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MULTI-SENSOR FUSION BASED UAV COLLISION AVOIDANCE SYSTEM

Rethnaraj Rambabu*, Muhammad Rijaluddin Bahiki, Syaril Azrad

Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43300 Serdang, Selangor, Malaysia

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*Corresponding author
rethnaraj@gmail.com

Graphical abstract

Abstract

This paper presents the development of a quadrotor unmanned aerial vehicle (UAV) that is capable of detecting and avoiding collision with obstacles through the implementation of Kalman filter-based multi-sensor fusion and cascaded PID position and velocity controllers. Sensor fusion of ultrasonic (US) and infrared (IR) sensors is performed to obtain a reliable range data for obstacle detection which then fed into collision avoidance controller (CAC) for generating necessary response in terms of attitude commands. Results showed that sensor fusion provided accurate range estimation by reducing noises and errors that were present in individual sensors measurements. Flight tests performed proved the capability of UAV to avoid collisions with the obstacle that was introduced to it during flight successfully.

Keywords: UAV, collision avoidance, sensor fusion

1.0 INTRODUCTION

In recent decades, UAVs have been employed extensively for military and civilian applications such as aerial surveillance, remote sensing, aerial inspections as well as search and rescue operations. In order to operate safely and to accomplish specified missions, one of the key features required for the UAVs is the ability to avoid collisions with environmental obstacles.

Significant collision avoidance researches have been carried out for individual UAVs and been demonstrated using multi-rotor platforms. In 2009, Sobers *et al*. [1] developed quadrotor equipped with infrared sensors for indoor mapping and localization that is inclusive of collision avoidance. In 2012, Chee and Zhong [2] developed UAV quadrotor that is capable of autonomous navigation and avoiding obstacles along the trajectory without any pilot inputs in outdoor environment. Position controllers that generate roll and pitch commands were implemented to regulate the distance to obstacles which was measured using 4 infrared sensors.

Becker *et al*. [3] presented the development of active control system for quadrotor UAV to avoid collisions during the flight. Four US sensors were implemented on-board the platform for detecting obstacles. However, due to onboard sensor limitations, cruise speed obstacle avoidance controller (OAC) was not implemented and flight tests were performed only for hovering OAC which produced evasive maneuvers when an obstacle approached the quadrotor. Gageik *et al*. [4] presented a simple approach for obstacle detection and collision avoidance of an autonomous flying quadrotor using 12 low-cost US sensors and simple data fusion of those sensors for indoor applications.

Abovementioned researches were only focused on single type of sensors namely IR or, US for range sensing, each with its advantages and drawbacks. An US sensor has higher accuracy compared to IR sensor especially when used outdoors, however it has lower refresh rate which is around 13Hz to 20Hz. In cluttered environments, small movements of the US sensors results in 'noisy' readings due to varying strength of the sonar return from different objects [1]. Whereas, infrared sensor has a shorter range and narrow beam width than the US sensor but better resolution and higher refresh rate of 100-250Hz. However, it is more suitable for indoor use and could not be used outdoors as the measurement accuracy is very poor. The accuracy of the sensor can be affected by reflections from the environment. The sensor has to be calibrated in each environment in which it will be used, as reflections magnitude varies in different environment [5].

In this paper, we present the development of a quadrotor UAV that is capable of detecting and avoiding collision with obstacles through the implementation of Kalman filter-based multi-sensor fusion and cascaded PID position and velocity controllers. Sensor fusion of US and IR sensors is performed to obtain a reliable range data for obstacle detection which is then fed into collision avoidance controller (CAC) for generating necessary response in terms of attitude commands. The CAC sends attitude (roll and pitch) commands to the available flight controller that is capable of attitude self-stabilization and altitude hold. Collision avoidance problem considered in this study is two-dimensional (x,y) only and flight altitude (z) is assumed to be constant.

2.0 KALMAN FILTER-BASED SENSOR FUSION

To eliminate noises and errors that occur due to individual sensor limitations and to increase accuracy of range data estimation, a Linear Kalman Filter (LKF) based sensor fusion [6] is performed for the IR and US sensors because of its fast recursive nature that requires low processing power:

$$\hat{x}^m_{k|k-1} = F_{k-1}\hat{x}^m_{k|k-1} + G_{k-1}u_{k-1}. \qquad \text{(Eq. 1)}$$

$$P^m_{k|k-1} = F_{k-1}P^m_{k|k-1}F^T_{k-1} + Q_{k-1}. \qquad \text{(Eq. 2)}$$

$$K^m_k = P^m_{k|k-1}H^T_k\left(H_kP_{k|k-1}H^T_k + R^m_k\right)^{-1}. \qquad \text{(Eq. 3)}$$

$$\hat{x}^m_k = \hat{x}^m_{k|k-1} + K^m_k\left(Z^k_m - H_k\hat{x}_{k|k-1}\right). \qquad \text{(Eq. 4)}$$

$$P^m_k = \left(1 - K^m_kH_k\right)P_{k|k-1}. \qquad \text{(Eq. 5)}$$

LKF-based sensor fusion algorithm for two sensors is shown below.

$$\hat{p}^f = \hat{p}^1 - \hat{P}^1\left(\hat{P}^1 + \hat{P}^2\right)^{-1}\left(\hat{p}^{1^T}\right). \qquad \text{(Eq. 6)}$$

$$\hat{x}^f = \hat{x}^1 + \hat{P}^1\left(\hat{P}^1 + \hat{P}^2\right)^{-1}\left(\hat{x}^2 - \hat{x}^1\right). \qquad \text{(Eq. 7)}$$

3.0 OBSTACLE DETECTION AND COLLISION AVOIDANCE

Relative positions (x_r, y_r) between quadrotor and obstacle are obtained from sensor fusion of IR and US sensors and fed into obstacle detection module. This module activates the CAC if any obstacles are detected within the preset desired safety distance (x_d, y_d) from quadrotor. Pilot's control inputs will be overridden by CAC within the safety radius. The CAC with cascaded control loops that consists of PI-position controller and P-velocity controller generates desired roll (φ_d) and pitch (θ_d) attitude commands that are converted into PWM signals and sent to flight controller board that runs attitude controller. This allows the quadrotor platform to perform evasive maneuver to avoid obstacles that exist in close proximity.

On the other hand, if no obstacles are detected within the safety radius, pilot will gain a full control over quadrotor platform and pilot's attitude inputs will be allowed into flight controller directly. The system setup is illustrated in Figure 1.

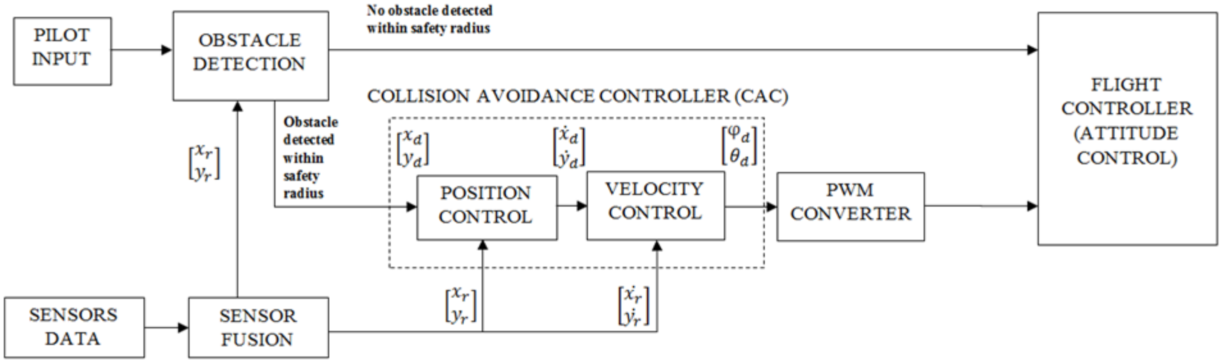

Figure 1 Obstacle detection and collision avoidance systems

4.0 IMPLEMENTATION

The sensor fusion and CAC algorithms have been implemented on-board of a quadrotor platform. The Sharp GP2Y0A02YK0F IR sensor and MaxBotix LV-MaxSonar®-EZ0 US sensor were selected for close obstacle avoidance during a forward flight. Arduino Mega microcontroller board was set up to run the collision avoidance program on-board of quadrotor. Sensor calibrations, controller design and testing were performed using Matlab Simulink before being coded and uploaded onto Arduino board. Xbee module was used to collect sensors data through serial communication during flight tests. Complete system set up can be seen in the Figure 2 and 3 below.

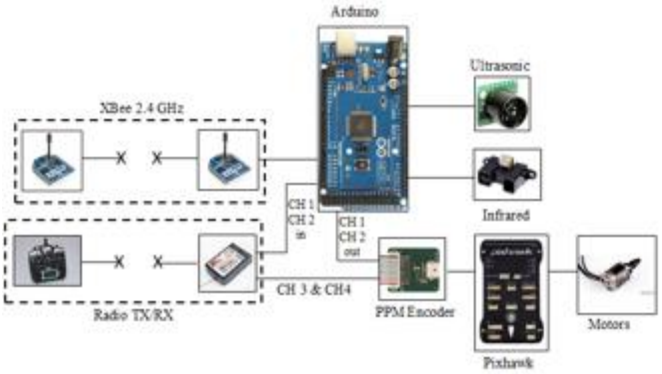

Figure 2 Hardware set up

Figure 3 Quadrotor platform with on-board sensors and microcontroller board

5.0 RESULTS AND DISCUSSION

Performances of individual sensors and fusion algorithm were evaluated through a simple experimental procedure as shown in Figure 4. IR and US sensors have an unusable detection range of 0-20cm and 0-15cm as well as a maximum detection range of 150cm and 645cm respectively. Since close proximity obstacle detection and collision avoidance are mainly focused in this research, the distance between obstacle and quad rotor platform mounted with sensors was varied from 20cm to 100cm at a step increment of 10cm for the experimental evaluation. Indoor positioning system that provided precise relative position data between flat obstacle and sensors was used as the reference to evaluate sensor performance. Figure 5 shows obstacle distance measurements by calibrated IR and US sensors and resulting LKF-based fusion readings when tested against flat obstacle placed at known distances.

For closer measurement range of 20 to 50cm, the standard error range for IR, US and fused readings were 0.2-0.4cm, 0.2-0.5cm and 0.1-0.3cm respectively. The repeatability of measurements was 99.41, 99.36 and 99.71 percentage correspondingly. For the measurement range of 60 to 100cm, the standard error range for IR, US and fused readings were 0.7-12cm, 0.2-16cm and 0.4-6cm respectively. The repeatability of measurements was 98.19, 99.16 and 99.62 percentage respectively. For the tested measurement ranges, experimental results revealed that implementation of LKF significantly reduced standard errors and increased repeatability compared to using IR or US sensors alone. Hence, the implementation of LKF-based sensor fusion played an important role in providing good estimation of obstacle distance data by reducing noises and errors present in the sensor measurements.

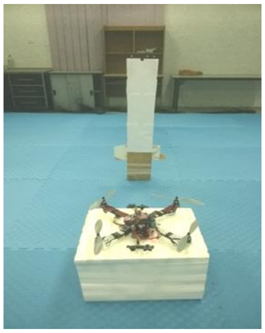

Figure 4 Experimental setup for evaluation of sensor performance

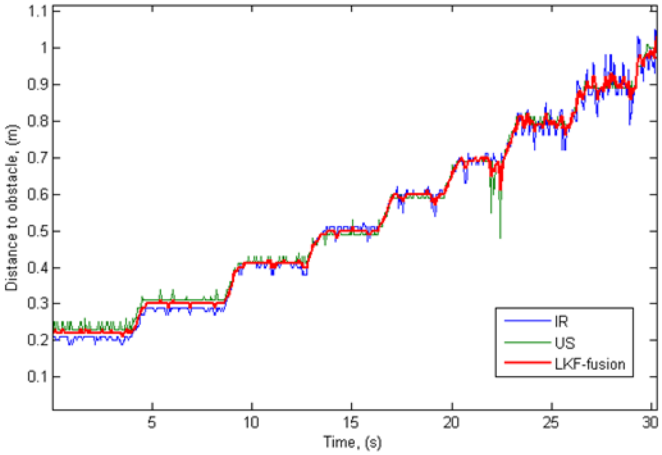

Figure 5 Obstacle distance estimation using LKF based sensor fusion

Evaluation of on-board collision avoidance system was done through flight tests that were carried out in indoor environment fitted with OptiTrack indoor positioning cameras. Special markers were attached to both obstacle and quadrotor to track and collect their positions using OptiTrack during flight tests and these positions served as a reference to validate the sensors' performance. Figure 6 illustrates the measured positions of quadrotor (dotted red line) and obstacle (solid blue line) during a dynamic test. Once CAC was activated, quadrotor attempted to maintain a desired distance of 60cm from the obstacle. The maximum obstacle detectable range was set to 130cm. If any obstacles are found beyond the maximum limit, no actions will be taken.

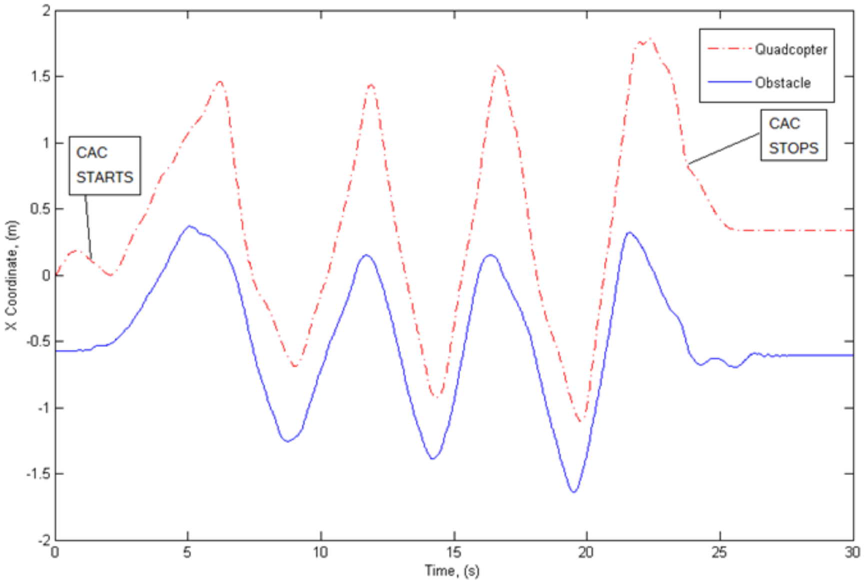

Figure 6 Dynamic collision avoidance flight test

6.0 CONCLUSION AND FUTURE WORK

This paper proposed the LKF-based sensor fusion of IR and US sensors and cascaded PID position and velocity control based CAC for outdoor and indoor UAV collision avoidance applications. Sensor fusion method proposed in this research provided a good estimation of obstacle distance data by reducing noises and errors that were present in individual sensors measurements. Furthermore, flight tests have shown that quadrotor UAV was able to avoid collision with the obstacle that was introduced to it during flight successfully. Despite of the positive results obtained through this study, several limitations to collision avoidance system existed. The flight tests were only able to be performed at lower velocities (< 3 m/s) due to low sensor sampling rate and limited effective measurement range. Furthermore, at the time of research, sensor performance was evaluated only in indoor environment fitted with positioning cameras. For outdoor applications, effects of environmental factors such as light intensity and cluttered flight surroundings on sensor have to be considered in order to obtain reliable measurements. Therefore, sensor weightage algorithm that detects sensor performance variation in changing environments and affects distance estimation accordingly will be developed in future. Furthermore, studies can be done on sensor fusion of IMU or visual-based depth sensing methods along with IR and US range sensors to achieve better range estimation and faster obstacle detection.

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