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RELATIVE POSITION-BASED COLLISION AVOIDANCE SYSTEM FOR SWARMING UAVS USING MULTI-SENSOR FUSION

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ABSTRACT

This paper presents the development of a quadrotor unmanned aerial vehicle (UAV) that is capable of quad-directional collision avoidance with obstacles in swarming applications through the implementation of relative position-based cascaded PID position and velocity controllers. A collision avoidance algorithm that decides evasive manoeuvres in two dimensional flight by the means of net error calculation was developed. Sensor fusion of ultrasonic (US) and infrared (IR) sensors was performed to obtain a reliable relative position data of obstacles which is then fed into collision avoidance controller (CAC) for generating necessary response in terms of attitude commands. Flight tests performed proved the capability of UAV to avoid collisions with the obstacles and dummy non-flying UAVs that existed at a closer distance in its four primary directions of detections during flight successfully.

Keywords: UAV, collision avoidance, relative position, swarming.

INTRODUCTION

Application of UAVs into military and civilian sectors is growing up at a rapid pace over the past few years. UAVs are used for aerial surveillance, remote sensing, aerial inspections as well as search and rescue operations. Recent researches and developments are focused on swarming ability of UAVs where multiple vehicles are able to cooperate and work autonomously together. In order to operate safely and to accomplish mission tasks, one of the important criteria required for the UAVs is the ability to avoid collisions with other member of swarms and environmental obstacles.

Significant relative-position based collision avoidance researches have been carried out for individual UAVs and been demonstrated using multi-rotor platforms. Sobers *et al.* [1] developed quadrotor equipped with infrared sensors for indoor mapping and localization that is inclusive of collision avoidance. Chee and Zhong [2] developed UAV quadrotor with 4 infrared sensors that is capable of autonomous navigation and avoiding obstacles along the trajectory without any pilot inputs in outdoor environment. Becker *et al.* [3] presented the development of active control system for quadrotor UAV to avoid collisions during the flight using four US sensors for detecting obstacles. 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.

On the other hand, while numerous studies on simulation-based autonomous formation control of UAVs have been done before, swarming ability using multiple flying UAVs have been attempted and demonstrated by several researchers around the world in both indoor and outdoor environments. Hauert *et al.* [5] demonstrated GPS-positioning based swarming using 10 fully autonomous fixed-wing UAVs in outdoor environment flown at different flight altitudes with a spacing of 10 m. Wilson *et al.* [6] demonstrated loose leader-follower formation flight of two fixed wing UAVs at a distance of 30 – 40m with each another. However, the leader's altitude was deliberately commanded to be 10 m higher than the follower to avoid collisions.

G. Vásárhelyi *et al.* [7] (COLLMOT project) successfully developed world's first outdoor GPS based swarm of 10 autonomous flying robots. However, the closest distance they could achieve without risk of collisions was at least 6-10 m between the UAVs flying in 0-4 m/s velocity range. It is important to notice that none of the researches above are able to perform outdoor swarming flight at a much closer proximity. This is due to the drawbacks of GPS-based position system such as low GPS update rate and inaccuracies in GPS position data considering ±2 m GPS accuracy which disables rapid response of UAVs flying in a tight flock or travelling at higher speeds. Thus, tighter flocks require better positioning accuracy to enable sufficient 'breaking distance' between units thus avoiding collision [7].

Kushleyev *et al.* [8] (Kumar V Lab) presented a notable swarming flight of 20 micro UAVs that were able to fly in close proximity in known three dimensional indoor environment with obstacles. However, the swarm relies on high-precision indoor positioning system called VICON for any flight and unable to operate outdoors. Thus, collision avoidance system for the swarm of UAVs based on relative position is important in order to ensure safe operability in both indoor and outdoor environment. However, none of the abovementioned researches carried out relative-position based collision avoidance system for swarming UAV applications.

In this paper, we present the development of a quadrotor UAV that is capable of detecting and avoiding collision with obstacles in four primary directions through the implementation of relative position-based collision avoidance controller (CAC). The collision avoidance system developed in this study is aimed toward achieving a safer close proximity flight in UAV swarming applications without collisions between the members of

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the group. Sensor fusion of US and IR sensors was 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.

RELATIVE POSITION BASED OBSTACLE DETECTION

For operating in a swarm safely, multi-rotor UAVs require collision avoidance system to prevent collisions with each another and environmental obstacles. Thus for obstacle detection, we relied upon relative positioning approach to obtain data regarding position of obstacles.

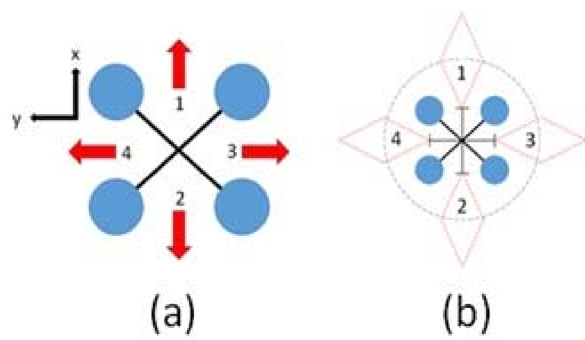

Figure-1. (a) Four primary flight directions; (b) Sensor location and obstacle detection directions.

Earlier researches [1,2,3,4] on low-cost collision avoidance systems were solely dependent of single type of sensors, namely IR and US sensors, for obstacle detection. However, the range measurement of IR sensor is influenced by light intensity of the environment and surface reflectivity of measured objects, whereas, US sensor is affected by material type of measured object, clutter level in the environment as well as cross interference when multiple sensor units are used. Therefore, in this research, relative position measurements (x_r, y_r) between quadrotor and obstacles are obtained from Linear Kalman Filter (LKF) based sensor fusion [5] of IR and US sensors to eliminate noises and errors that occur due to individual sensor limitations and to increase accuracy of range data estimation.

A pair of IR and US sensors was mounted in between quadrotor arms in four primary directions as shown in Figure-1. Obstacle detection algorithm continually monitors the presence of obstacles in the primary directions. This algorithm activates the CAC if any obstacles are detected within the preset desired safety distance (x_d, y_d) from quadrotor and necessary evasive response produced to prevent collision. Within the safety radius, pilot's control inputs will be overridden by CAC.

COLLISION AVOIDANCE CONTROLLER

Our CAC architecture contains cascaded control loops made up of PI-position and P-velocity controllers. For simplifying the system complexity into two-dimensional problem, we kept the flight altitude (z) constant and a pair of collision avoidance attitude controllers are implemented for avoiding impact in (x) and (y) directions relative to quadrotor.

Table-1 below shows 4 types of scenarios that are considered by our CAC algorithm (refer Algorithm I) in the process of decision-making for direction of evasive manoeuvre. We have embedded the decision-making process of evasive manoeuvre into CAC algorithm by the means of error calculation that is fed into position controller. For each direction, distance errors are calculated by subtracting desired distance with relative position to obstacle.

Table-1. Four types of collision avoidance scenarios.

Safety distance = 0.5 m	Front/Right obstacle > safety distance	Front/Right obstacle < safety distance
Rear/Left obstacle > safety distance	Scenario 1	Scenario 3
Rear/Left obstacle < safety distance	Scenario 2	Scenario 4

Algorithm-1. Four types of collision avoidance scenarios.

```
If CAC on and (distance1 or distance2 < safety distance)
        then
        Calculate distance errors (desired – current
distance) for a pair of directions
        Calculate net distance error
                PI-Position control
                Generate desired velocity
                P-Velocity control
                        Generate desired attitude
angle
        Convert attitude angle to PWM
        Override pilot's command by writing out PWM
else
        PWM in = PWM out
end if
```

Net distance error between a pair of perpendicular and opposite directions in each axis is further calculated before fed into position controller as feedback error. By doing so, resulting direction evasive response of quadrotor depends on resultant magnitude of feedback error. For example, a negative resultant feedback error in x-direction results in a positive pitch attitude command whereas positive resultant feedback error results in negative pitch attitude evasive manoeuvre command. On the other hand, when obstacles on both sides of the pair directions are less than safety distance, a resultant

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feedback error is generated such that quadrotor stay in between obstacles without collision.

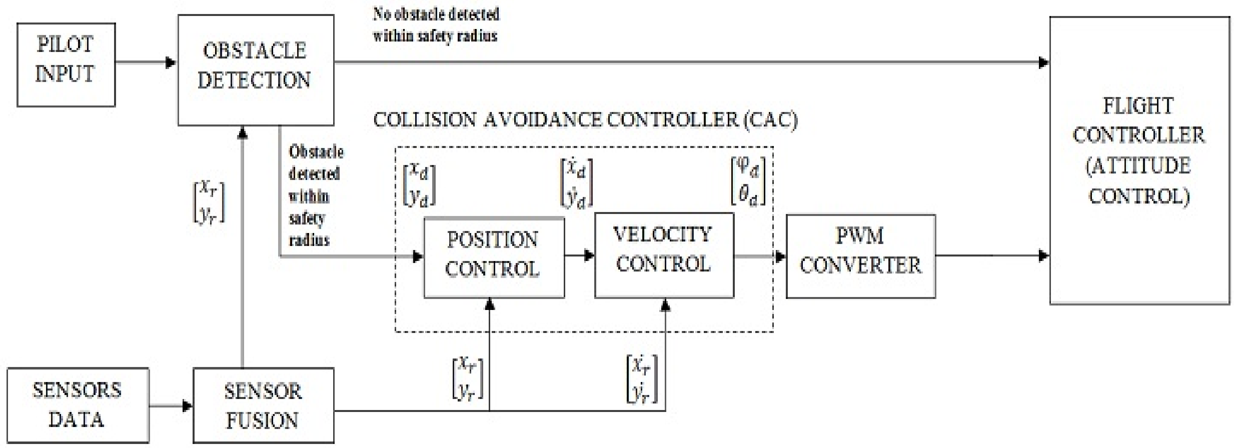

Figure-2. Obstacle detection and collision avoidance system.

The vehicle velocity data was solely estimated from the rate of change of range data and implemented with a linear Kalman filter to obtain smooth velocity estimation. The generated attitude commands are later converted into PWM signals and sent to flight controller board that runs attitude controller. PWM output signals are bounded by preset upper and lower limit values to prevent excessive attitude response of quadrotor. On the other hand, if no obstacles are detected within the safety distance radius, pilot will gain a full control over quadrotor platform and pilot's attitude inputs will be allowed into flight controller directly.

IMPLEMENTATION

The obstacle detection and CAC algorithms have been implemented on-board of a quadrotor platform. Four Sharp GP2Y0A02YK0F IR sensors and four MaxBotix LV-MaxSonar®-EZ0 US sensors were selected for range measurement of obstacles in four primary directions of 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. During the flight sessions, Xbee modules were used for remote data acquisition and to monitor on-board range sensors measurements as well as the status of collision avoidance system at the ground station through serial communication. No interference has been recorded between Xbee and radio transmitters/receivers even though both modules were operating over 2.4 GHz spectrum. Complete system set up can be seen in the Figure-3.

RESULTS AND DISCUSSION

Experiments to validate the ability of quadrotor to avoid collisions with obstacles and other UAV platforms were carried out in an indoor environment fixed with Opti Track motion capture cameras. In the first experiment, quadrotor UAV was flown in altitude hold mode in between four obstacles (foam boards) which were positioned in front, back, right and left sides of the quadrotor. Reflective markers were attached onto the quadrotor and all the four obstacles. By doing so, their positions in the test bed can be tracked using motion capture cameras that provide high precision data. Figure-4 (a) shows the experimental setup carried out in UAV test bed.

As per shown in Table-1, four different flight scenarios with obstacles were tested in the indoor environment. When distances to obstacles are greater than predefined safety distance of 0.5 m, CAC was not initiated and thus quadrotor hovered freely in between the obstacles. When obstacles appear within the safety distance, quadrotor with on-board CAC system produced evasive responses to avoid collisions. During the experiment, the obstacles were moved towards and away from the quadrotor hovering at a constant altitude. Corresponding responses of quadrotor in avoiding collision with those obstacles were recorded and are presented in the Figure-5 (a) and (b).

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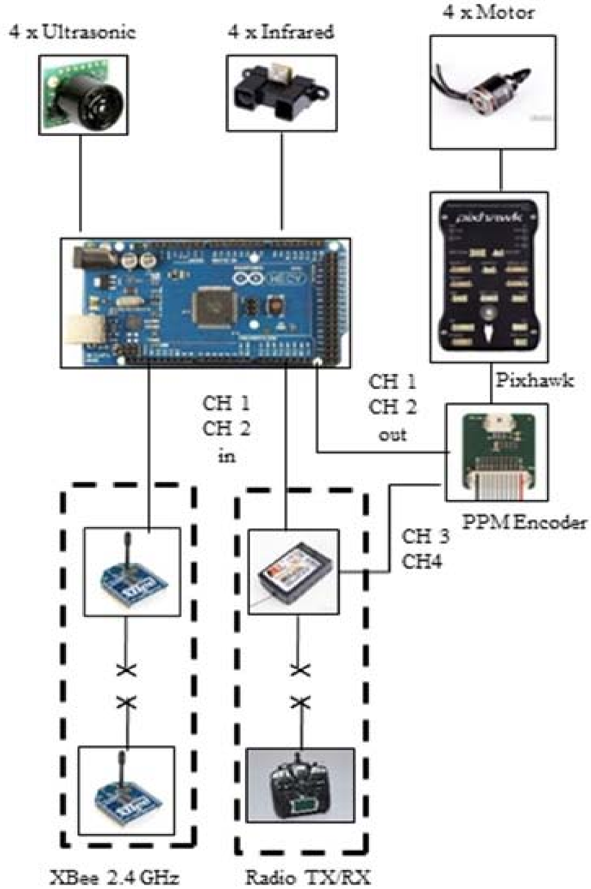


(a)

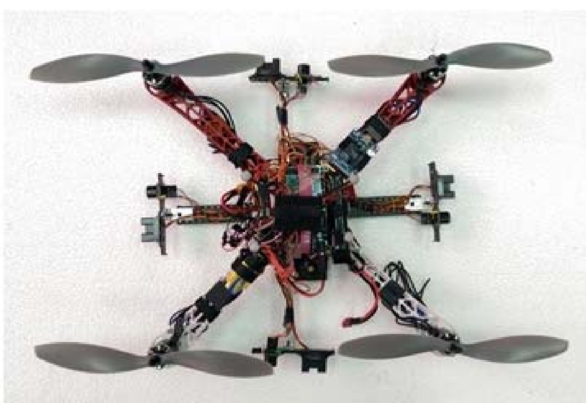

(b)

Figure-3. (a) Hardware setup; (b) Quadrotor UAV with quad-directional collision avoidance system.

Figure-5 (a) and (b) show results for the collision For the flight scenario number 4, when all the obstacles were detected at less than the safety distance for each of the directions, quadrotor managed to hover in the limited area without collisions on every side.


(a)

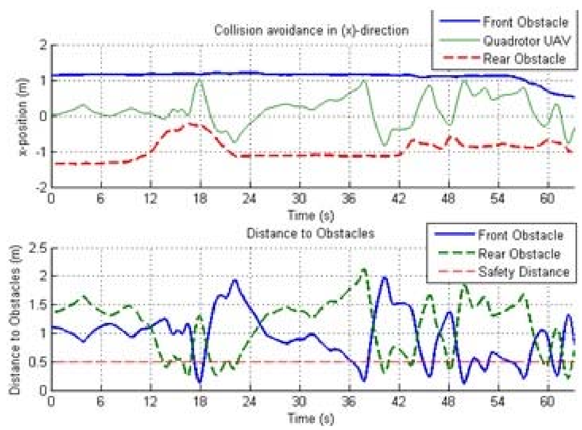

(b)


(c)

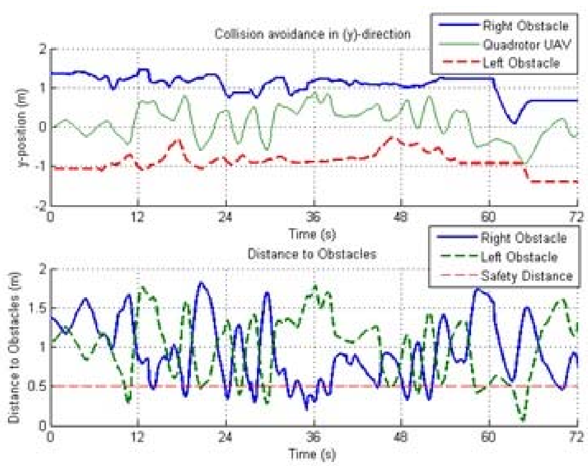

(d)

Figure-4. (a) Quadrotor flying in between 4 obtacles; (b) approaching rear obstacle; (c) evading right obstacle; (d) evading front and right obstacles.

On the other hand, to evaluate the effectiveness of the collision avoidance system for UAV swarming applications, flight tests were carried out in indoor environment with two non-flying dummy multi-rotors and one quadrotor with collision avoidance system (Figure-6 (a)). One of the dummy multi-rotor was placed statically at a height of 0.5m and used to test collision avoidance in y-direction. Whereas another dummy multi-rotor was moved manually by a person as if it was flying and used to test collision avoidance in x-direction. Corresponding responses are shown in Figure-6 (b) and (c). Quadrotor managed to evade from a number of 7 and 5 collisions with other multirotors in x and y-directions respectively. However, we noticed that quadrotor took longer time to detect the dummy multirotors compared to flat tall obstacles we used in the previous experiment. This is probably due to uneven and limited surface area available for the sensor-based obstacle detection. However, when a small cardboard placed in between the multi-rotor arms to increase the surface area of detection, quadrotor managed to detect multirotor much faster and evaded from colliding with the multirotor.



(a)

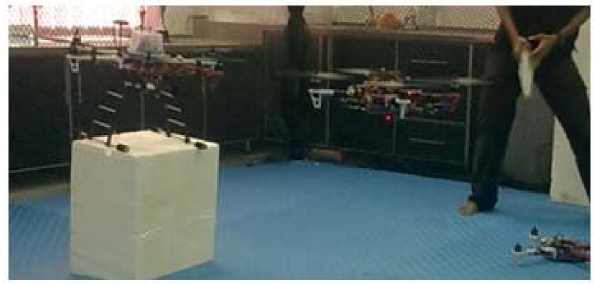


(b)

Figure-5. (a) Collision avoidance in (x)-direction; (b) Collision avoidance in (y) direction during the flight between 4 obtacles.

CONCLUSION AND FUTURE WORK

This paper proposed a relative position-based collision UAV avoidance system for swarming UAV applications. LKF-based sensor fusion of IR and US sensors proposed in this research provided a good estimation of obstacle distance data by reducing noises and errors that were present in individual sensors measurements. Cascaded PID position and velocity control based CAC was developed for outdoor and indoor swarming UAV collision avoidance applications. Furthermore, flight tests performed proved the capability of UAV to avoid collisions with the obstacles and dummy non-flying UAVs that existed at a closer distance in its four primary directions of detections during flight successfully.



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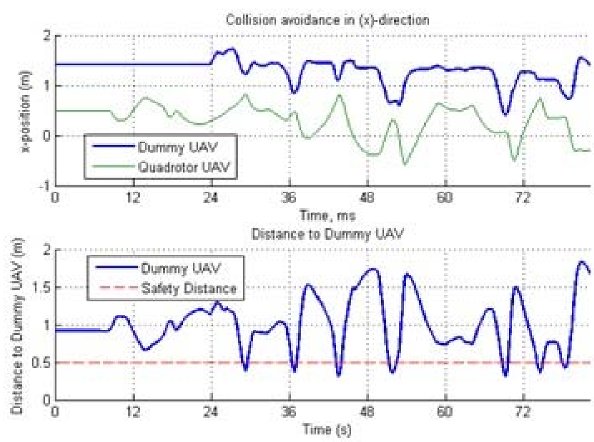

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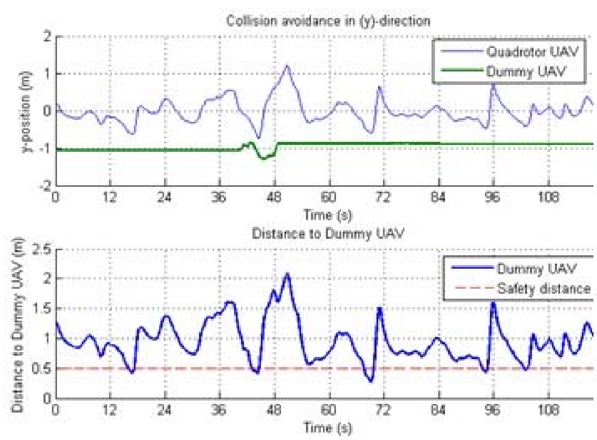

(c)

Figure-6. (a) Quadrotor UAV detecting dummy UAV; (b) collision avoidance in (x) direction; (c) collision avoidance in (y)-direction during the flight with dummy UAVs.

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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. 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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