Integrated Simulation Platform for Indoor Quadrotor Applications

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ABSTRACT

In this paper, an integrated simulation platform is developed for indoor quadrotor applications. The simulation platform mainly consists of two subsystems, the controller subsystem; the other subsystem is an indoor interactive environment. The two integrated subsystems can be highly deployed in quadrotor systems development cycle and validation of different algorithms for indoor navigation. Moreover, the simulation platform has visualization capability and tuning flexibility. These features provide the necessary ability to implement and inspect the developed algorithm in different scenario conditions before implementing them for indoor applications.

1. INTRODUCTION

Rotary wing unmanned aerial vehicles (UAV) have received considerable attention in the past decade [1–4]. Rotorcrafts are highly agile and maneuverable vehicles including indoor hovering. Recently, UAVs are widely immerging to the field of indoor applications [5-9]. Among these UAV, quadrotor's high maneuverability and compact size has made it the most suitable flying platform for indoor applications, yet the limited flying space and the existence of obstacles has made obstacles avoidance the biggest challenge within indoor flying environments. Quadrotors UAV should also be provided with autonomous navigation capabilities or approaches. These capabilities are important to maintain the quadrotor safe while navigation indoor dynamic environments.

Simulation platform can provide a rapid development cycle for quadrotor industry and research. Due to these demands recent researches tends to develop flight simulation environments for the developed hardware. In these simulation environments navigation algorithms [5], adaptive controller [6] and fully autonomous indoor quadrotor [7] were examined.

This paper provides a simulation platform of a quadrotor equipped with different sensors, which can be used to investigate different algorithms and controllers for indoor applications before implementing those algorithms on the physical systems, which reduces the risk during algorithms validation on the physical system and speed up the development cycle.

Quadrotor modeling and control is discussed in the next section. Section three demonstrates the integrated simulation platform. Finally, the concluded remark is summarized in section four.

2. QUADROTOR MODELING AND CONTROL

The Quadrotor main idea was to have a helicopter that can handle larger capacity and can maneuver in areas that were difficult to reach. Generally it consists of four propellers (front, rear, right and left), as shown in figure 1.[10]

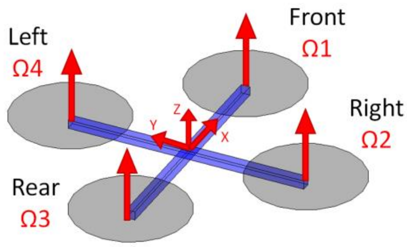

Figure 1 Quadrotor propellers and movements

By changing the control command to these motors Ω_i, their speed will vary and the quadrotor direction is updated, accordingly the quadrotor can navigate in different directions. For instance, the quadrotor can move in the vertical *Z* direction by varying the speed of all propellers at the same time and by the same amount as shown in figure 2.

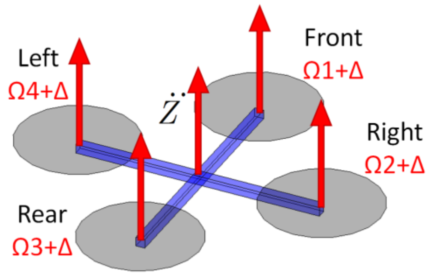

Figure 2 Vertical movement

To command the quadrotor to move in the *X* direction, the speed of the front and rear propellers should be changed by the same amount and in opposite directions as shown in figure 3. Moving the quadrotor in the *Y* direction can be done by changing the speed of the right and left propellers by the same amount and in opposite directions as shown in figure 4.

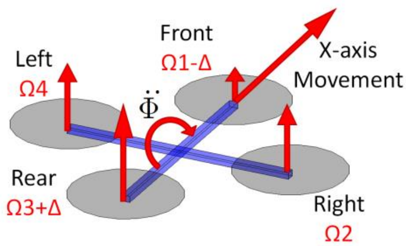

Figure 3 Movement in *X* direction

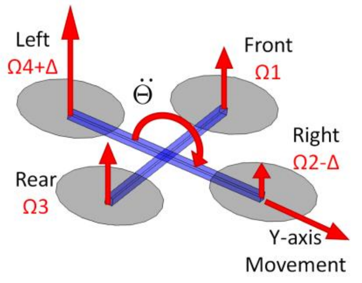

Figure 4 Movement in *Y* direction

To control quadrotor heading, the speed of all propellers is commanded by the same amount but in different directions, front and rear propellers with the same direction and right and left the propellers with opposite direction, as shown in figure 5.

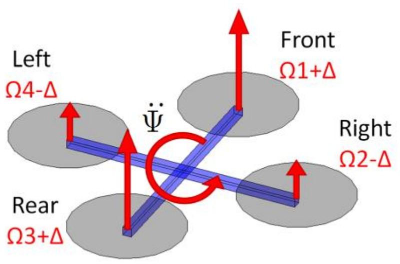

Figure 5 Changing the quadrotor heading.

2.1. Quadrotor Model

The quadrotor's model, mainly includes the nonlinear aero dynamical equations of the quadrotor along with the actuators dynamics and saturation limits [10-13]. The model is represented as follows:

$$\ddot{X} = (\sin\Psi\sin\Phi + \cos\Psi\sin\Theta\cos\Phi)\frac{U1}{m} \tag{1}$$

$$\ddot{Y} = (-\cos\Psi\sin\Phi + \sin\Psi\sin\Theta\cos\Phi)\frac{U1}{m} \tag{2}$$

$$\ddot{Z} = -g + (\cos\Theta\cos\Phi)\frac{U1}{m} \tag{3}$$

$$\dot{p} = \frac{Iyy - Izz}{Ixx}qr - \frac{U2}{Ixx} \tag{4}$$

$$\dot{q} = \frac{Izz - Ixx}{Iyy}pr - \frac{U3}{Iyy} \tag{5}$$

$$\dot{r} = \frac{Ixx - Iyy}{Izz}pq - \frac{U4}{Izz} \tag{6}$$

Where X, Y, Z are the position of the center of mass WRT inertial frame, $\emptyset, \theta, \psi$ are the Euler angles, p, q, r are the body rates, m is the quadrotor's mass, I_{XX}, I_{YY}, I_{ZZ} are the moments of inertia, U_1, U_2, U_3, U_4 are the throttle, roll, pitch and yaw forces and moments respectively.

For the actuator's dynamics they are described as in the following equations:

$$U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \tag{7}$$

$$U_2 = bl(-\Omega_2^2 + \Omega_4^2) \tag{8}$$

$$U_3 = bl(-\Omega_1^2 + \Omega_3^2) \tag{9}$$

$$U_4 = d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \tag{10}$$

Where b is the thrust factor, d is the drag factor, l is the radius of the quadrotor and Ω_i is the propeller's speed of motor i.

2.2. Controller Design

A Proportional-Integral-Derivative controller (PID) is used to find the appropriate command signals $[U1, U2, U3, U4]^T$. Generally, the PID controller is described as follows:[14]

$$U_i = K_P e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt}e(t) \tag{11}$$

Where *e* is the error signal defined as the difference between the predefined desired value and the actual measured one. The equivalent rotational speed for each motor based on these command signals is fussed using inverse kinematics as follows:

$$\Omega_1 = \frac{U_1}{4b} - \frac{U_3}{2bl} - \frac{U_4}{4d} \tag{12}$$

$$\Omega_2 = \frac{U_1}{4b} - \frac{U_2}{2bl} + \frac{U_4}{4d} \tag{13}$$

$$\Omega_3 = \frac{U_1}{4b} + \frac{U_3}{2bl} - \frac{U_4}{4d} \tag{14}$$

$$\Omega_4 = \frac{U_1}{4b} + \frac{U_2}{2bl} + \frac{U_4}{4d} \tag{15}$$

The general structure for the used controller is shown in figures 6 and 7. PID controllers were used to control the position, attitude and altitude of the quadrotor throughout the simulation. A parallel set of six different PID controllers were developed for *X*-position, *Y*-position, Altitude, Roll, Pitch and Yaw movements, as shown in figure7. As it can be noticed the proposed controller structure requires four set points shown in vector λ. As for the roll and pitch desired angles, they are generated from *Y* and *X* PID controllers respectively, based on a cascade controller structure, as shown in figure 6.

$$\lambda = \begin{bmatrix} X \\ Y \\ Z \\ \Psi \end{bmatrix}_{desired} \tag{16}$$

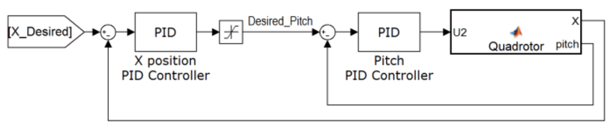

Figure 6 PID controller structure for *X* position command.

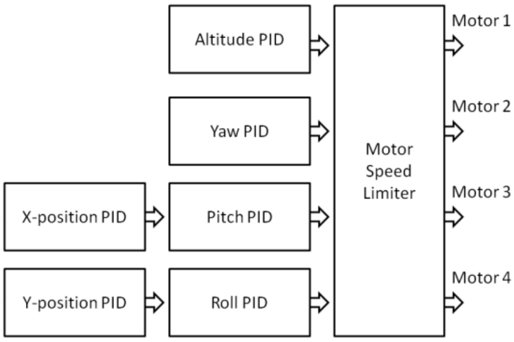

Figure 7 General structure of quadrotor controller

2.3. Controller Validation

The proposed controller is validated against different complex three dimensional predefined paths to make sure that the tracking capability of the quadrotor to any desired path is achieved. In one of these conducted evaluation scenarios, the quadrotor is commanded to follow a three dimensional spiral path starting from the origin in X,Y and Z and rising up with time, as shown in figure 8.

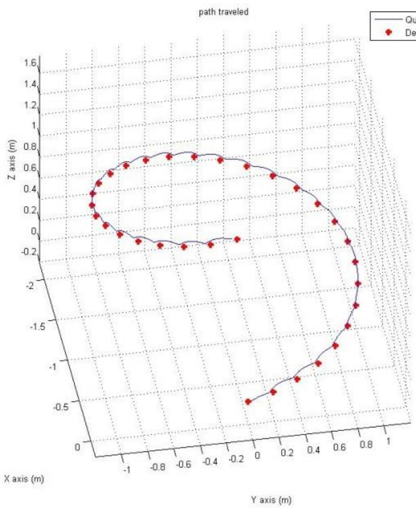

Figure 8 The quadrotor response to the spiral predefined desired path.

The roll, pitch and yaw responses during this path are demonstrated in figures 9, 10 and 11, respectively. As it can be noticed from the response, the agreement with the predefined path for the quadrotor is achieved.

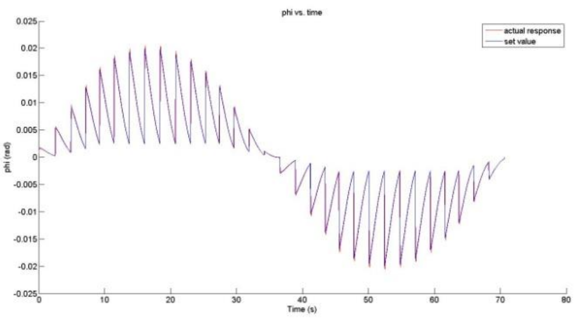

Figure 9 Roll response

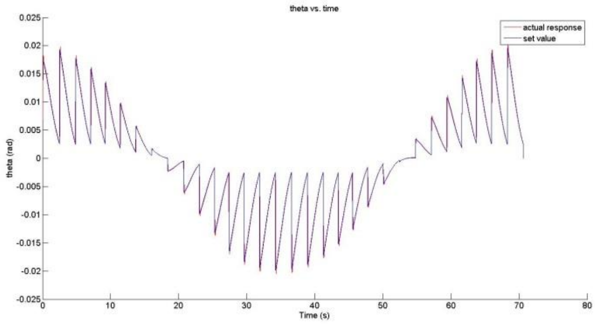

Figure 10 Pitch response

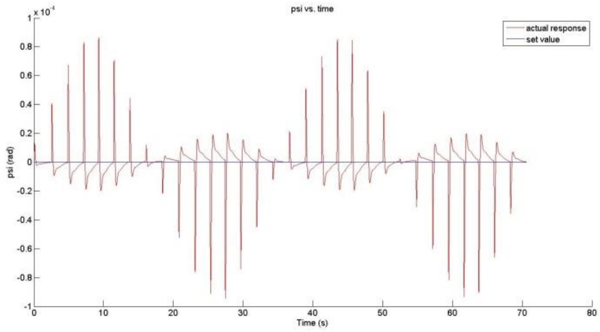

Figure 11 Yaw response

The X, Y and Z position responses are shown in figures 12,13 and 14, respectively. These responses come to an agreement with the predefined path for the quadrotor. The propellers speed that commanded the quadrotor throughout evaluation path is shown in figure 15 for the four motors.

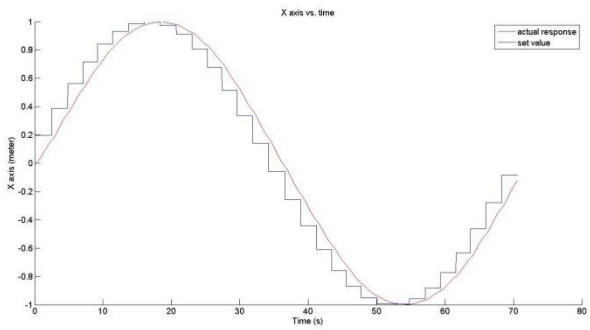

Figure 12 X response

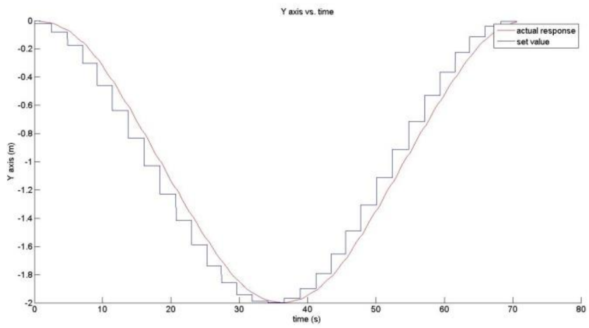

Figure 13 Y response

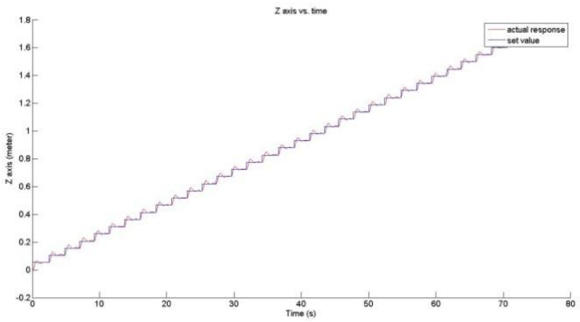

Figure 14 *Z* response

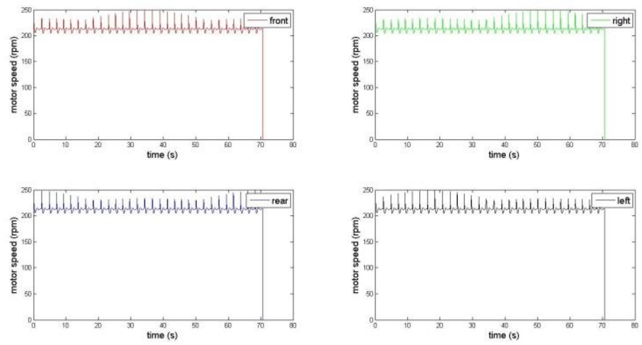

Figure 15 propellers speed throughout the path.

3. INDOOR SIMULATION PLATFORM

An integrated indoor simulation platform was developed to include the vehicle dynamics, onboard sensors and the indoor environment. The main idea of the integrated simulation is to enhance the development time cycle of algorithms concerned with quadrotor indoor navigation applications. The visualization capability that the simulation platform has, provides the algorithm developer with a better R/D tool to examine and optimize the developed algorithm based on monitoring the quadrotor behavior throughout the simulation time. On the other hand, it reduces the damages that can happen during testing phases to the quadrotor and it reduces the testing time as the quadrotor needs to be recharged quite often.

The developed simulation platform is built completely using MATLAB software. All the states of the quadrotor can be monitored and plotted after the simulation is completed. This tool will provide better understanding for the vehicle performance under the developed algorithm or navigation approach to achieve optimal performance.

3.1. Simulation structure

The simulation was developed under the MATLAB platform. It mainly integrates three subsystems: the sensors subsystem, the controller subsystems, and the Quadrotor model subsystem, as shown in figure 16.

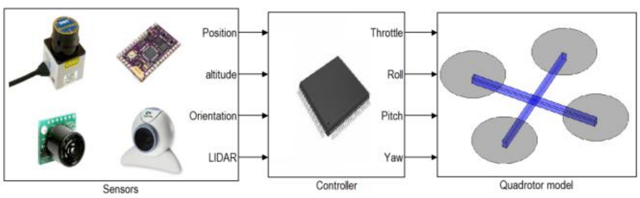

Figure 16 simulation structure

In the sensors subsystems, models have been created to simulate the measurements of position, orientation and altitude of the quadrotor. Moreover the laser sensor model is integrated to detect any available obstacles within the indoor environment.

In the Controller subsystems, different algorithms can be utilized and their functionality and performance in avoiding obstacles and driving the quadrotor to the target location can be examined within the indoor environments. In this research the PID controller for following a predefined path is considered.

In Quadrotor model's subsystems, the nonlinear equations of motion are provided to simulate the quadrotor's response to a given control commanded from the controller subsystem.

3.2. Simulation Platform Validation:

In order to validate the developed integrated simulation platform, a path following scenario was conducted to examine the performance of the integrated indoor environment. During this scenario, the quadrotor should follow a predefined path between different obstacles and navigate the addressed indoor environment while moving.

Figure 17 shows a sequence of screen captures from the simulated flight scenario. As it can be noticed, arrows were provided to show the direction on which the quadrotor is moving. While the predefined path is indicted by a small red marks.

Figure 18 shows the overall path traveled by the quadrotor throughout the simulation scenario under PID controller commands. In figures 19 and 20 the *X*-axis and *Y*-axis PID responses throughout the simulation scenario are shown, respectively.

As it can be noticed from figure 17, 18, 19 and figure 20, the controller managed to stabilize the quadrotor and succeeded in driving it autonomously through the structured environment. Moreover, the integrated laser sensor managed to detect all the obstacles that appear throughout the predefined path. The feedback from the laser sensor's reading can highly be utilized in different obstacles avoidance algorithms or can be used to map the area around the quadrotor.

4. CONCLUSION

This paper provided the required development approach to implement a simulation platform for indoor quadrotor applications. The developed simulation platform offers powerful tools to examine and optimize different algorithms and controllers for quadrotor applications. These tools can highly reduce the development time cycle and possible risk problems during the design phase. The integration of the navigation sensors, controllers, quadrotor dynamics and the navigation environment, provide an interesting platform which can be utilized for obstacles avoidance algorithms, localization, or mapping of navigated area surrounding the quadrotor.

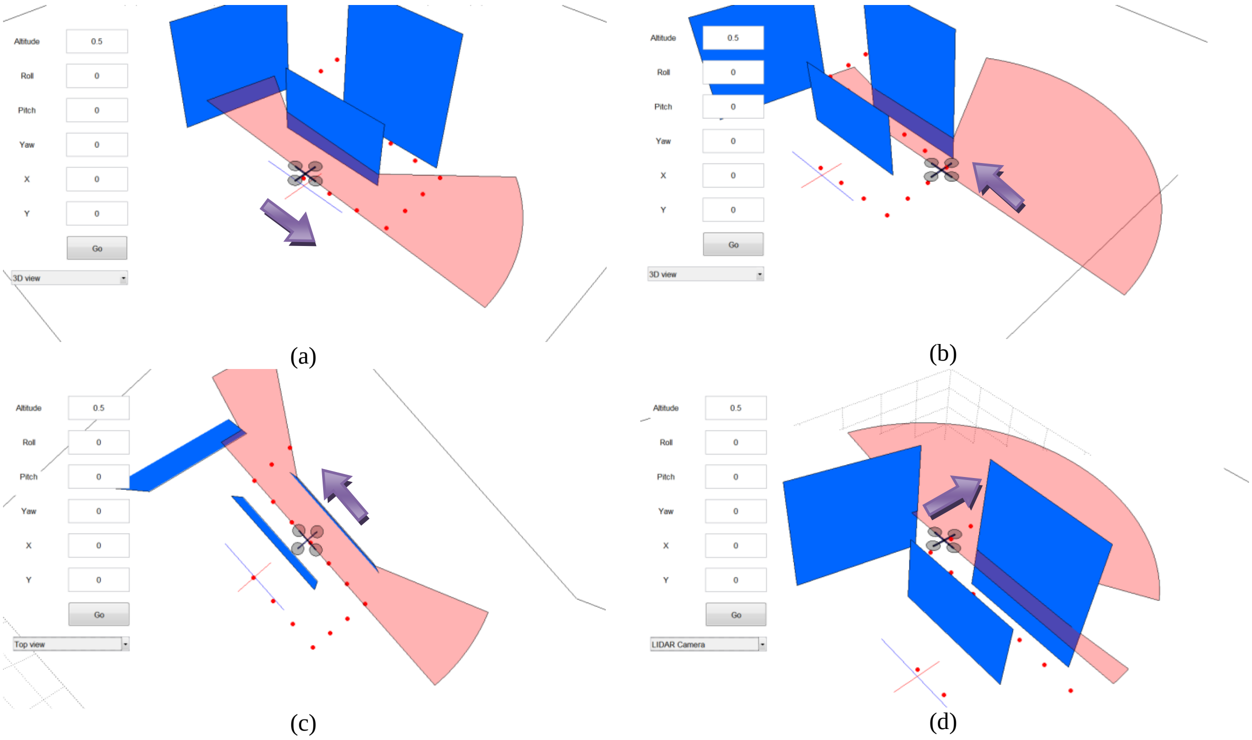

Figure 17 Sequence of screen captures through the path following scenario

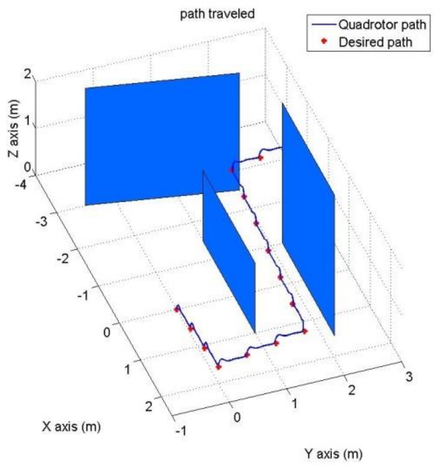

Figure 18 Quadrotor's path throughout the simulation scenario.

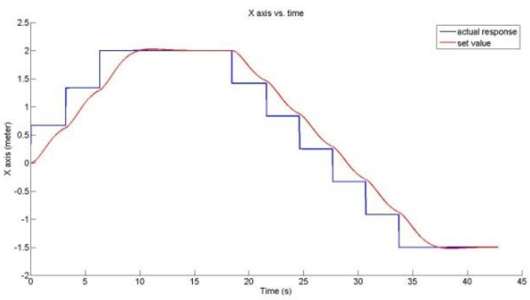

Figure 19 Response on *X*-axis throughout the simulation scenario

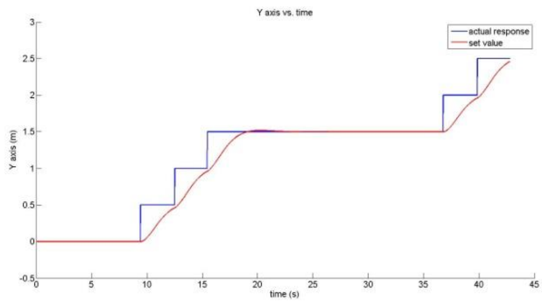

Figure 20 Response on *Y*-axis throughout the simulation scenario

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