Relative positioning-based system with tau control for collision avoidance in swarming application

M R Bahiki, N N A Talib and S Azrad*
Department of Aerospace Engineering, Universiti Putra Malaysia, Malaysia

*syaril@upm.edu.my

Abstract. In this paper, a relative positioning system by fusing infrared and ultrasonic range sensors data is employed to provide a more reliable relative distance data between quadcopters to achieve close proximity formation flight. This is due to lack of accuracy of positioning data from GPS due to its error of two to five meters. A leader-follower formation control strategy is used to control the distance between the quadcopters by applying data from the relative positioning system. An experiment to test the capability of the proposed strategy was done in the test platform environment equipped with Optitrack motion capture camera. Tau control was implemented as a braking system for the follower to avoid aggressive maneuvers that will make the quadcopters having high pitch along the formation control, which will affect the range detection of sensors. It has been proven from the results that close proximity formation flight is able to be achieved.

1. Introduction

The formation control or cooperative work of multiple unmanned vehicles has been proven to be more effective in terms of time consumption and overall performance. The advantages of cooperative work in unmanned vehicles including ground, aerial, space, marine and also underwater robots are of great interest to modern industries and societies. Beyond military applications, formation flights have been used widely in civilian sectors for field control and supervision, coastal surveillance and rescue, and exploration of new areas for mapping purposes. Swarm flight of unmanned aerial vehicles (UAVs) is being studied extensively by researchers as it gives a lot of advantages to not only the military forces and government agencies, but also civilian businesses and private individuals. It is promising for many applications, including search and rescue tasks for natural disaster, mobile surveillance and monitoring tasks. A high precision control of swarm flight has been made by Kushleyev et al. [1], which had 20 units of drones in flight. They used VICON motion capture that has a high precision positioning and a computer as a central control for each multi-copters. Although its performance is very high, it is not applicable for outdoor applications because of its dependencies to high precision camera and central computer. Meanwhile, a 10-autonomous flying robot was successfully developed by Vásárhelyi et al. [2] as the world's first outdoor GPS-based swarm. However, the closest achieved distance between the UAVs was around 6 to 10 m. In addition, it was only be able to fly in the velocity range of 0 to 4 m/s. Not many works are known on the capability to perform outdoor swarm flight with close proximity. This is due to limitation of the GPS-based positioning data with error of two to five meters. Therefore, a tighter swarm flight requires a better positioning accuracy to enable the sufficient ‘breaking distance’ between units, which is critical in collision avoidance.

There is a lack of on-board sensors technology available in the market that can provide the relative positioning between UAVs, both indoors and outdoors. In previous research by Roberts et al. [3], they
were able to design such sensor for indoor application. Their 3-D relative positioning sensor design is consisted of infrared emitters and receivers that are positioned in a spherical ring. However, this kind of module is only capable to operate indoor because of its limitation of high sensitivity to sunlight.

Many significant works in relative position-based collision avoidance have been carried out for both individual UAVs and multi-rotor platforms. For collision avoidance, Sobers et al. [4] developed a quadrotor that is equipped with infrared sensors for indoor mapping and localization. Chee and Zhong [5] developed a quadrotor UAV with four infrared sensors that is capable of autonomous navigation and avoiding obstacles along the trajectory without any pilot inputs in outdoor environment. Becker et al. [6] presented development of active control system for quadrotor UAV to avoid collisions during the flight using four ultrasonic sensors for detecting obstacles. Gageik et al. [7] presented a simple approach for obstacle detection and collision avoidance of an autonomous flying quadrotor using 12 low-cost ultrasonic sensors and simple data fusion of those sensors for indoor applications.

In this work, a strategy of leader-follower formation control is proposed that integrates the relative positioning system with the Tau control by Kendoul [15]. The relative positioning system is equipped with low cost ultrasound and infrared sensors with the range data that are fused together to optimize the collected range data. This relative positioning system using sensor fusion was done in the previous work and the results were convincing enough to be implemented for close formation flight application [8]. The advantage of using this relative positioning system is the capability of the formation flight to operate in close proximity at both indoor and outdoor environment. The idea of the relative positioning system is to assist the quadcopters to have relative position data with a higher accuracy than GPS. In addition, the Tau control acts as a braking system for the follower to avoid any aggressive manoeuvres caused by limited detection range of sensors due to high-pitch-rate manoeuvre and oscillatory motion in the formation flight. The quadrotor used in this study is as shown in Figure 1.

2. **Leader-follower formation control**

Formation control involves a broad field of robotics that addresses the challenges in coordinating a system of mobile robots. This term applies to aerial and ground vehicles as well as to robots of varying sizes. Previous researches regarding formation flight have applied several different control techniques and methodologies in order to achieve the goal of maintaining a formation of robots while in motion. The incorporation of a “leader” into the formation is a common approach in which the motion of the lead robot is planned. In addition, the robots can have minimal sensing capabilities and communicate to at least one other robot.

The first element of the whole formation flight control scheme is a path planner as seen in Figure 2. This is where a path is constructed that represents a compromise between the risks involved in by passing obstacles and the power consumes related to the path length. Mission planning related is also implemented at this level. The second element shown in the same figure is the trajectory generator. It is used to generate a practical trajectory for the quadcopters in computing the corresponding control inputs for the formation leader while taking part for its dynamics. The next element is the formation controller of multiple quadcopters. The purpose of this part is to maintain the formation configuration during flight. The formation configuration is defined as a trajectory generator to the followers where certain desired positions and velocities are computed.

![Figure 1. Quadcopter with relative positioning system installed](image1)

![Figure 2. Leader-follower formation control scheme for multiple quadcopters](image2)
2.1. Tau theory

TauPilot by Kendoul [15] is a bio-inspired autopilot that is used to guide and control the movement of various crucial manoeuvres in unmanned aircraft system (UAS) such as docking, braking and landing. It is based on the tau theory that have been proposed by David Lee in 1976 who hypothesized that the action of a car might be visually controlled when braking at the obstacle. The approach of automated UAS is usually based on position-based guidance, navigation and control (GNC) system that requires explicit computation of position and velocity, which then limits the sensor to the position sensors like Global Positioning System (GPS). On the other hand, TauPilot can be used with a much wider range of sensors including low-cost and lightweight cameras, thus can be used in GPS-denied environment and on board of small platform with limited payload.

Existing bio-inspired autopilot is basically based on visual cues. The difference is in terms of the way the cues are used in guiding and controlling the movement, and also the type of visual cues that is used. TauPilot introduces the method that imitates the movement in humans and animals with much sophisticated guidance and control strategy, yet the strategy is simple and allows complex manoeuvres in wide range of application. TauPilot is a combination of tau information and also tau strategy in achieving various manoeuvres required for UAS to arrive at the right place in the right way within the desired time. It consists of the Tau-Navigation System and the Tau-Guidance System as described in the following sections.

2.1.1. Tau-navigation system. The system is responsible to compute taus of different gaps to achieve the desired task by identifying the gaps that need to be closed. This system generally requires the data generated from the sensing system.

2.1.2. Tau-guidance system. This system is responsible to generate the desired or reference taus, which result in task achievement if successfully tracked by the system. In this study, the focus is placed on the constant tau-dot (tauD) strategy that implemented tau law. The law posits that stopping or braking with zero velocity at the contact can be controlled by monitoring and adjusting the values of tau-dot to remain constant and positive. The law is given by Equation 1.

\[ \tau_{ref}(t) = kt + \tau_0, \quad \tau_0 = \frac{x(0)}{\dot{x}(0)} < 0 \]  

where \( t = 0 \) and \( \tau_0 \) are time and tau at initiated point, respectively. It have the advantages of avoiding the computation of \( \dot{\tau}(t) \), which would give a significant noise due to the derivation of already noisy signal \( \tau(t) \), and giving more stable control between control input and controlled variable \( \tau(t) \) as it tracks \( \tau_{ref}(t) \) instead of \( \dot{\tau}_{ref}(t) \). The value of \( k \) has to be kept in the range of 0 to 0.5 to ensure that all trajectories (distance, velocity and acceleration) converge to zero (origin) as time goes to infinity.

2.1.3. Tau control system

This system is designed to compute and adjust the control inputs, \( u \) that are used to force actual tau in tracking the reference tau (tau-ref). The non-linear ratio control system law introduced the method of tracking error by taking the ratio between reference tau and tau. The law therefore can be defined as in Equation 2.

\[ U = \begin{cases} k_p \left[ 1 - \frac{\tau_{ref}(t)}{\tau(t)} \right] & \text{if } \tau(t) \neq 0 \\ 0 & \text{otherwise} \end{cases} \]  

This tau-controller copes well when the system operates near its singularity point when the input, \( u \) is zero, thus give a good tracking performance. The tau-controller, by considering one direction only (x-axis), can be formulated by Equation 3.

\[ \mu_x = \sigma_x \left[ k_p \left( 1 - \frac{\tau_{ref}(t)}{\tau(t)} \right) + k_i \int \left( 1 - \frac{\tau_{ref}(t)}{\tau(t)} \right) \right] \]
where \( \mu \) is the intermediary control input and \( \sigma \) is the saturation function. The approximation control input is therefore given by Equation 4.

\[
\theta_{\text{ref}} = \sigma \left[ \mu_x \cos(\beta' - \phi) - \mu_y \sin(\beta' - \phi) \right] \tag{4}
\]

where \( \phi \) is the yaw angle and \( \beta' \) is the heading angle.

3. Relative positioning system

Previous works by other researchers on relative positioning are depending solely on a single type of sensors object detection. However, to have a more reliable data that can be operated both indoor and outdoor, both IR and US data are fused together using Linear Kalman Filter (LKF) based sensor fusion [10] to eliminate noises and errors from each individual sensors limitation, and increase the accuracy of the relative position \((x_r, y_r)\) between quadcopters. The LKF provides estimation for the state vector, \( \hat{x}_k \), using set of observed data, \( Z_k \) for every discrete time, \( k \). The LKF is implemented in two steps, namely, prediction and update steps. The prediction equations determine priori estimate of the state and error covariance given Equation 5 and Equation 6.

\[
\hat{x}^m_{k|k-1} = F_{k-1} \hat{x}^m_{k|k-1} + G_{k-1} u_{k-1} \tag{5}
\]

\[
p^m_{k|k-1} = F_{k-1} p^m_{k|k-1} F_{k-1}^T + Q_{k-1} \tag{6}
\]

\[
K_k^m = p^m_{k|k-1} H_k^T (H_k p^m_{k|k-1} H_k^T + R_k^m)^{-1} \tag{7}
\]

\[
\hat{x}^m_k = \hat{x}^m_{k|k-1} + K_k^m (Z_k - H_k \hat{x}_{k|k-1}) \tag{8}
\]

\[
p^m_k = (1 - K_k^m H_k) p^m_{k|k-1} \tag{9}
\]

In the update step, the priori estimates are updated using the calculated gain matrix, \( K_k \) (in Equation 7) and posteriori estimates of the state and error covariance given by Equation 10 and Equation 11.

\[
\hat{p}^f = \hat{p}^1 - \hat{p}^1 (\hat{p}^1 + \hat{p}^2)^{-1} (\hat{p}^1 \hat{x})^T \tag{10}
\]

\[
\hat{x}^f = \hat{x}^1 + \hat{p}^1 (\hat{p}^1 + \hat{p}^2)^{-1} (\hat{x}^2 - \hat{x}) \tag{11}
\]

The above equations apply to both IR and US individual sensors for the estimation of range based on sensor measurement data. The posteriori estimates of individual sensors are fused together to obtain combined final estimates of state, \( \hat{x}^f \) and error covariance, \( \hat{p}^f \).

Four primary directions of the quadcopters are mounted with a pair of IR and US sensors between the quadcopter arms shown in Figure 3. In previous work [10], a relative position-based collision for swarm application using cascaded control loops made up of PI-position and P-velocity controllers was proposed. The idea was to have a formation flight using formation controller with collision avoidance override the formation controller when the distance between quadcopters was too close. However, this would increase oscillation of the follower during formation due to several act of aggressive avoidance. Therefore, in this paper, a close proximity formation flight conducted using formation controller with Tau D control as braking to avoid aggressive act and collision between quadcopters was developed. This is shown in Figure 4.
4. Hardware setup and implementation
The development and testing of this project was done in an indoor environment that was equipped with the Optitrack motion capture camera for indoor positioning system. Due to slow rate of data acquisition from the flight controller to Arduino Mega, all IMU data was computed using motion capture camera to get the sampling rate of 100Hz. Quadcopter dynamics and stability control algorithm was done in computer on ground. Xbee S2 2.4Ghz was used as communication module to control the quadcopter from ground. The sensors were installed on Arduino on-board of a quadcopter platform. The Sharp GP2Y0A02YK0F infrared sensor and MaxBotix LV-MaxSonar®-EZ0 ultrasonic sensor were selected for close formation forward flight. Xbee module was also been used for sending data to the ground control. The overall setup of the hardware can be seen in Figure 5.

5. Result and discussion
An experiment was carried out in an indoor environment, fixed with Optitrack Motion Capture camera to validate the performance of the follower quadcopter to control distance with the dummy leader. The purpose of the motion capture camera is to make an indoor positioning system as testing environment to replace global positioning system (GPS) since it is easier to simulate and test the algorithm indoor repeatedly. In the experiment, there were two quadcopters fixed with at least three reflective markers onto each of them so that they can get their position and attitude data from the motion capture camera and only one of them equipped with the relative positioning system to act as the follower quadcopter.

Two quadcopters were used in the experiment, which are dummy leader and follower quadcopters. In this experiment, only the follower quadcopter was flying and the dummy leader was handled by a person. Relative position module was embedded on the follower quadcopter as the formation controller is on the follower with the PID gain setting as shown in Table 1.

As seen in Figure 6, the dummy leader was attached with a piece of cardboard. This is necessary to help the range sensor to easily detect the follower due to the range sensors having difficulties to detect cluttered surface. The predefined desired distance between the quadcopters to stay in formation was 0.5 meter apart measured from the relative positioning system. The experiment started by hovering the follower in altitude hold flight mode at a point. The dummy leader was held 1 meter away from the follower at the same altitude. The formation controller was automatically started when the relative positioning system on the follower detected the dummy leader in a distance. Approximately around 1 meter distance of forward and backward trajectory for the dummy leader was done in linear motion at y-axis.

Figure 7 shows the results for linear formation flight response and distance between quadcopters in y-direction that were recorded. During the test, the follower was able to follow the leader in formation.
as shown in Figure 7(a) and achieved to maintain its distance with the leader. As can be seen in Figure 7(b), the closest distance of the follower with the leader is approximately 0.4 meter measured from the centre of the follower to the surface of the leader recorded. Nevertheless, the pattern showed a good result from the formation controller that having just a small oscillation of controlling distance around 0.5 meter (red line in Figure 7(b)) as defined earlier.

Figure 7. (a) Linear formation flight in y-direction, (b) Distance between quadcopter during formation

6. Conclusion and future work
This paper proposed a formation flight of quadcopters using relative positioning system implemented with fused sensors of IR and US to measure relative position between quadcopters by considering the inaccuracy of GPS by two to five meters for operating close formation flight control. The focus was on a close proximity formation flight that would be difficult to operate in GPS-denied environments. In view of that, the relative positioning system was considered to be embedded into the quadcopters to measure relative position between them by fusing infrared and ultrasound range sensor to gain more reliable data. As reflected by the results, the close proximity flight was able to be performed by having relative positioning system with Tau control embedded into the quadcopters without fully relying on GPS in this test. However, due to range sensors that have small angle of detection, the flight can only be operated at lower velocity. This is because, to have higher velocity, the quadcopter needs to have a higher pitch angle and this will affect range detection of the sensors. Future work may also include replacing the range sensor with optical image sensor so that the quadcopter may be able to perform at higher velocity. By using image sensor, the field of view is much larger than conventional sensors and the accuracy of the sensor is higher.

References
[1] Kushleyev A, Mellinger D, Powers C and Kumar V 2013 Auton. Robots 35 287–300
[2] Virágh C, Vásárhelyi G, Tarcai N, Szörényi T, Somorjai G, Nepusz T and Vicsek T 2014 Bioinspir. Biomim. 9 11
[3] Roberts J F, Stirling T, Zufferey J C and Floreano D 2012 *Auton. Robots* **33** 5–20

[4] Sobers D, Chowdhary G and Johnson E 2009 AIAA *Guidance, Navigation, and Control Conference*

[5] Chee K Y and Zhong Z W 2013 *Sensors Actuators, A Phys.* **190** 66–76

[6] Bouabdallah S, Becker M and De Perrot V 2007 *XII Int. Symp. Dyn. Probl. Mech.*

[7] Gageik N, Müller T and Montenegro S 2012 *Microdrones Conference: UAVweek*

[8] Rambabu R, Bahiki M R and Azrad S 2015 *J. Teknol.* **8** 89–93

[9] Raol J R 2009 *Multi-Sensor Data Fusion with MATLAB* (Boca Raton: CRC Press)

[10] Rambabu R, Bahiki M R and Azrad S 2015 *ARPN J. Eng. Appl. Sci.* **10**

[11] Nonami K, Kendoul F, Suzuki S, Wang W and Nakazawa D 2010 *Autonomous Flying Robots* (Tokyo: Springer Japan)

[12] How J P, Bethke B, Frank A, Dale D and Vian J 2008 *Control Syst. IEEE* **28** 51–64

[13] Abas M F, Pebrianti D, Azrad S, Iwakura D, Song Y and Nonami K 2013 *Autonomous Control Systems and Vehicles* **65** 109–132

[14] Chen M 2003 *Formation and Flight Control of Affordable Quad-rotor Unmanned Air Vehicles Design* Masters Thesis The University of British Columbia

[15] Kendoul F and Ahmed B 2012 *IEEE/RSJ International conference on intelligent robots and systems*