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Navigating Urban Skies: Obstacle Avoidance Strategies for Quadrotor MAVs

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Abstract. Micro Aerial Vehicles (MAVs) has gained attentions since more than two decades ago starting from the applications in air combat up to civil applications such as packet deliveries, environmental monitoring, and surveillance. In an environment such as cities that grows denser, navigation and control for drones becomes challenging to ensure safe navigation around buildings and other obstacles. This study proposes an approach for obstacle avoidance for MAVs by using ultrasonic sensors. Four sensors are strategically positioned to cover the front, right, back, and left directions. Additionally, a downward-facing sensor measures the quadrotor's height above ground. Our goal is to develop autonomous MAV that can avoid obstacles, ensuring safe flight even in complex urban landscapes. The scenario implemented in the study is by introducing obstacle in any directions. When an obstacle is detected by the ultrasonic sensor, the signal will be sent to microcontroller and the attitude of the MAVs, roll or pitch will be adjusted to avoid the obstacle by moving to the counter direction of the obstacle. We conducted 20 trials of experiments by varying the gain values of Proportional Integral Derivative (PID) values, we fine-tune our obstacle avoidance algorithm. Modifications include optimizing roll and pitch adjustments, refining detection height thresholds, and implementing countermeasures after obstacle clearance. The results show that our proposed method has 10% overshoot when detecting any obstacles in different directions to avoid the obstacles. Our findings contribute to the advancement of safe and efficient urban drone operations, bridging the gap between technology and real-world challenges.

1. Introduction

In recent years, Quadrotor Micro Aerial Vehicles (MAVs) has transformed the landscape of urban mobility. The applications of MAVs are ranging from packet deliveries [1,2]**,** environmental monitoring [3,4], inspection [5–7], agriculture [8–10], disaster management [11–13] and surveillance [14–16]**.** As

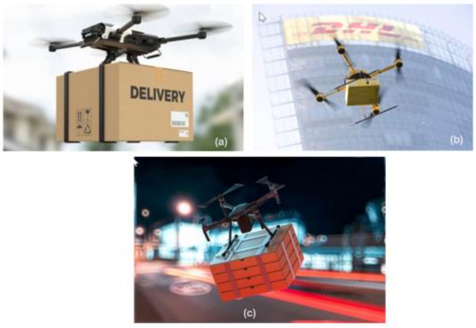

Figure 1. Quadrotor navigating around buildings.

Figure 2. Mission Planner Window.

cities grow more complex and interconnected, ensuring the safe navigation of these MAVs around buildings and other obstacles becomes important. Figure 1 shows MAVs conducting tasks of delivering package around buildings [1].

Urban areas include buildings, power lines, trees, and other obstacles, are challenging environments in current era when MAVs are part of human daily life [17]. The complexity in the environment setting makes the navigation and control of MAVs in urban areas become challenging. A low quality of navigation and control strategy on MAVs will give effect on the safety and energy consumption. Focusing on the safety, the navigation and control strategy in MAVs must ensure the MAVs will not be harmful to the human and buildings surrounding. In real-time applications, MAVs may face obstacles anywhere and at any time. In this case, the decision-making is crucial to adapt to changing scenarios and avoid collisions.

Leveraging a combination of sensors (such as LiDAR [18], cameras [19], and inertial measurement units [20] allows MAVs to perceive their surroundings. Sensor fusion techniques enhance accuracy and reliability. Researchers have developed advanced path planning algorithms that optimize trajectories while avoiding obstacles. These methods balance safety, efficiency, and real-time responsiveness. Machine learning models which include deep neural networks, learn obstacle patterns, and predict collision risks are now commonly used in the Guidance, Navigation, and Control of quadrotor MAVs. Additionally, reinforcement learning enables MAVs to adapt their behavior based on feedback from the environment.

This article presents an initial approach toward formulating obstacle avoidance strategies for quadrotor Micro Aerial Vehicles (MAVs). The main objectives of this project are 1) To develop an obstacle avoidance system for quadrotor MAV using ultrasonic sensors that can sense and avoid incoming obstacle by controlling the attitude of the quadrotor MAV and implement it onto the quadrotor MAV hardware and 2) To analyse the performance of the developed system in term of motor speed response.

The outline of the study will be divided into five sections. **Section 1** will be the introduction, which includes the motivation of the research, **Section 2** will discuss about the experimental setup, **Section 3** will be the controller design for the autonomous MAVs, **Section 4** will be the results and discussion which includes the analysis from theoretical aspect, and the real experiment result on the developed platform and lastly, **Section 5** will discuss the conclusions of the project and its future works.

2. Experimental Setup

This project mainly focusses on adding obstacle avoidance capabilities to the existing quadrotor which only can fly autonomously according to a pre-set altitude or pathway. The sensors used are five low-cost ultrasonic sensors (HC-SR04), which have capability to sense objects or obstacles in all 4 directions of the quadrotor.

In this project, Mission Planner (Windows) is chosen as the interface for the Ground Control Station (GCS). Mission Planner has many functions and configuration utilities. It can be a dynamic control supplement for autonomous vehicle when carry out autopilot missions.

Figure 2 shows the Mission Planner home screen. The window provides the **Menu Bar** that contains *File*, *Config/Tuning* and *Simulation* which allow access to various functions and settings. Another feature includes **Toolbar** for providing quick access to essential features, **Head-Up Display (HUD)** which shows the information about altitude, speed and artificial horizon line, **Main Map Area** which helps to visualize flight paths and terrain, and **Status Bars** which show information like GPS status and vehicle mode.

Figure 3 shows the overall design of the platform. 4 ultra sonics sensors are attached closed to the Pixhawk flight controller to optimize the layout of the quadrotor. Additionally, 1 ultra sonic sensor are placed on one arm of the quadrotor facing downward. The placement of ultrasonics sensors is designed carefully to maintain the center of gravity of the platform fulfill the aerodynamics requirement.

Additionally, this arrangement provides **360° spatial awareness** around the drone, enabling comprehensive obstacle detection. By strategically placing the sensors in all directions, the drone can autonomously navigate complex environments without human intervention.

Figure 3. Quadrotor MAV with 5 Ultrasonic sensors.

3. Mathematical Model and Controller Design

3.1. Mathematical Model of Quadrotor MAV

The modelling of the quadrotor aims to design the controller for the autonomous navigation of the drone. The mathematical model is derived based on rigid body dynamics and kinematics. The derived mathematical model is then programmed in MATLAB to simulate and find the best controller for the autonomous drone.

The control inputs of a quadrotor are commonly defined as U_1, U_2, U_3 and U_4. The total force to control the input is represented by U_1. U_2 is defined as roll torque, U_3 is pitch torque and U_4 is yaw torque. The matrix is expressed in Equation (1).

$$U = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ bl(-\Omega_1^2 + \Omega_4^2) \\ bl(\Omega_1^2 - \Omega_3^2) \\ d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \end{bmatrix} \tag{1}$$

where *b* and *d* are constant values which can be obtained from Equation (2) and (3).

$$F_i = \frac{1}{2}\rho C_T \Omega_i^2 = b\Omega_i^2 \tag{2}$$

$$H_i = \rho C_d \Omega_i^2 = d\Omega_i^2 \tag{3}$$

where C_T is the thrust constant that relies on polar lift slope, the velocity through the Brushless Direct Current Motors (BLDCM) ration of area surface, BLDCM disc area and geometric blade; ρ is air density; C_d is drag constant and Ω_i is rotational speed of propeller.

The dynamic system of quadrotor can be written in state space in term of $\dot{x} = f(X, U)$, as shown in Equation (5), with the inputs vector, U in Equation (1) and state vector, X in Equation (4).

$$f(X,U) = \begin{bmatrix} \dot{x} \\ \frac{(cos\phi sin\theta cos\psi + sin\phi sin\psi)U_1}{m} \\ \dot{y} \\ \frac{(cos\phi sin\theta sin\psi - sin\phi sin\psi)U_1}{m} \\ \dot{z} \\ -g + \frac{(cos\phi cos\theta)}{m}U_1 \\ \dot{\phi} \\ \frac{U_2 + \dot{\theta}\dot{\psi}(I_{yy} - I_{zz})}{I_{xx}} \\ \dot{\theta} \\ \frac{U_3 + \dot{\psi}\dot{\phi}(I_{zz} - I_{xx})}{I_{yy}} \\ \dot{\psi} \\ \frac{U_4 + \dot{\theta}\dot{\phi}(I_{xx} - I_{yy})}{I_{zz}} \end{bmatrix} \tag{4}$$

where I_{xx}, I_{yy} and I_{zz} are moment of inertia about the x, y and z axis, g is the gravitational field strength, and m is the quadrotor mass. Additionally, x, y, z are position along the x, y, z axis, respectively. $\dot{x}, \dot{y}, \dot{z}$ are the velocity along the x, y, z axis, respectively. ϕ, θ, ψ are angle of roll, pitch and yaw, respectively. Additionally, $\dot{\phi}, \dot{\theta}, \dot{\psi}$ are angular rate of angle of roll, pitch and yaw, respectively.

3.2. Control Architecture

The controlled parameters for a quadrotor are basically altitude, roll, pitch and yaw angles. These angles are controlled by Proportional Integral Derivatice (PID) controller. Altitude control and positon control is both manipulated by the outer PID controllers. The outer loop generates reference values for the inner loop. Figure 4 shows the quadrotor controller architecture block diagram. The information from Ultrasonic sensors will be used to trigger command to quadrotor to choose a safe path in addition to the position information from the Global Positioning System (GPS).

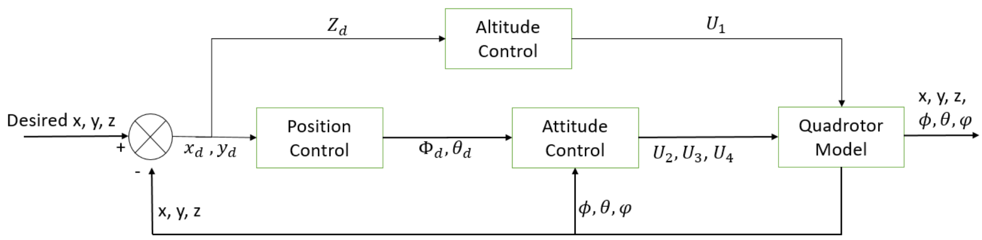

Figure 4. Controller Architecture of Quadrotor.

4. Result and Discussion

4.1. Simulation Result

Simulation is needed in this study to verify the gain values of PID controller work appropriately before the hardware implementation. The scenario is by introducing obstacles along 4 different directions.

Figure 5 shows one of examples when an obstacle appears at the left side of the MAV. Theoritically, when an obstacle appears at the left side of the MAV, MAV will change the roll orientation to the positive direction that will move the MAV to the right side. The simulation is began by introducing obstacle on the left side of the MAV at the time of $t = 100\ seconds$. Once obstacle is detected, the roll angle will be adjusted to its positive value to move to the right side as seen the middle figure of Figure 5. As seen in the figure, the roll angle will be increased (positive value) until a certain period of time then it will be decreased to be back on the hovering position. Another obstacles are introduced to quadrotor on different direction and the result shown in Figure 5 shows that the obstacle avoidance is succesfully conducted in simulation environment.

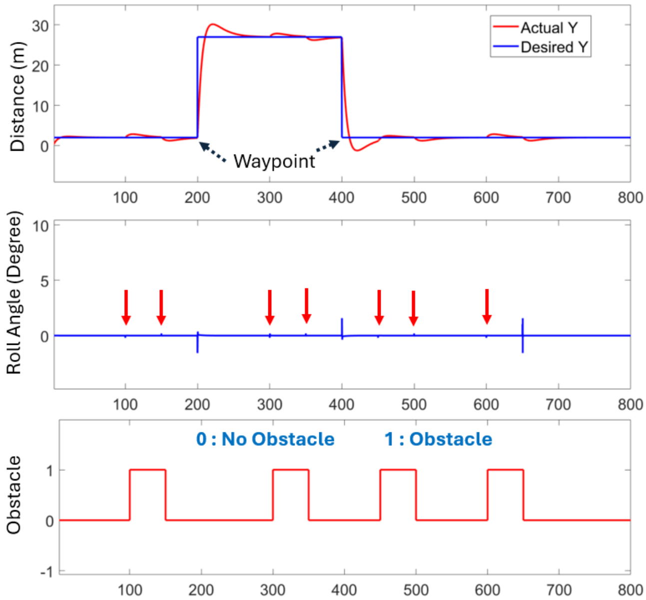

Figure 5. Simulation of Obstacle Detection for Left Sensor

4.2. Reaction of Each Motor According to Different Location of Obstacles

This test is conducted to finetune the PID gain values to be implemented on real flight. The best combination of PID gain values are those which will give the lowest reaction time delay or faster response when obstacle is detected. The reaction time delay in each set of graphs is obtained by looking at the graph. The delay is the difference between time where obstacle appear, and time of motor response occur. The stopping time delay is obtained by looking at the graph. The delay is the difference between time where obstacle move away and time of motor response. Changing the PID value of the flight controller will cause changes to the reaction time and stopping time. The faster the reaction time and stopping time, the better chance of avoiding an obstacle. Figure 6 shows the output graph from the front detection using PID values of $K_{p\_roll} = 0.135$, $K_{i\_roll} = 0.0090$, $K_{d\_roll} = 0.036$, $K_{p\_pitch} = 0.135$, $K_{i\_pitch} = 0.090$ and $K_{d\_pitch} = 0.036$.

The optimized PID gain values are then implemented on real hardware of MAV. Two different scenarios are tested to analyze the performance of the developed system. Scenario 1 is illustrated in Figure 6 (a). In this situation, the obstacle avoidance system will command the quadrotor to move forward while maintaining the difference between the two distances to be about 50 cm. Otherwise the obstacle avoidance system will not do anything.

Scenario 2 which is shown in Figure 6 (b), is the situation where the obstacle avoidance system will command the quadrotor to move backward as long as the difference between the two distances to be about 50 cm. Otherwise the obstacle avoidance system will not do anything.

Figure 7 shows different reactions highlighted in red rectangles. The first reaction is when only sensor 1 detected an obstacle. The second reaction is when only sensor 3 detected the obstacle. And the

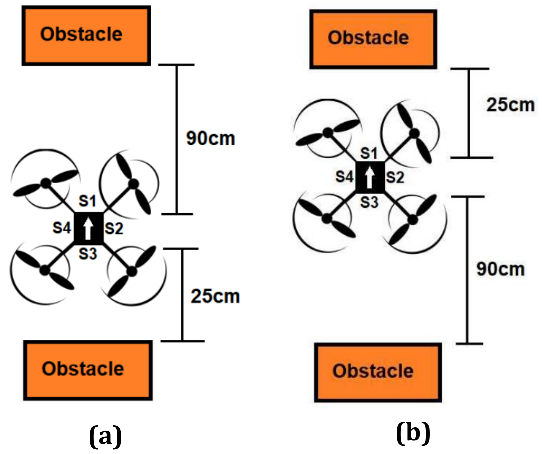

Figure 6. Scenario for Obstacle Avoidance Real Flight Test (a) Scenario 1 (b) Scenario 2

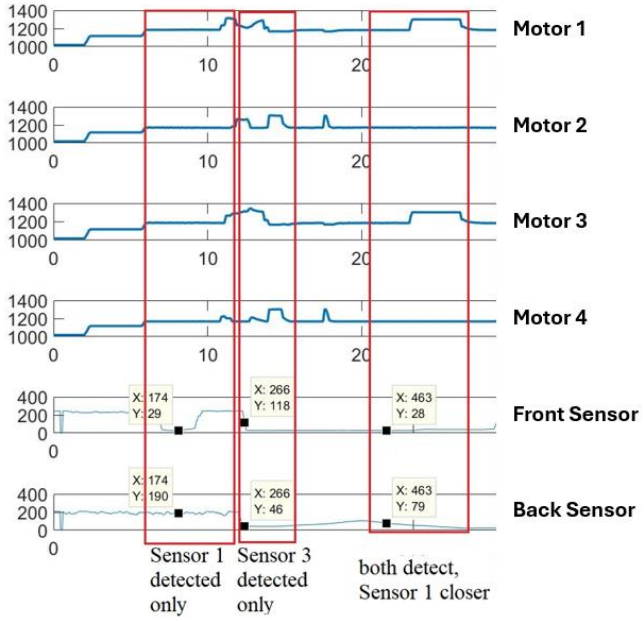

Figure 7. Motor Response for Scenario 1 and 2

third reaction is both sensors detected obstacle but sensor 1 is closer to the obstacle compared to sensor 3. The highlighted part shows the relation between the distance from obstacles to the sensor, the two figures in the lower part and the PWM signals of the four motors on MAV, the four figures at the upper part.

As seen in the figure, when $t = 10\ seconds$, the distance to the front obstacle is 29 cm, while the distance to the back obstacle is 190 cm. This means that the differenc of the distance to the front and back obstacle is about 161 cm. The strategy is to move toward the back obstacle by adjusting the speed of motor 1 and 3 to be higher than motor 2 and 4. As can be seen from the four upper graphs, the graph of motor 1 and motor 3 are higher than motor 2 and 4.

At the end of the task, when $t = 25\ seconds$, it is seen that the front sensor reading is 28 cm, while the back sensor reading is 79 cm. This show that the proposed system can maintain the position of the quadrotor to have differences in the distance to the obstacles at the front and back of MAV to be around 50 cm.

The full result of the real flight test can be accessed through https://bit.ly/MovingObstacles and https://bit.ly/StaticObstacles.

5. Conclusion and Future Works

This project is divided into two parts which are software and hardware implementation. Software implementation is conducted to develop strategy for obastable avoidance for 360° direction and to find the best Proportional Integral Derivative (PID) controller gain for the MAV based on the mathematical model derived at the beginning. The most optimum PID value that has been tested is the combination of $K_{p\_roll} = 0.135$, $K_{i\_roll} = 0.0090$, $K_{d\_roll} = 0.036$, $K_{p\_pitch} = 0.135$, $K_{i\_pitch} = 0.090$ and $K_{d\_pitch} = 0.036$. The simulation result shows a good performance for the proposed system. This is proven by the result that shows when an obstacle is detected in any direction, MAV can avoid the obstacle by moving towards the opposite direction with a 10% overshoot value. Additionally, we tested the proposed system in the real flight. The result shows consistent result compared to the simulation result.

However, the system has a response time delay of 1 second and a stopping time delay of 1 second on average after testing with both non-flight and real flight test. Future works may include tuning the controller gain values, other faster control strategy or faster computation on-board micro-processor to achieve a more stable obstacle avoidance with a faster reaction and stopping time. This obstacle avoidance system can help the society by reducing drone related accidents.

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