Faculty of Engineering and Computer Science
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PhD Dissertation Research Proposal

Formation Control of Multiple Unmanned Aerial Vehicles

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Abstract

Recently, the great interest in using robots in various applications has led to great advances in using unmanned vehicles in highly expensive, risky and tedious work. So far, a lot of unmanned vehicles have been developed to accommodate various applications in different working environments, such as unmanned aerial vehicles (UAVs), which are used in this research.

UAVs can be used in civilian applications as well as military ones, as in emergency situations such as in nuclear disaster, volcano, flood, forest fire fighting and rescue. However, most of these tasks can be achieved using single UAV. Using multiple cooperative UAVs allow them to share information for rapidly and effectively accomplishing their mission with better performance, more fault tolerant and less time of mission duration.

In particular, this research proposal aims to outline the research which will be conducted to design and develop novel control schemes with applications to a single UAV as well as a team of multiple UAVs. Therefore, the proposed research provides advanced levels of trajectory tracking control, decentralized formation control, which then applied in forest fire detection and fighting application to detect, confirm, observe and fight forest wildfires. During a mission, UAVs should maintain a predefined formation shape necessary for the mission. Furthermore, such risky tasks require task completion even with fault existence, in which the remaining UAVs should react to minimize the fault and accomplish the required task and reconfigure formation shape according to the new situation. The control schemes expected from this research proposal are planned to be verified first by a set of simulations to check their effectiveness and performance. Moreover, they will be verified by a set of experimental testing to insure their real-time performance.

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1 Introduction

In the last century, unmanned vehicles have been receiving growing attention because of their capability of working without human assistance, replacing human in complicated and uncertain environments, which enables longer endurance. As a result, they have been used for various military and civilian applications in air, space, sea, and on the ground [8, 39].

Moreover, among various types of unmanned vehicles used, the importance of unmanned aerial vehicles (UAVs) appeared earlier in several military applications. Their developments started during the World War I and increased more in the World War II, when they have been used in attacking naval and land targets, and in aerial reconnaissance [39]. UAVs are also known as drones, remotely operated aircrafts (ROAs), remotely piloted vehicles (RPVs), and unmanned aerial systems (UASs). UAVs are continuously developed very rapidly and becoming an important assistant to human beings.

Based on their shapes and geometric structures, UAVs can be roughly characterized into fixed-wing UAVs, rotory-wing UAVs, flapping-wing UAVs and other unconventional UAVs [7]. Fixed-wing and rotory-wing UAVs are currently the dominant in most of practical applications due to their simplicity comparing to other types [8]. Moreover, an important type of rotory-wing UAVs are the vertical take-off and landing (VTOL) vehicles, which are considered very important because of their challenging control problems and their broad fields of applications. As widely known, VTOL vehicles have specific characteristics like flying in very low altitudes and easy for hovering. These characteristics make them suitable for a lot of applications compared to other types. Furthermore among the rotory-wing UAVs, quadrotor and coaxial helicopter are the best configurations [41]. A quadrotor is a rotary-wing UAV composed of four rotors laid up symmetrically around its center. It is capable of hover, forward flight and VTOL. Hence, it is classified as a rotary-wing VTOL aircraft.

Furthermore, most of the major research interests are focusing on small UAVs which called miniature aerial vehicles (MAVs). This type of UAVs has several advantages when used in air surveillance, search and rescue missions in complex environment after disasters, such as earthquakes, explosions and fires [41].

Recently, multiple unmanned vehicles (MUVs) have been widely used in various applications such as reconnaissance and cooperative vehicle reconnaissance [46], surveillance [23], search and exploration [16] and firefighting [9]. Although these tasks have been performed with one vehicle in most existing works, multiple vehicles will be more flexible and efficient in performing the tasks. In addition, building and using several simple UAVs can be easier, cheaper, and more fault-tolerant than having a single powerful UAV.

In cooperative control, a group of UAVs having common objectives in cooperation to ensure mission execution successfully. These UAVs can perform the task while maintaining a certain geographical shape with constant relative distances [45], avoiding obstacles and collision between agents, and tolerate faults occurred at individual member of the team while performing the task.

2 Related Work

2.1 State-of-the-art of UAV control

Recently UAV control, especially quadrotors receive more attention from researchers in both civilian and military applications. So, trajectory tracking became a challenging research problem for researchers. These challenges come from operating conditions and nonlinear and underactuated nature of the UAV dynamics [21]. In trajectroy tracking, quadrotor should follow a predefined path. So, a quadrotor controller is responsible of calculating the actuators inputs periodically to get the exerted forces and torques required to achieve the desired path [16]. Due to model imperfection and other disturbances, feedback is necessary to determine and reduce the actual deviation between the current position and the planned position of UAV.

Several control systems are used in UAVs, which are classified into three main categories such as linear [15] and nonlinear [43] controllers, and learning-based control systems [11]. Linear controllers can be used with the linearized UAVs model but still lack for accuracy and robustness due to UAVs nonlinearity. As a result, nonlinear controllers have been developed to overcome drawbacks of linear controllers. Furthermore, learning-based controllers can be used with UAVs, they are model free and provide system flexibility and direct mapping between navigation data and UAV actuator. However, It is still difficult to analyze stability and robustness issues and still need more experimental work in different environments and flight scenarios [19].

Real time applications of UAVs, such as forest fire detection and fighting is still challenging and needs accurate and robust controllers. Nonlinear controllers give accuracy and robustness but sometimes, the computational time results in a lot of delays in real time applications. As a result, the combination of linear and nonlinear controllers gives almost the same accuracy and robustness as nonlinear controllers, while reducing computational burden.

Sliding mode control (SMC) is a non-linear control algorithm dealing with nonlinear dynamics. Moreover, it is a simple approach to robust control which can deal with system uncertainties, maintaining stability and consistent performance in the face of modeling imprecisions which already exist in UAVs model [40]. In [22], SMC and adaptive SMC are used to control single quadrotor, while a combination of PID with SMC are used to control single quadrotor in [43]. Also, a controller based on backstepping and sliding mode techniques is used to control a miniature quadrotor helicopter in [26]. Further work is done in [32] on a new quadrotor with a tilt-wing mechanism in which the position and yaw angle were controlled using LQR, while another controller using SMC was used in altitude and attitude on the same UAV. Full linear controller of a quadrotor is done using LQ servo and H_∞ with wind disturbance in [3].

2.2 State-of-the-art of formation control approaches

Researchers have developed many strategies and algorithms for multi-vehicle coordination and control such as behavioral approach, virtual structure and leader-follower approach. More approaches are investigated by Zhang et al [45].

The behavior based approach assigns several behaviors for each UAV and the final decision and control is derived from a weighting of the relative importance of each behavior. Systems using this approach are able to navigate to waypoints, while avoiding obstacles and keeping formation at the same time [4]. However, this approach lacks for theoretical modeling [45].

In virtual structure approach, the whole team is considered as one unit and each UAV follows a certain path so it can perform only synchronized maneuvers. This coordination behavior is robust and not complex. However, due to its centralization feature, single point failure can lead to failure in the whole mission as well [45].

In leader-follower approach, one of the UAVs are assigned as a leader while the others are followers, which should maintain certain relative position with the leader. Main advantage of this approach is its simplicity and reliability, but it has no feedback from followers to leader and it is not robust in case of leader failure due to its centralization feature [45]. This problem can be solved by designing formation control law on each follower to avoid centralization, obtaining decentralized leader-follower approach. In [1], PID and SMC are used separately for circular leader-follower formation between two quadrotors. While LQR was used for the control of a leader and followers, leader tracks the shortest path between two points, while the follower UAV has to track the leader by a 2m offset in [36]. In [27], SMC and PID was used to control both of the leader and followers, while SMC is used for the formation control giving the velocity as an input to the followers. In this research, SMC is applied to the formation of a leader-follower approach in order to achieve the desired formation parameters d-α, the formation controller feed the desired accelerations to the follower UAV controller.

2.3 State-of-the-art of fire detection and fighting cooperative control of UAVs

Forest fire detection became a very important problem in the whole world, especially in North America. According to the National Interagency Fire Control, wildland fires have consumed approximately 27 million acres of land during 2005-2007 [20]. As a result, a lot of people have been displaced causing a very big financial loss, apart from this socio-economic loss. Smoke-related effects on human and wildlife are the dominant.

Forest-fire fighting is commonly based on estimations made by fire fighting experts from visual observations. These estimations may lack of accuracy due to human errors and smoke occluding the flames, resulting errors in fire localization. So, this field attracted researcher's great efforts to apply new technologies for forest fire detection and fighting. Satellites, manned aerial vehicles and ground stations are used for detection up to now. However, these technologies still have different practical problems such as low reliability, high costs, etc... [29].

Current fire-tracking strategies are divided into two categories, strategic and tactical. Satellites are used for the strategic platforms as they provide regional views of fires in a specific area. However, using satellite systems have a lot of problems such as long delays in data transmission, low spatial, temporal resolution and limited monitoring time for a certain place due to their cycle [44]. On the other hand, manned aircrafts equipped with different sensors are more suitable for tactical platforms, as they provide accurate, frequently updated fire characteristics, including location, intensity, and movement of the fire [6].

Forest fires are highly complex, non-structured and risky environment, in which the use of manned aircrafts may cause extreme danger for human operators. Therefore, UAVs can play a very important role in forest fire detection and fighting. They provide reliability in extreme operational conditions and monotonous repeated tasks for longer duration, enabling long-term data gathering and situational awareness [20]. Moreover, They have been already successfully applied in fire detection, observation and localization [28, 29, 30].

Forest fires cause heavy smoke which can occlude the visual detection. So, various types of sensors should be used, such as charge-coupled devices (CCD) cameras, smoke sensors and thermal and infrared cameras where the use of multiple sources of information at different locations is essential. Therefore, using multiple UAVs in forest fire detection loaded with different types of small and light sensors is better than using a single powerful one [13].

Multiple UAVs are used for fire detection and fighting, they need very accurate controllers for fire monitoring and tracking in real time. The fire evolution and its dynamic nature, which is very difficult to predict, has various parameters such as its shape, position, spread rate and max height of flames [13]. All these information must be available to fire brigades to minimize time for fire fighting and rescue with minimum losses. This information is provided only via tactical strategies. Researchers are trying to develop accurate models for forest fire propagation to predict the fire growth, and accordingly provide UAVs with the required trajectories to successfully monitor and track the fire front [20, 33, 35].

Forest fire detection attracts researchers as it has a lot of challenges in several fields such as development in sensors and sensors fusion techniques [5], image processing techniques [34], path planning algorithms [37] and trajectory tracking and control of UAVs [20]. Due to the dynamic nature of fire evolution, a robust controller is required for fire front tracking.

Fire detection and fighting has not yet been fully investigated. The related work mainly focus on either the search stage and area coverage for fire detection [37, 38] or the coverage and tracking of the fire front, for confirmation and observation stages [20]. However, no research considers performing the all three stages which are search, confirmation and observation with a predefined formation shape including formation reconfiguration.

2.4 State-of-the-art of fault-tolerant cooperative control of UAVs

Obviously, most UAVs application, especially for forest fire detection and fighting, are too risky and have very high degree of importance. In addition to maintaining a formation shape during task executions, UAVs also should exhibit a fault-tolerance capability such that if one or more UAVs suffer faults, the other healthy UAVs must react to minimize the fault effect on the mission. If not, the formation would be broken [10].

Fault-tolerant cooperative control (FTCC) can be achieved with task re-assignment as well as motion re-coordination. The basic idea of FTCC is that if one or more UAVs subject to a fault, then there are two cases: (1) The UAV subjects to a severe fault, and is not able to accomplish its assigned task. For this purpose, the mission should be re-assigned to the remaining healthy UAVs; (2) The UAV subjects to a fault. However, it is still able to complete the mission but with degraded performance. In this case, the other healthy UAVs will reconfigure their controllers considering the capability of the faulty UAV.

FTCC has not yet been fully investigated in the literature. The related works mainly focus on communication faults [17], and the obstacle avoidance problem to avoid the collision of the faulty UAV [24]. However, few studies are focused on actuator faults and how to reconfigure the formation shape due to fault occurrence. In [25], a leader-follower formation control of multiple UAVs is proposed to keep the desired formation, while dealing with the potential collision and actuator faults. The proposed FTC approach was done without changing the formation. In [10], the FTCC problem for a team of UAVs is considered. The formation recovery algorithm is based on a trajectory re-planning technique. In the fault-free case, a differential flatness method is applied for each UAV to plan its trajectory. Once an actuator fault occurs, a formation supervisor commands all UAVs to replan their trajectories considering the capabilities of the faulty UAV. On the other hand, FTCC strategy for a team of UAVs and UGVs in the presence of actuator faults are investigated in [18]. When a severe fault occurs to one of the UAVs, the leader sends the new formation to all the followers. A Hungarian algorithm is used to solve the assignment, as an optimal problem, and the formation is reconfigured to a new shape in order to complete the task. In [42], an adaptive fault-tolerant control algorithm for a team of UAVs is presented. The fault is modeled as a disturbance signal. Once a fault occurs, the fault is estimated by an observer and accommodated by a compensator to be added into the normal controller. However, the formation reconfiguration of the healthy UAVs is not considered.

3 Scope and Objectives of the Dissertation Research

The proposed dissertation research can be stated as: "*Formation Control of Multiple Unmanned Aerial Vehicles, where the proposed algorithm is used in an important and risky application as the fire detection and fighting. Two cases are considered during performing the fire detection and fighting tasks. First, a normal case in which no fault occurs for any UAV in formation, then faulty case where one or more UAV subject to a fault, then the other team members can tolerate the fault and complete the mission*". The main objectives of the proposed dissertation research can be described as:

- Conduct a comprehensive investigation on UAV modeling and control to understand the existing control laws applied for UAVs either in a single UAV case or a multiple UAVs formation control case.
- Develop a novel algorithm for solving the trajectory tracking problem of a quadrotor UAV based on a combination of a linear quadratic regular and sliding mode control. LQR is applied to the quadrotor outerloop for linear position control, while the SMC is used with the nonlinear dynamics for inner loop attitude stabilization.
- Apply the proposed control algorithm to solve the problem of formation control of UAVs in a decentralized manner. While, using another SMC for the formation controller rather than each UAV controller.
- Apply the proposed algorithm in fire detection and fighting application, while using the graph theory in formation reconfiguration between the detection phase and confirmation, observation and extinguish phase.
- Study the fault tolerant cooperative control of UAVs, and develop a FTCC algorithm capable of reconfiguring the formation shape of the team once a severe fault has occurred to one or more UAVs, which prevent the UAV from accomplishing its mission.

4 Detailed Research Methodology Plan

Review of the relevant studies is aimed to build the essential knowledge and revealing the gaps in recent researches of the proposed work. In the following subsections, the research methodology associated with the principal phases of the research study are presented and formulated based on the reviewed articles and objectives of the present study.

4.1 Developement of a novel algorithm for solving a trajectory tracking problem

This phase aims to develop a novel algorithm to solve the trajectory tracking problem of UAVs. The proposed algorithm is based on a combination of a linear quadratic regulator controller and sliding mode control. As mentioned in Section 2.2, applying a nonlinear SMC with UAVs has a problem of high computational time in real time implementation as well as chattering effect which causes high frequency oscillation in system dynamics. While, using linear controller such as LQR with the UAVs linearized dynamics will solve the computational time problem, especially in multiple UAVs formation, but results in low accuracy and non-robust system.

To this end, a combination between linear controller such as LQR is applied to control the quadrotor outer loop which is the position, while a nonlinear controller such as SMC is used to control the inner loop which is the quadrotor attitude. The main advantage is that this method results in a robust controller due to using SMC while reducing computational time and chattering effect due to using LQR.

4.1.1 Dynamic model of quadrotor UAV

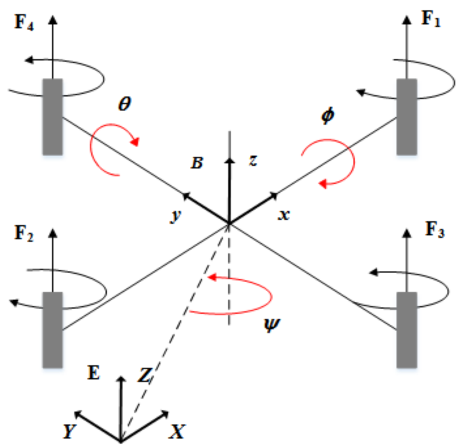

Figure 1: Quadrotor configuration with inertial and body-fixed frames.

The UAV considered in this work is a quadrotor which is a four-rotor helicopter, where four rotors laid up symmetrically around its center which has its body-fixed frame B and an inertial-earth-fixed frame E as illustrated in Fig. 1.

A simplified dynamic model can be presented as in [22]:

$$\begin{aligned}
\ddot{x} &= (\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi)\frac{U_1}{m} - \frac{k_1}{m}\dot{x}, & \ddot{\phi} &= \frac{U_2}{J_{xx}} - L\frac{k_4}{J_{xx}}\dot{\theta} \\
\ddot{y} &= (\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi)\frac{U_1}{m} - \frac{k_2}{m}\dot{y}, & \ddot{\theta} &= \frac{U_3}{J_{yy}} - L\frac{k_5}{J_{yy}}\dot{\phi} \\
\ddot{z} &= -g + (\cos\theta\cos\phi)\frac{U_1}{m} - \frac{k_3}{m}\dot{z}, & \ddot{\psi} &= \frac{U_4}{J_{zz}} - \frac{k_6}{J_{zz}}\dot{\psi}
\end{aligned} \tag{1}$$

where $k_i, i = 1, \ldots, 6$ are the drag coefficients which can be neglected at low speeds and indoor flight for simplification. $U_i, i = 1, \ldots, 4$, are the control inputs which are defined as:

$$
\begin{aligned}
U_1 &= F_1 + F_2 + F_3 + F_4 \\
U_2 &= L(F_3 - F_4) \\
U_3 &= L(F_1 - F_2) \\
U_4 &= K_{yaw}(F_1 + F_2 - F_3 - F_4)
\end{aligned} \tag{2}
$$

where $F_i, i = 1, \ldots, 4$, is the thrust generated by the ith propeller, L is the distance between the motor and the quadrotor center. K_{yaw} is a constant relating the propeller's thrust with the yawing moment. More details on the quadrotor model can be found in [14].

4.1.2 Single UAV trajectory tracking

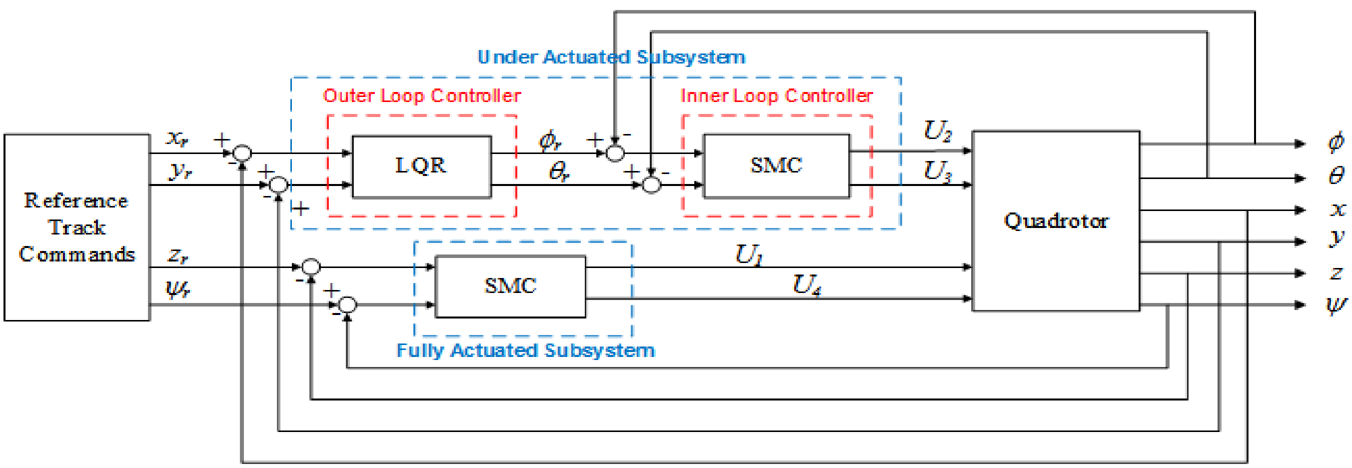

Figure 2: UAV control system block diagram.

The same trajectory tracking control system is used for both the leader and follower UAVs. For controlling the quadrotor helicopter, the dynamic model is divided into two subsystems. Full and under-actuated subsystems. A diagram of the proposed trajectory tracking control system is illustrated in Fig. 2. The full-actuated subsystem can be represented by the following equation:

$$
\begin{bmatrix} \ddot{z} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \frac{U_1}{m}\cos\theta\cos\phi - g \\ \frac{U_4}{J_{zz}} \end{bmatrix} \tag{3}
$$

while the under-actuated subsystem is defined as:

$$
\begin{aligned}
\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} &= \frac{U_1}{m} \begin{bmatrix} \cos\psi & \sin\psi \\ \sin\psi & -\cos\psi \end{bmatrix} \begin{bmatrix} \sin\theta\cos\phi \\ \sin\phi \end{bmatrix} \\
\begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} &= \begin{bmatrix} \frac{U_2}{J_{xx}} \\ \frac{U_3}{J_{yy}} \end{bmatrix}
\end{aligned} \tag{4}
$$

Full-Actuated Subsystem Control The full-actuated subsystem in (3) is used to design the altitude and heading angle controller, z and ψ respectively. Its objective is to minimize the error in the altitude and the heading yaw angle e_z and e_ψ respectively. This means that the controller aims to satisfy the following conditions

$$\lim_{t\to\infty} \|e_z\| = \|z_r - z\| = 0 \tag{5a}$$

$$\lim_{t\to\infty} \|e_\psi\| = \|\psi_r - \psi\| = 0 \tag{5b}$$

where e_z and e_ψ are the altitude and yaw angle tracking error respectively, z_r and ψ_r are the reference altitude and yaw angle respectively.
The best control input u for the altitude z and yaw angle ψ can be obtained using equations (1), (5) and (24) as:

$$\hat{U}_1 = \Big(\frac{M}{\cos\theta\cos\phi}\Big)(g + \ddot{z}_r - \lambda_z \dot{e}_z) \tag{6}$$

$$\hat{U}_4 = J_{zz}(\ddot{\psi} - \lambda_\psi \dot{e}_\psi) \tag{7}$$

where λ_z and λ_ψ are control gains with $\lambda_z > 0$ and $\lambda_\psi > 0$. In order to satisfy sliding condition, a discontinuous term is added across the surface $s = 0$ such that:

$$U = \hat{U} - ksgn(s) \tag{8}$$

where

$$sgn(s) = \begin{cases} +1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases}$$

k is a positive constant and is large enough to achieve the condition of (25). In SMC, high frequency switching across the surface causes oscillation within its neighborhood. In order to reduce these oscillations which called chattering effect, the sign function is replaced by saturation function as illustrated below:

$$sat(s) = \begin{cases} sgn(s) & \text{if } |s| > \rho \\ \frac{s}{\rho} & \text{if } |s| \leq \rho \end{cases}$$

where ρ is a thin boundary layer around the sliding surface, and can be chosen to be as small as possible to reduce the chattering effect. More details are available in Appendix (A).

Under-Actuated Subsystem Control The under-actuated subsystem in (4) is controlled via two independent loops. The outer-loop is designed to control the translational dynamics of the quadrotor to achieve trajectory tracking to the desired position in x and y axes. Its output is the reference orientation angles, roll ϕ_r and pitch θ_r. According to these reference data, the inner-loop controller calculates the minimum system input U_2 and U_3. LQR is used for the outer-loop controller as shown in (2), while SMC is used for controlling the inner-loop. The same control strategy is used for the leader and all the followers UAV in this work.

1. Position controller (outer-loop)
   LQR is used for position control to obtain the desired altitude by converging the error and ex-

tracting the desired attitude angles ϕ_r and θ_r, using the quadrotor linear dynamic model for x and y defined as:

$$\begin{aligned} \ddot{y} &= -\phi g \\ \ddot{x} &= \theta g \end{aligned} \tag{9}$$

The linear dynamics in (9) of x and y are given in the following state-space form to obtain the matrices A and B

$$\dot{x} = Ax + Bu \tag{10}$$

The controller aims to find the matrix K of the optimal control vector u such that $u(t) = -Kx(t)$, and (10) will be $\dot{x} = (A - BK)x$ to minimize the quadratic cost function J as follows:

$$J = \int_0^\infty (x^T Q x + u^T R u) dt \tag{11}$$

with

$$Q = \begin{bmatrix} q_1 & 0 & \cdots & 0 \\ 0 & q_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & q_n \end{bmatrix}, R = \begin{bmatrix} r_1 & 0 & \cdots & 0 \\ 0 & r_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_p \end{bmatrix}$$

where Q and R are weighting matrices with $Q \in \Re^{n \times n} \geq 0$ and $R \in \Re^{p \times p} > 0$, n and p are the number of states and inputs respectively. The gain matrix K can be obtained by solving the Ricatti equation [31].

2. Attitude controller (inner-loop)

The attitude angles ϕ and θ are driven to their desired values in the inner loop using SMC as shown in Fig. 2. These desired values ϕ_r and θ_r are the inner-loop control inputs obtained from the outer-loop controller. The same procedures as in the fully actuated subsystem are done on the attitude angles ϕ and θ to converge to their desired values. SMC is used to generate the control inputs U_2 and U_3 to achieve accurate stabilization through the following control laws:

$$\hat{U}_2 = J_{xx}(\ddot{\phi} - \lambda_\phi \dot{e}_\phi) \tag{12}$$

$$\hat{U}_3 = J_{yy}(\ddot{\theta} - \lambda_\theta \dot{e}_\theta) \tag{13}$$

where λ_θ and λ_ϕ are control gains with $\lambda_\theta > 0$ and $\lambda_\phi > 0$. e_ϕ and e_θ are the errors in roll and pitch angles, $e_\phi = \phi_r - \phi$ and $e_\theta = \theta_r - \theta$. ϕ_r and θ_r are the desired roll and pitch angles respectively. In order to satisfy the sliding conditions, Eq. (8) should be applied.

4.2 Applying the proposed algorithm to a team of UAVs

In this section, another controller is designed to achieve the desired formation using a decentralized leader-follower method as the same principle as in [27] but with different formation control output. Considering a team of i quadrotors under a leader-follower approach, such that $i \in \{L, 1, 2, 3, \ldots, N\}$, where L is the leader while N are the number of followers. The objective of the formation controller is to achieve the desired leader-follower formation configuration in X-Y plane, after following the leader in the Z direction to either same or different height.

Assumption 1. *Each UAV can collect or receive sufficient information on-board to plan and adjust its path autonomously.*

This formation shape is maintained via keeping a constant distance d and angle α between each follower and the leader, d_x and d_y are the X and Y coordinates of the actual distance d as shown in Fig. 3.

$$\begin{aligned} d_x &= -(X_L - X_F)cos(\psi_L) - (Y_L - Y_F)sin(\psi_L) \\ d_y &= \quad (X_L - X_F)sin(\psi_L) - (Y_L - Y_F)cos(\psi_L) \end{aligned} \tag{14}$$

The proposed control algorithm is shown in Fig. 4 applying SMC in its design to keep the formation even in perturbed and uncertain environment. Formation control errors of x, y and z should satisfy the following conditions:

$$\lim_{t\to\infty} \|e_x\| = \left\|d_x^d - d_x\right\| = 0 \tag{15a}$$

$$\lim_{t\to\infty} \|e_y\| = \left\|d_y^d - d_y\right\| = 0 \tag{15b}$$

$$\lim_{t\to\infty} \|e_z\| = \left\|d_z^d - d_z\right\| = 0 \tag{15c}$$

where d_x^d, d_y^d and d_z^d are the desired disatance between the leader and follower in the X, Y and Z coordinates respectively. Assuming zero yaw angle for simplicity, then the formation problem is solved for each follower according to (24) as:

$$\begin{aligned} \ddot{X}_{F_i} &= \ddot{X}_L + \lambda_x(\dot{X}_L - \dot{X}_{F_i}) \\ \ddot{Y}_{F_i} &= \ddot{Y}_L + \lambda_y(\dot{Y}_L - \dot{Y}_{F_i}) \\ \ddot{Z}_{F_i} &= \ddot{Z}_L + \lambda_z(\dot{Z}_L - \dot{Z}_{F_i}) \end{aligned} \tag{16}$$

where (16) denotes the desired accelerations which then enhanced using Eq. (8) to be used as the input for each follower controller to achieve the required distance between each leader and follower.

4.3 Cooperative forest fire detection using a team of quadrotor UAVs

This phase aims to apply the proposed control algorithm to a real application. Forest fire detection and fighting is selected due to its importance and risk to human life.

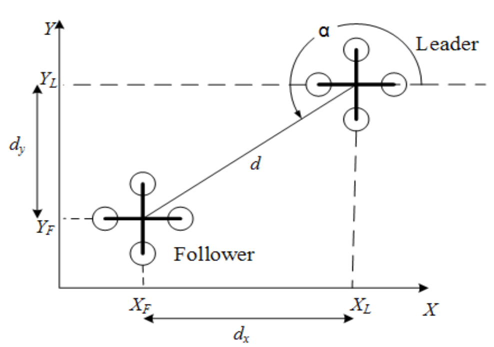

Figure 3: Quadrotors formation distance.

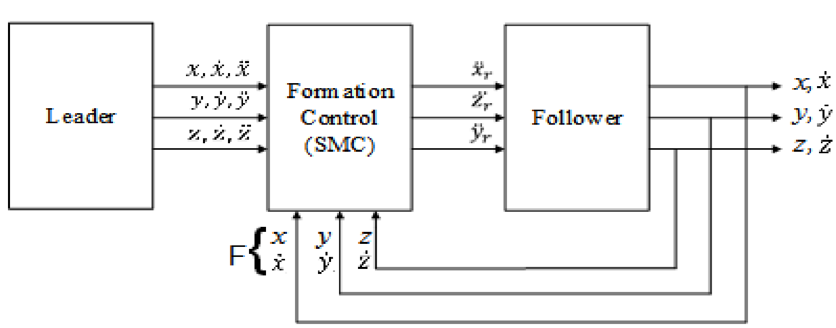

Figure 4: Formation control system block diagram.

A simplified scenario is proposed to achieve this task as follows:

i. A team consists of N quadrotor UAVs is assigned to cover a certain area. The team moves in a predefined leader-follower formation configuration. As mentioned in Section 2.2, each UAV is equipped with different type of fire detection sensors.
ii. Once a fire is detected by i agent, it will send an alarm to the leader and send the sensory data to the ground station (GS). Based on these sensory data, GS will re-plan both the reference trajectory and the new formation reconfiguration based on the fire front model as in Eq. (18). These information will then be sent to the team.
iii. The leader receives the new reference trajectory from the GS, while the followers compute their relative positions as explained in Section 4.2, following the fire front perimeter to confirm the fire alarm with different types of sensors.

The following assumptions are asserted for the fire detection and fighting scenario:

Assumption 2. *The searching and coverage path is already planned.*

Assumption 3. *Each UAV has different type of fire detection sensors to confirm and avoid false alarms.*

Assumption 4. *The sensor radius can cover the area assigned under each UAV foot prints based on the existing formation shape.*

Assumption 5. *All UAVs are within a specified proximity to communicate with each other and with the ground station, and there is no loss of communications between UAVs.*

The quadrotor team will follow the fire front perimeter at the beginning, in order to confirm the fire detection alarm. Then the team will remain tracking the fire front for information update about the fire and its propagation. Under constant conditions for homogeneous, non-spotting fuels it is generally accepted that a fire ignited at a point will expand, at a constant rate, as an ellipse of the form [35]:

$$\begin{aligned} x(s,t) &= at\cos(s) \\ y(s,t) &= bt\sin(s) \end{aligned} \tag{17}$$

where t is the time, the origin being the point of ignition and the y axis being the wind direction. The forward rate v, lateral rate u and the back rate w are defined as $b+c$, a and $b-c$ respectively. The Canadian Forest Fire Behaviour Prediction System (CFFBPS) assumes elliptical growth and has documented values of u, v and w for a very large set of constant parameters affecting a fire [35]. The fire front at time t is represented parametrically in Cartesian co-ordinates by the closed curve $(x(s,t), y(s,t))$ where $0 < s < 2\pi$. It is assumed that each point on the fire front is an ignition point for a small fire that expands, igniting in time dt a small elliptical region around it. Taking θ to be the clockwise angle to the y axis defining the wind direction. Then, the axes are rotated to make y direction as the direction of wind; the x co-ordinate is then scaled by $b(s,t)/a(s,t)$, i.e. the following transformation is applied:

$$\begin{aligned} X &= [b(s,t)/a(s,t)](x\cos\theta - y\sin\theta) \\ Y &= x\sin\theta + y\cos\theta \end{aligned} \tag{18}$$

Changing team formation can be done by applying a formation reconfiguration method such as Graph Theory [12] in which the internal behavior of the team is described by the pair $(r, \mathcal{H})$ where r

describes the formation shape and $\mathcal{H}$ is the control graph representing the control strategy used by each UAV. According to this theory, an $N \times N$ adjacency matrix G is exploited to represent the initial control graph, where N is the number of UAVs in formation. The elements of matrix G are either 0 or 1. If an element (n, m) is 1, this will represents an incoming edge from UAV n to UAV m, and 0 represents no edge between the UAVs n and m which means that the motion of UAV m is independent from UAV n. Similarly, a matrix H represents the final formation shape.

The appearance of a 1 in a column for any UAV defines its controller as: ([12])

$$\sum_{columns} 1's = \begin{cases} 0 & \text{leader} \\ 1 & \text{follower with } l-\psi \text{ control} \\ 2 & \text{follower with } l-l \text{ control} \end{cases}$$

where $d-\psi$ control means that one UAV follows another by controlling the relative distances between them (as a leader-follower case), and $d-d$ control means that the UAV maintaining a specified distance from two UAVs. The transition from one control graph to another is presented by a transition matrix T, where $T = H - G$. There are 3 possible values of the (n, m) elements in the matrix T

$$\begin{cases} 0 & \text{no edge connection between } n \text{ and } m \\ -1 & \text{the edge connection needs to be broken} \\ 1 & \text{new edge needs to be established.} \end{cases}$$

4.4 Developement of a fault-tolerent cooperative control algorithm

Forest fire detection and fighting applicaltion using multiple and cooperative UAVs is such a risky and very important task, which need to be accomplished as fast as possible. UAVs are required to fly with a safety height over the fire flames in order to assure safety of UAVs. However, height should not be very high to gather required and detailed information about the fire and evacuation routes, sometimes flames could reach UAVs resulting in partial or full damage to one or more of the UAVs. Therefore, designing a FTCC algorithm is a must. This algorithm should be capable of reconfiguring the formation shape of the team once a severe fault has been occurred to one or more UAVs in the team, and it seems that the faulty UAV(s) is/are unable to complete the mission.

When an actuator fails, then the control inputs will be:

$$u_i^F = u_i(1 - \gamma_k^i), \qquad 0 \leq \gamma_k^i \leq 1, \quad i = 1, \ldots, m \tag{19}$$

where γ_k^i are the control effectiveness factors. If $\gamma_k^i = 0$, then control input is normal; if $\gamma_k^i = 1$, then u_i is an outage. Then the state equation with partial actuator failures can be written as: [2]

$$z(k+1) = A(k)z(k) + B(k)u(k) - B(k)U(k)\gamma(k) \tag{20}$$

where

$$U(k) = \begin{bmatrix} u_k^1 & 0 & \ldots & 0 \\ 0 & u_k^2 & \ldots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \ldots & u_k^m \end{bmatrix}, \qquad \gamma_k = \begin{bmatrix} \gamma_k^1 \\ \gamma_k^2 \\ \vdots \\ \gamma_k^m \end{bmatrix}$$

The basic idea of the proposed FTCC algorithm is to deal with the actuator faults occurred in one or more UAVs according to the fault signal γ sent from the faulty UAV to the other healthy UAVs. The following equation represent the value of γ:

$$0 \leq \gamma_j \leq 1 \qquad j = 1, \ldots, N \tag{21}$$

Depending on that signal, the following situations may take place:

- If $\gamma_j = 0$, then the jth UAVs are fault-free, the team will continue with the same formation.
- If $\gamma_j = 1$, then the jth UAVs are subject to actuator fault. The faulty UAVs detected the fault, estimated the value of γ and it seems that they are unable to complete the mission. So the remaining healthy UAVs start to reconfigure their formation based on the new situation. i.e, each UAV switch to a new desired formation F^d.
- If $0 < \gamma_j < 1$, then the jth are subject to actuator fault but still able to complete the mission with a degraded performance.

The following assumptions are asserted for the FTCC algorithm:

Assumption 6. *Each UAV in the formation has each own fault detection and diagnosis (FDD) algorithm. So it can detect the fault and estimate of value of the control effectiveness factor γ.*

Assumption 7. *There is no loss of communications between UAVs.*

This objective can be done by applying the same formation reconfiguration method such as the Graph Theory which illustrated in Section 4.3.

5 Timelines

Activities	**2014**			**2015**			**2016**		
	W	**S**	**F**	**W**	**S**	**F**	**W**	**S**	**F**
Course work									
Literature review									
Comprehensive examination									
Single UAV trajectory tracking and formation control									
Formation control in a cluttered environment									
Fire detection and fighting									
Practical implementation									
Synthesis of research results and analysis									
Publications									
Thesis writing and submission									
Note: **F**: Fall, **W**: winter, **S**: Summer semesters									

6 Anticipated Significance of the Work

It is an essential issue to improve the performance of the team of UAVs in both structured and unstructured environments. This cooperative team can be used in many useful applications such as fire detection and fighting. In such risky applications UAVs may suffer fault due to burning or overheating of actuators which require fault tolerant control to complete the assigned mission successfully.

The merits of this proposed research can be reflected by an anticipated significant contribution to apply a combination between linear (LQR) and nonlinear controller (SMC) to the formation control of UAV in a decentralized manner in real-time solving the computational time and chattering problem of SMC. In addition, adding an obstacle and collision avoidance algorithm to significantly improve the performance of the UAVs team. Furthermore, the proposed system will be used in real application such as forest fire detection and fighting. In addition, the system will be equipped with a fault tolerant control system to guarantee the completion of its mission against actuator faults.

The results of the research proposed here will be published in journal and conference publications. Some preliminary results of the proposed research have been presented in the following conferences:

[1] K. A. Ghamry and Y. M. Zhang, "Formation control of multiple quadrotors based on leader-follower method," in *International Conference on Unmanned Aircraft Systems (ICUAS)*, 2015, pp. 1037–1042.

[2] M. A. Kamel, K. A. Ghamry and Y. M. Zhang, "Fault tolerant cooperative control of multiple UAVs-UGVs under actuator faults," in *International Conference on Unmanned Aircraft Systems (ICUAS)*, 2015, pp. 644–650.

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A Single UAV Trajectory Tracking

To achieve this goal in Eq.(5), first-order sliding mode controller is used to minimize this error. First, a time-varying surface $S(t)$ in the state-space R^n is defined by the scalar equation $s(e,t) = 0$, as in [40] where:

$$s(e,t) = (\frac{d}{dt} + \lambda)^{n-1} e \tag{22}$$

where λ is a positive constant and it represents the slope of the sliding line, if $n = 2$ for the first-order SMC. s will be a weighted sum of the position error e and the velocity error $\dot{e}$ as

$$s = \dot{e} + \lambda e \tag{23}$$

Differentiating s once, the input u appear in (24) after substitution with (1) and (5). Because (22) contains e^{n-1}, thus the second-order tracking problem is transferred to a first-order stabilization problem.

$$\dot{s} = \ddot{e} + \lambda \dot{e} \tag{24}$$

$$\frac{1}{2}\frac{d}{dt} s^2 \leq -\eta |s| \tag{25}$$

Equation (25) is a Lyapunov candidate function chosen for the control law u to maintain scalar $s = 0$ in (23). This function states that s^2 is the squared distance to the sliding surface, where η is a positive constant.

B Progress to Date

With respect to the presented timeline in Section 5, this appendix provides a short review of the progress to date towards achieving the objectives of this research project.

B.1 Simulation results

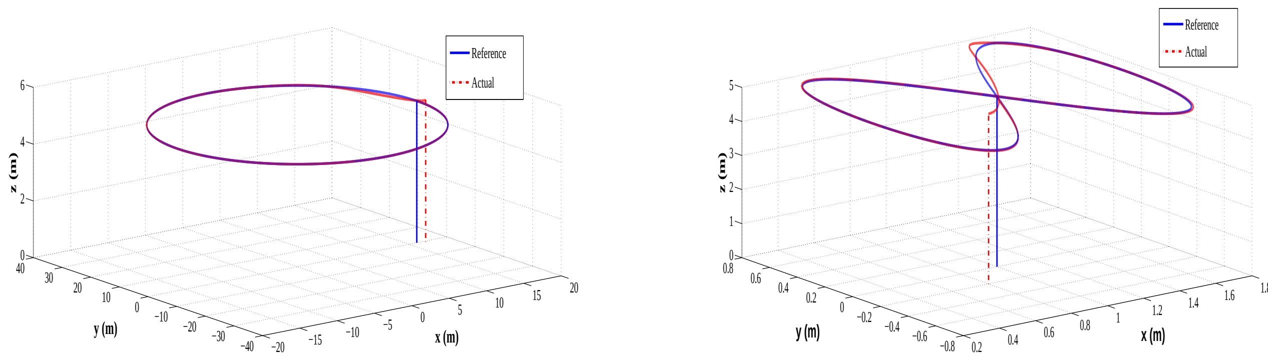
Figure 5 shows two simulation results for single UAV trajectory tracking. The first case in Figure 5(a), single UAV tracks an ellipse-shaped trajectory. The UAV initial position is $(x, y) = (17, -0.5)$, while the reference trajectory is defined by:

$$x_r(t) = 1 + 0.7 \sin\left(\frac{2\pi}{30}\right), \qquad y_r(t) = 0.7 \sin\left(\frac{4\pi}{30}\right) \tag{26}$$

The second case in Figure 5(b), single UAV tracks an ∞-shaped trajectory. The UAV initial position is $(x, y) = (0.8, -0.2)$, while the reference trajectory is defined by:

$$x_r(t) = 16 \cos\theta, \qquad y_r(t) = 32 \sin\theta \tag{27}$$

Where $\theta = 0 : 2\pi$. Fig. 5 shows that the UAV succeeded in tracking different reference trajectories.



(a) Ellipse

(b) Infinity shape

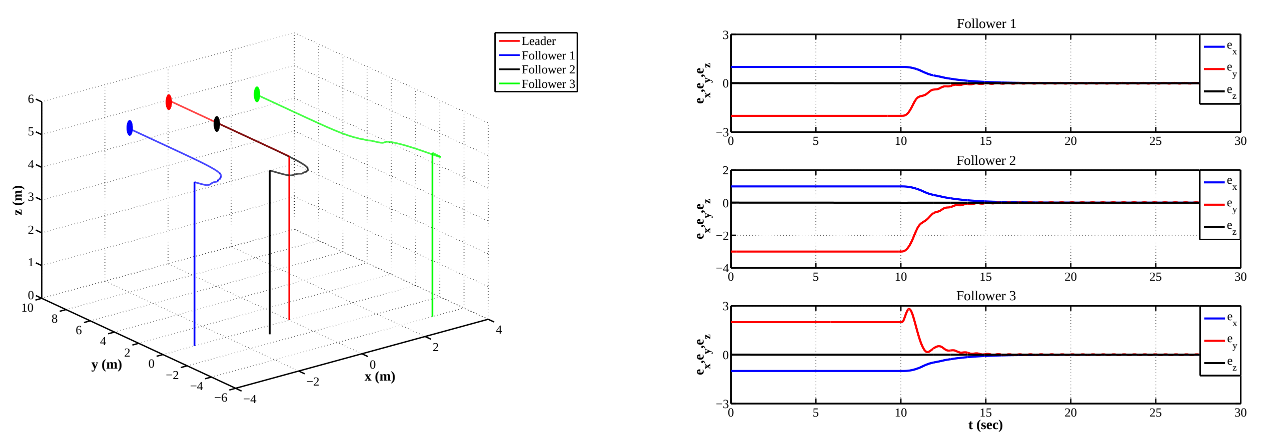
Figure 5: Simulation results of single UAV trajectory tracking.

B.2 UAV formation control

Four quadrotor UAVs are used to perform diamond formation, a leader and three followers. the leader's initial position is $[0,0,0]^T$, while the follower's initial positions are $F_1(0) = [-3,0,0]^T$, $F_2(0) = [-1,-1,0]^T$ and $F_3(0) = [3,-4,0]^T$ respectively, and their desired formation distances with respect to the leader are $d^d_{F_1} = [-2,-2,0]^T$, $d^d_{F_2} = [0,-4,0]^T$ and $d^d_{F_3} = [2,-2,0]^T$. Fig. 6(a) and Fig. 6(b) show that the required formation is achieved and that errors in all coordinates x, y and z were converged to zero.

The second case is an extension of case 1 with disturbances added to all the three followers to prove the robustness and effectiveness of the controller. After 20 seconds, an external disturbing signal was added to all followers in the lateral direction acting upon the pitch angle θ, to mimic a lateral sudden wind gust.

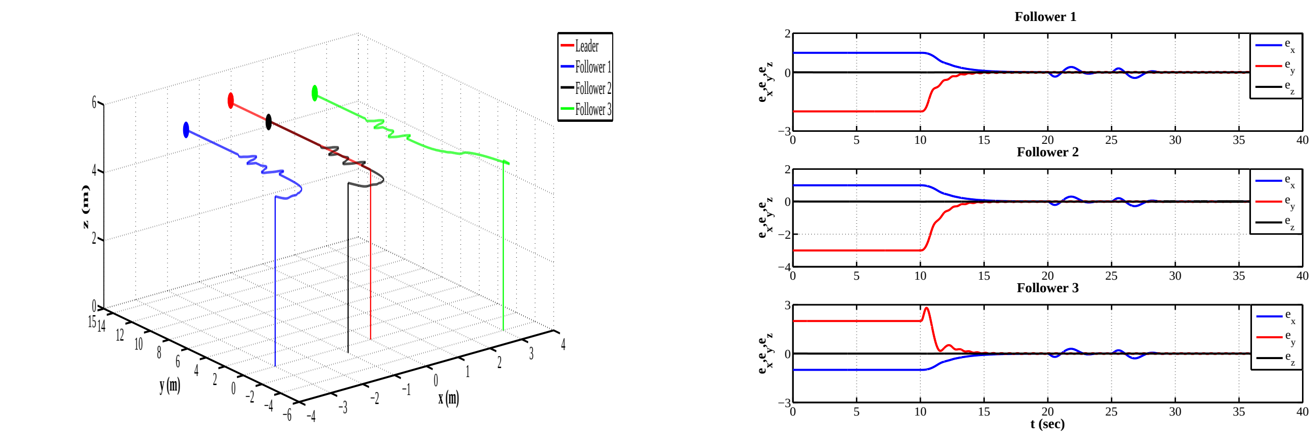
It is clear from Fig. 7(a) that all UAVs succeeded in keeping their diamond formation, while Fig. 7(b) shows the convergence of all formation errors.



(a) Diamond formation of four UAVs team

(b) Error in x, y and z coordinates for all followers

Figure 6: Diamond formation.



(a) Diamond formation of four UAVs team with disturbance

(b) Error in x, y and z coordinates for all followers with disturbances

Figure 7: Diamond formation with disturbance.

B.3 Fire detection and fighting

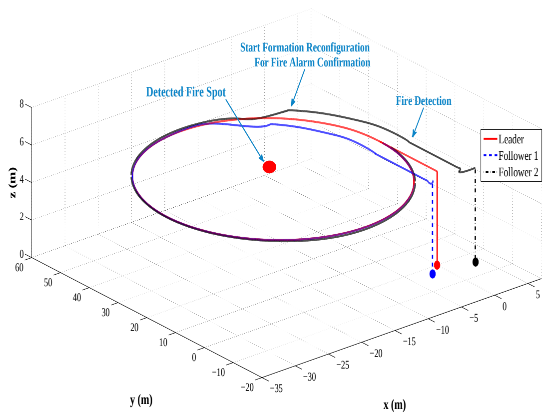
The effectiveness of the proposed control strategy to cooperatively detect and track fire fronts with the help of multiple UAVs were verified in simulation results. Three UAVs are used to scan a certain area assuming that coverage and detection track is already planned and known.

UAVs are moving in a triangular formation, while one of the UAVs detect a fire spot with its sensor. The UAV sends an alarm to all other UAVs and sends the detected data to the ground station for further analysis, then the GS sends the reference predicted fire front trajectory according to fire front model as in Eq. (18) to the leader. Accordingly, the leader sends the new formation shape to followers, which is reconfigured according to the graph theory.

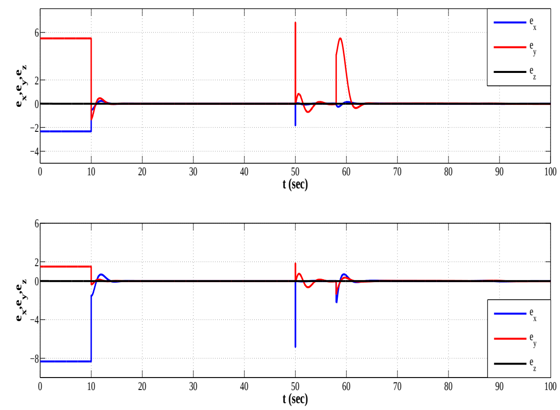
In this case, three quadrotor UAVs are used in simulation, a leader and two followers. The leader begins its route by following the required height z from its initial position $(x_0,y_0,z_0)=[0,0,0]^T$, then following the required track in X-Y plane. The initial positions of the two followers are at $F_1(0) = [-2,-3,0]^T$ and $F_2(0) = [4,-4,0]^T$ respectively. The desired triangular formation distances during fire detection are 5m, while the angles are 150° and 210° for both followers with respect to the leader respectively. Thereafter, a fire spot is detected and the formation shape is reconfigured, the UAVs then move to the fire confirmation stage and track the fire front. The new desired formation distances are 1m and 180° angle for the first follower with respect to the leader, while the second follower is at 4m and 180°. Hence, they move on the same ellipse shaped path, fire front, gathering more information with different fire sensors to confirm if this alarm is a true or false alarm.

As shown in Fig. 8(a), it is clear that the UAVs team succeeded in following their leader with the required triangular formation during the fire detection task. A fire spot was detected, therefore the team succeeded in formation reconfiguration to confirm the fire detection. Fig. 8(b) shows that errors in all coordinates x, y and z were converged to $zero$, then at time $t = 50$ sec, the team reconfigured and all errors converge again to zero.

Fig. 9(a) shows how the formation achived the desired distances d_{F1} and d_{F2} between the followers and their leader. While, Fig. 9(b) shows that the desired formation angles η_{F1} and η_{F2} were achieved.

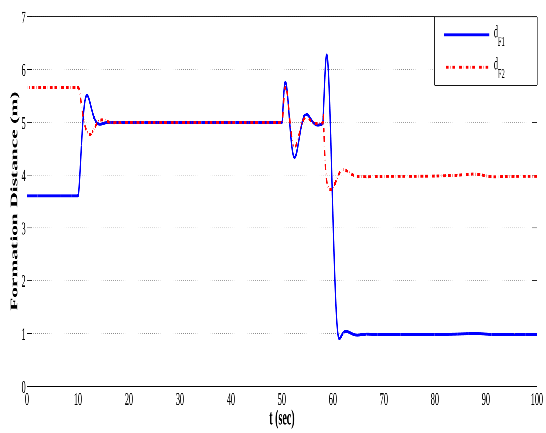


(a) Three UAVs during fire detection and confirmation task

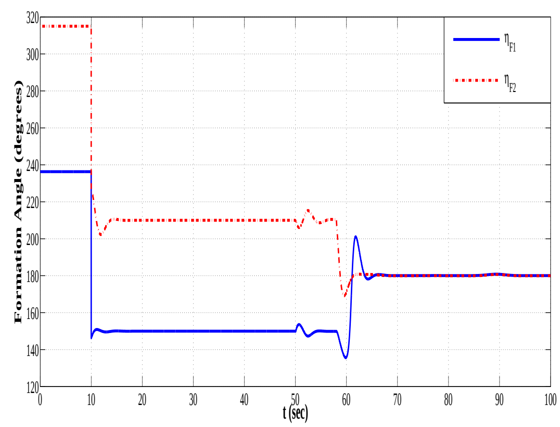


(b) Error in x, y and z coordinates for all followers

Figure 8: UAVs formation and reconfiguration during fire detection and confirmation.



(a) Desired formation distances between the leader and followers



(b) Desired formation angles between the leader and followers

Figure 9: UAVs desired formation distances and angles during fire detection mission execution.