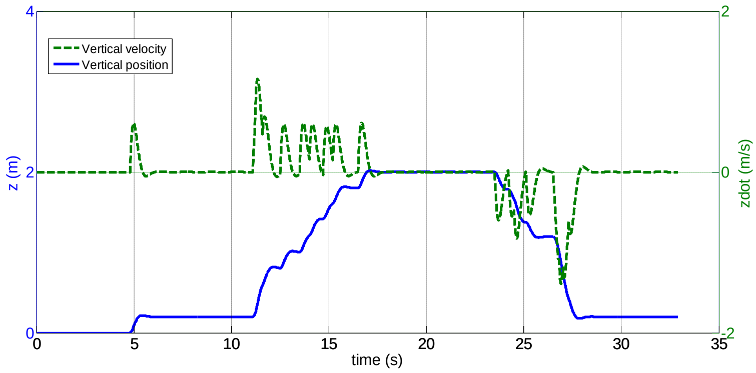

Fig. 17: Vertical position and velocity resulted from throttle stick input

Verification to check whether the simulation runs in real time or not was conducted by evaluating using Real-Time Synchronization block diagram as shown in Fig. 18. According to MATLAB/Simulink help, the Real-Time Sync block allows to synchronize the Simulink model with the real-time clock at Real-Time Sync block sample hits. The only parameters are those dealing with sample time and missed ticks.

The sample time value representing how frequently the Simulink program wants to synchronize the simulation model with the real-time clock. The number of missed ticks allows the simulation model of the lag behind the real-time kernel. When the simulation model lags by more than this number, the block reports an error and simulation stops. Otherwise, simulation continues even if some ticks are missed. In this research, Real-Time Synchronization block usessample time 0.01 s to synchronize the simulation modelwith the real-time clock, and the number of missedticks scope (Setiawan, J. D.,*et al*., 2012)as shown in Fig 18. During theexperiment, it was found that the missed ticks valuewas always zero at all time, thereby it can be stated thatthe simulation runs in real time or there is no lag in realtime behind the real-time kernel.

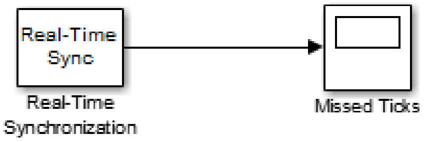

Fig. 18: Real-time synchronization in real time windows target

5. *Experimental Result:*

PD compensator is implemented in real time control using Hardware in the Loop (HIL) set-up. The roll and pitch motions are tested using the flight test stand as shown in Fig. 1. As presented Fig. 19 and Fig. 20 Pilot in the Loop test is conducted by providing pilot command input as command for the roll and pitch angles. Figs.19 and 20 show that the roll and pitch angle responses can follow the pilot input excited through the roll and pitch channel sticks of the radio transmitter. In this test, the PD control gives small value of steady state error in both roll and pitch angles. This small steady state error was expected since the quadrotor. It was observed that the arrangement suffered unmodeled friction force from the way of holding quadrotor on the test bench and from the additional load from the umbilical cable that connected the quadrotor to the data acqusition and controller cards.

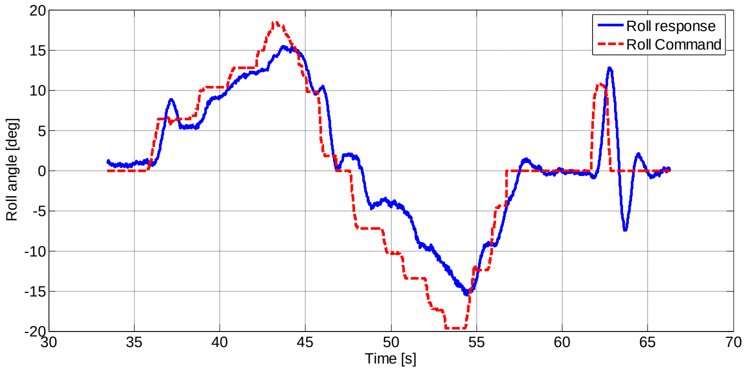

Fig. 19: Roll angle test in PIL

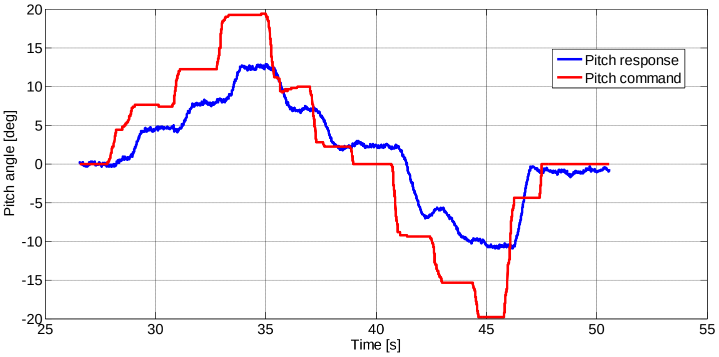

Fig. 20: Pitch angle test in PIL

Conclusion:

This work presented a methodology for developing a pilot in the loop simulation using real-time flight simulator of quadrotor systems. By evaluating the dynamic of the quadrotor in three flight directions, it can be seen that the PD compensators make the closed system stable. It was also confirmed that simulator run in real time and the hardware arrangement produces a simulation that is very closed to realistic situation of a flying quadrotor. The simulator enables engineers and pilots topredict behavior of model without conducting practicaltest. It is very beneficial to reduce cost and time indesign process. The experimental results give a promisethat hardware arrangement in this work can be a closerstep to having Hardware-In-the-Loop (HIL) simulationwhich is being developed for future study ofautonomous mode fly of the quadrotor.

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