

MULTI-AGENT CONTROL OF MULTIPLE UAV-LOAD SYSTEMS

BY

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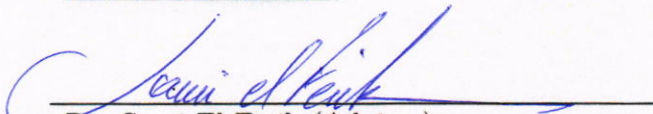
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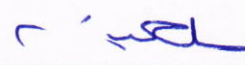

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*To my parents, siblings, wife, children and Abdulaziz Muhammad
Ibrahim Al-Yahaya*

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THESIS ABSTRACT

NAME: Abdulrahman Aliyu
TITLE OF STUDY: Multi-agent Control of Multiple UAV-Load Systems
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Quadrotor Unmanned Aerial Vehicles (UAVs) are highly nonlinear and underactuated in nature as they possess fewer control inputs than control variables. A combination of multiple UAVs conveying single load is complex but it offers some advantages due to its complimentary nature, as such, heavier loads can be conveyed compared to using single UAVs. Consequently, the need to avoid inter-agent collision necessitates the use of multi-agent control strategies in the presence of load disturbances. Therefore, we conceptualize the problem of cooperative tracking control for a Multi-agent UAV Load Systems (MUAVLs) whereby each UAV is divided into global position and local attitude subsystems. To ensure that formation is maintained in a desired path, we used two methods. In the first method, based on directed graph theory a Neural Network Graph-theoretic Distributed Adaptive Control (NNGDAC) is used for the position subsystem with a modified virtual force artificial potential field for obstacle avoidance. Another

Adaptive Feedback Linearization (AFBL) controller is also designed for the attitude subsystem which is verified by simulation results. However, in the second method; using rigid or undirected graph theory, an Adaptive Backstepping Multi-agent Control (ABMC), based on Lyapunov theory was designed for the position subsystem in the presence of load disturbances. Furthermore, another Backstepping Finite-time Sliding Mode Control (BFSMC) is designed for the attitude subsystem which is also verified by simulation.

ملخص الرسالة

ويبدأ من محرك للبدء :مبدأ

ةدلتعتملا رابط نودب تارناطلا ليمحة تمظلاًل ملوعلا دلتعتملا :ةساردا ناونع

قزيجاًل وحمكتلا ةسلسننه :صصختلا

ةقيملاعلا ةجردلا خيرات :2022 ويأخذ

عند كتابة ملخص ، ضع في اعتبارك مجرد ملخصاًثبتت المركبات الجوية غير المأهولة (sVAU) بشكل متزايد أنها لا غنى عنها بسبب مناطق تطبيقها التي تتكشف ، خاصة في الحالات التي يتم فيها إرفاق الحمولات بها. الطائرات بدون طيار rotordauQ هي تلك التي تحتوي على أربعة دوارات وأنظمة غير نشطة بشكل عام. يزداد تعقيد النظام عندما يتم إرفاق الحمل لأغراض النقل. لذلك ، تصبح الحاجة إلى التحكم بشكل مناسب في هذه الأنظمة أمراً بالغ الأهمية لأنها تنتقل عادةً في بيئات مزدحمة. في هذا العمل ، وضعنا تصوراً لمشكلة التحكم في التتبع التعاوني لنظام تحميل الطائرات بدون طيار متعدد العوامل (sLVAUM) حيث يتم تقسيم كل طائرة بدون طيار إلى مواقع عالمية وأنظمة فرعية للمواقف المحلية. لضمان الحفاظ على التكوين في المسار المطلوب ، يتم استخدام رسم بياني للشبكة العصبية تحكم تكيفي موزع نظري للنظام الفرعي للموضع مع مجال محتمل اصطناعي لقوة افتراضية معدلة لتجنب العوائق. تم تصميم وحدة تحكم أخرى في التغذية المرتدة الخطية (LBFA) أيضاً للنظام الفرعي للموقف الذي تم التحقق منه من خلال نتائج المحاكاة.

CHAPTER 1

INTRODUCTION

Over the past few years, unmanned aerial vehicles (UAVs) have been employed in numerous fields for various applications springing from both civilian and military purposes. Examples of such applications are delivery, surveillance, fumigation, traffic monitoring, construction purposes for example pick and place objects, rescue missions, patrolling forests in case of fire outbreak, warfare, and other risky missions [2]. However, the more adapted they are to an environment the more versatile they become.

The major advantages of UAVs is that it does not require a particular airfield base and they are free from rugged terrains experienced by ground robots. A UAV is generally an underactuated system having four inputs but with six degrees of freedom comprising of position and attitude orientation. However, the degrees of freedom increases when two or more UAVs are combined to carry a load as a multi-agent system. The evolution of UAVs is discussed in [3], [4].

Multi-agent UAV-load (MUAVLs) systems are those with more than one UAV concurrently conveying an attached or suspended load. These systems are highly

non-linear in nature and are difficult to characterize due to the complexity their aerodynamics [5]. However, they poses some advantages over single UAV-load system due to their redundancy and ability to carry heavier payloads. Such a system requires a controller for each UAV, a formation strategy and collision avoidance which is paramount for execution of clinical tasks. This is indeed a difficult task given the nature of the system. Therefore, the need to formulate a multi-agent system becomes necessary as it provides a means of coordination and information sharing between agents.

1.1 Multi-agent Systems

We provide a brief discussion of networked multi-agent systems together with their applications in some scientific and engineering disciplines. Synchronization behavior in nature and social systems as a distributed system is based on information locally available in a network of a group of systems. These systems are increasingly gaining attention in a plethora of fields [6], [7], [8], with [9], [10] listing application areas of cooperative multi-agent systems. This unprecedented attention is due to the emergence of gaining understanding of how inter-elemental actions affects the collective functionality of multilayered systems in the field of biology and material science.

Moreover, advances in networked technological systems such as sensor networks and multi-vehicle systems which mimic biological behaviours can be easily synthesized [11]. Reynolds'rule [12] stipulated the rules governing the the collective motion in a large group based on the motion of the neighbors of individual agent as follows;

1. Separation; Collision avoidance.
2. Alignment; Velocity matching.
3. Cohesion; Flock centering.

1.1.1 Information Exchange through Graph

In this work, we deal with the behaviors and interactions of UAVs that are interconnected by the links of a communication network called edges. An edge is modelled as directed and undirected graph which will be discussed later. Each UAV constitutes an agent or node with edges allowing flow of information between agents.

Agents can perceive information about each other and their environments through the use of sensors. Despite the limitations of sensors in terms of resolution and range, they can be utilized effectively. Some common sensors include vision-based such as cameras and range sensors which includes infrared, laser and sonars. Other sensing modalities exist with their peculiar geometric constraints.

1.1.2 Cooperative Control of Multi-agent Systems

Cooperative control based on graphs allows interaction between agents and communication graph topology. This shows the importance of the graph topology which might limit any control performance if care is not taken. In this case, control protocols must be distributed, meaning that each agent depends only on immediate neighbour information. Cooperative control stipulates that each agent is responsible for its state variables and dynamics whereby the daunting task is to ensure that all states are

able to reach a specified value. These states could include sensor readings, vehicle position or orientation, etc. Consequently, care must be taken to ensure that control laws agree with graph topology to avoid undesirable outcomes. Cooperative control started with two seminal papers presented [13], [14] which formed the basis for motivation for several interesting works [15], [16] and those presented in these survey papers [17], [18]. Therefore, the main focus of this work is cooperative control of Multi-agent UAV-Load Systems (MUAVLs) interconnected by communication graph topology.

1.2 Motivation

Numerous challenges associated with load transportation has been extensively explored in a bid to provide safe, swing-free and robust flight for a UAV-load system with gripped or suspended load. MUAVLs constitute a highly nonlinear multi-system that requires careful attention. These types of systems poses difficulties, some of which are;

1. Changes in the Centre of Gravity (CoG) of the UAV due to load disturbance.
2. Under-actuation meaning lesser input to state.
3. High nonlinearity.
4. Connections between agents introduce additional dynamics, reducing maneuverability and increasing disturbance and stability issues.

Moreover, for multi-UAV formulation, even though the payload becomes more controllable as the cable force is spreading outward [19], it still possesses additional challenges

such as;

1. Connections between agents introduce additional dynamics, reducing maneuverability and increasing disturbance and stability issues.
2. The trajectory generation should also guarantee that the UAVs does not collide during flight, taking in consideration load distributions and swing control.
3. Load distribution also contributes to the complexity.
4. The difficulty is further compounded by a scenario of communication delay or packet losses between UAVs.

As with other research areas, there are still gaps that requires unprecedented approaches to provide improved flight. Nevertheless, the solution to contemporary challenges still relies on appropriate modelling and control strategies to solve the aforementioned problem.

Several modelling techniques have been successfully employed for various MUAVLs formulation. Based on Lagrange model [20], a coordinate-free dynamical model of the system is used to develop equations of motions directly on the unit sphere and the special orthogonal group. Newton -Euler [21] was employed, because it allows for analysis of each link or body separately. However, Kane's [22] method was adopted due to the ease in decoupling attitude dynamics. An Udwadia Kalaba [23] method is scalable and it is based on Gauss' principle applied due its ease when dealing with embedded and augmented systems.

Therefore, in this work, we address the following issues associated with control of such systems which includes;

1. Swing free trajectory for non-sensitive load suspended by a cable.
2. Load swing suppression for sensitive load suspended by a cable.
3. Stability of the system.
4. Obstacle avoidance.

Details of the control literature are given in chapters 3 and 4.

1.3 Problem Statement

This work builds a relationship between the relative position error based on the graph theoretic distributed adaptive control to generate inter-agent collision free trajectory.

We decouple the system into two subsystems, translational and rotational and designed two controllers which are robust to load disturbance while maintaining inter-agent distance for the translational subsystem while another set of controllers were utilized for the rotational subsystem. Furthermore, a modified artificial potential field with a virtual force is utilized for obstacle avoidance. Herein, we attempt to achieve the following;

1. Maintain inter-agent collision free formation pattern.
2. Track the desired trajectory.
3. Load disturbance rejection.

4. Avoid Obstacle.

1.4 Thesis Organization

This work is summarized as follows; chapter 1 presents an introduction highlighting the motivation behind this work, the problem statement and the thesis structure. In chapter 2, the MUAVLs model was given, in addition to introduction a short description of Radial Basis Function Neural Network which we utilized. In chapter 3 and 4, two control designs (Adaptive Formation Control of Multi-agent Quadrotor UAVs conveying Load with Obstacle Avoidance and Backstepping Adaptive Formation Control of Multi-agent Quadrotor UAVs conveying Load) were proposed, implemented and discussed in detail followed by concluding remarks in chapter 5.

CHAPTER 2

PRELIMINARIES

Essentially all methods for obtaining equations of motion are equivalent. However, the ease of use of the various methods differs as some are more flexible and better suited for multibody dynamics than others. Quadrotor modeling has been presented in a number of works [24] but for the purpose of completeness we present a detailed modeling of the Newton-Euler formulation in the next subsection under the following assumptions;

1. The cable is rigid and mass-less.
2. The load has no effect on the UAV while it is on the ground.
3. The load yaw angle is defined by the line connecting the two UAVs.
4. Negligible aerodynamic effects on the load and UAVs.

2.1 Quadrotor Modelling

Various formulation of modelling the quadrotors offer a great deal of advantages, necessary to give an in-depth knowledge of the multi-system. Mathematical models are undoubtedly helpful because they create an avenue and exposure to the system which is necessary in order to solve associated problems. A detailed model of a quadrotor UAV is given in [25]. For the MUAVLs diagram in Fig. 2.1, consider that the center of mass of each quadrotor aligns with the inertial and body fixed frame which is taken as the origin.

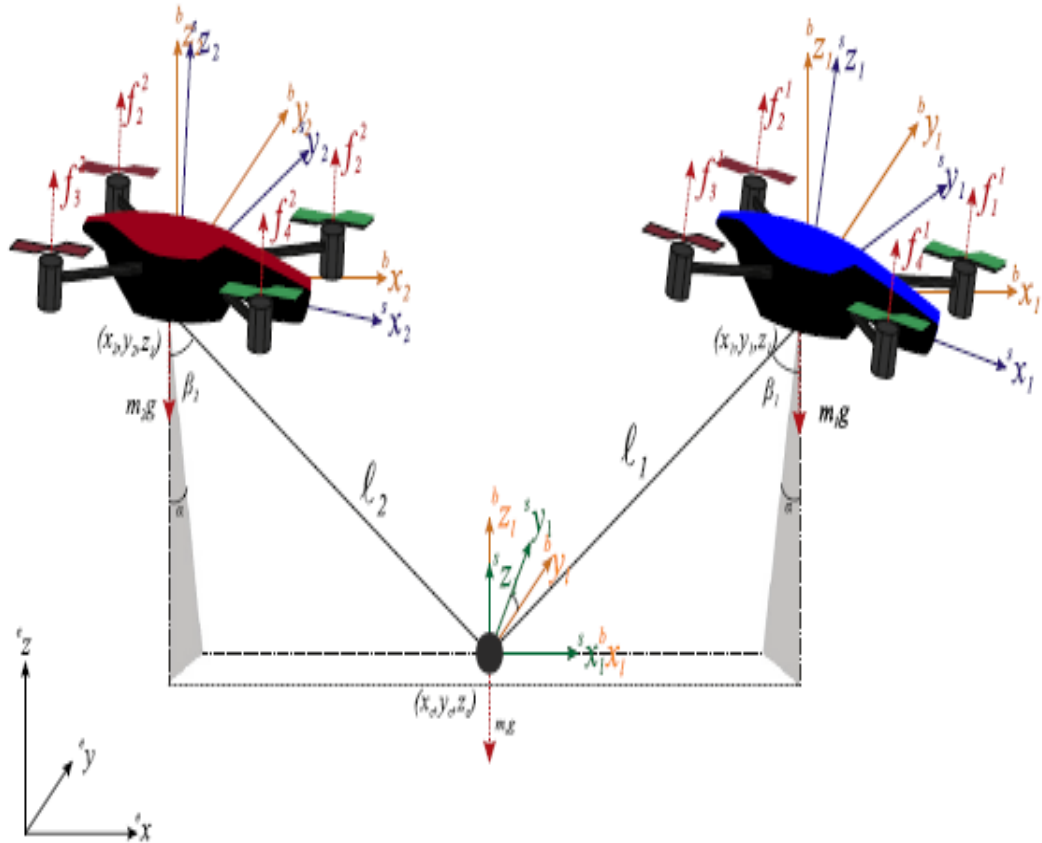


Figure 2.1: Dual UAV with Load [1]

The position in the inertial frame is represented by $\zeta = [x, y, z]$ while the rotational Euler angles (roll, pitch and yaw) are represented $\xi = [\phi, \theta, \psi]$. The rotation matrix R gives the transformation from body fixed frame to the inertial frame.

$$R = \begin{pmatrix} c_\psi c_\theta & c_\psi s_\theta s_\phi - s_\psi c_\phi & c_\psi s_\theta c_\phi + s_\psi s_\phi \\ s_\psi c_\theta & s_\psi s_\theta s_\phi - c_\psi c_\phi & s_\psi s_\theta c_\phi - c_\psi s_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{pmatrix}$$

The thrust force generated by each rotor, $i(i = 1, 2, 3, 4)$ $T = b.f_i^2$, where b and f_i are the thrust factor and rotor speed respectively. The differential equation for the acceleration of the quadrotor translational axis is given by;

$$\ddot{\zeta} = -g \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R(1/m)T \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (2.1)$$

where $T = d \sum_{i=1}^4 f_i^2$ is the total thrust produced by the quadrotor, d is the thrust factor, g is acceleration due to gravity and m_q is the mass of the quadrotor. Consider an inertia matrix is given by $I = \text{diag}[I_x, I_y, I_z]$, where M_T is a vector describing the torque applied to the quadrotor body and M_G representing the gyroscopic torques the rotational set of differential equation is obtained as:

$$I\ddot{\xi} = -(\dot{\xi} \times I\dot{\xi}) - M_G - M_T \quad (2.2)$$

M_T is given by;

$$M_T = \begin{pmatrix} Lb(f_2^2 - f_4^2) \\ Lb(f_1^2 - f_3^2) \\ d(f_1^2 + f_3^2 - f_2^2 - f_4^2) \end{pmatrix}$$

with the drag factor d and the length L of the lever and M_G is given by;

$$M_G = J_R(\dot{\xi} \times \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix})(f_1 - f_2 + f_3 - f_4) \quad (2.3)$$

The overall dynamic equation therefore yields [24];

$$\begin{aligned} \ddot{x} &= \frac{1}{m_q}(\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)u_1 + ds_1 \\ \ddot{y} &= \frac{1}{m_q}(\cos \phi \sin \theta \sin \psi + \sin \phi \cos \psi)u_1 + ds_2 \\ \ddot{z} &= -g + \frac{1}{m_q}(\cos \phi \cos \theta)u_1 + ds_3 \\ \ddot{\phi} &= \dot{\phi}\dot{\theta}\frac{(I_y - I_z)}{I_x} - \frac{J_R}{I_x}\dot{\theta}g(u) + \frac{L}{I_x}u_2 \\ \ddot{\theta} &= \dot{\phi}\dot{\psi}\frac{(I_z - I_x)}{I_y} + \frac{J_R}{I_y}\dot{\phi}g(u) + \frac{L}{I_y}u_3 \\ \ddot{\psi} &= \dot{\phi}\dot{\theta}\frac{(I_x - I_y)}{I_z} + \frac{1}{I_z}u_4 \end{aligned} \quad (2.4)$$

where I_x, I_y, I_z , represent the moment of inertia of the quadrotor. J_R represents the

rotor inertia. The transformed inputs $\mathbf{u} = (u_1, u_2, u_3, u_4)^T$ is given by;

$$\mathbf{u} = \begin{pmatrix} b(f_1^2 + f_2^2 + f_3^2 + f_4^2) \\ b(f_2^2 - f_4^2) \\ b(f_1^2 - f_3^2) \\ d(f_1^2 + f_3^2 - f_2^2 - f_4^2) \end{pmatrix}$$

with $g(\mathbf{u}) = (f_1 - f_3 + f_2 - f_4)$. Each quadrotor ($i = 1, 2$) is divided into two subsystems, the outer and inner loop, $\ddot{\zeta}_i$ and $\ddot{\xi}_i$ comprising the translation and rotational axis respectively. Therefore, equation (2.4) can be written as

$$\begin{aligned} \ddot{\zeta} &= f(\xi, u) + Ds, \text{ and} \\ \ddot{\xi} &= f(\xi) + g(u) \end{aligned} \tag{2.5}$$

where $Ds = [ds_1, ds_2, ds_3]'$, represent external load disturbances. From equation (2.4), the desired angles can be derived as [26];

$$\begin{aligned} \theta_d &= \arctan\left(\frac{u_x \cos \psi_d + u_y \sin \psi_d}{u_z + g}\right) \\ \phi_d &= \arcsin\left(\frac{u_x \sin \psi_d - u_y \cos \psi_d}{\sqrt{(u_x^2 + u_y^2) + (u_z + g)^2}}\right) \end{aligned} \tag{2.6}$$

where u_x, u_y, u_z are the virtual control input to be discussed in subsequent sections.

Table 2.1: Table of parameters for Parrot AR.drone UAV

$m = 0.380[kg]$
$I_x = 9.57e - 3[kgm^2]$
$I_y = 18.57e - 3[kgm^2]$
$I_z = 25.55e - 3[kgm^2]$
$m_l = 0.200[kg]$
$g = 9.81$
$J_R = 2.8385e - 5$
$L = 0.25$
$b = 2.92e - 6[kgm]$
$d = 1.12e - 7[kgm^2]$

2.2 Load model

The cable suspended load carried is modeled as [1];

$$m_l I \ddot{\zeta}_l + G_l = R_l S_l \quad (2.7)$$

where m_l is the load mass, $S_l = [S_1 \ S_2]^T$ and

$$R_L = \begin{pmatrix} \sin\beta_1 \cos\alpha & \sin\beta_2 \cos\alpha \\ \sin\beta_1 \sin\alpha & \sin\beta_2 \sin\alpha \\ \cos\beta_1 & \cos\beta_2 \end{pmatrix}$$

Thus the disturbances on each UAV becomes;

$$Ds_i = \begin{pmatrix} S_i \sin\beta_i \cos\alpha \\ S_i \sin\beta_i \sin\alpha \\ S_i \cos\beta_i + m_l g \end{pmatrix} \quad (2.8)$$

where α is the load lateral oscillation angle and β_i which are formed by the normal axis centered in the load center and the cables, for $S_i(i = 1, 2)$ is the cable tension given by;

$$S_1 = m_l g \frac{\sin \beta_2}{\sin \beta_1 + \beta_2}$$

$$S_2 = m_l g \frac{\sin \beta_1}{\sin \beta_1 + \beta_2}$$

It is important to state that the tension affects the quadrotors only when the it lifts beyond the length of the cable.

2.3 Recurrent Radial Basis Function Neural Network (RBFNN)

It is important to introduce RBFNN because they are used for universal function approximation and they also exhibits fast learning speed. RBFNN has is generally used in adaptive control design [27], [28], [29] for function approximation. Consider the function $G(x) \in R^m$, for m RBFNN nodes, Fig. 2.2. The RBFNN over a compact set $\nabla \in R$ is expressed as:

$$G(x) = M^T \nabla(x) + \epsilon \quad \forall x \subseteq q \quad (2.9)$$

where x is the RBFNN input, $\nabla(x) = [\nabla_1(x_1), \dots, \nabla_m(x_m)]^T$ represents the radial basis function vector. The weight vector and approximation error are represented as

M^T and ϵ respectively, with $M^T \in R^m$ and $\epsilon \leq \epsilon_*$ where ϵ_* is constant represented by

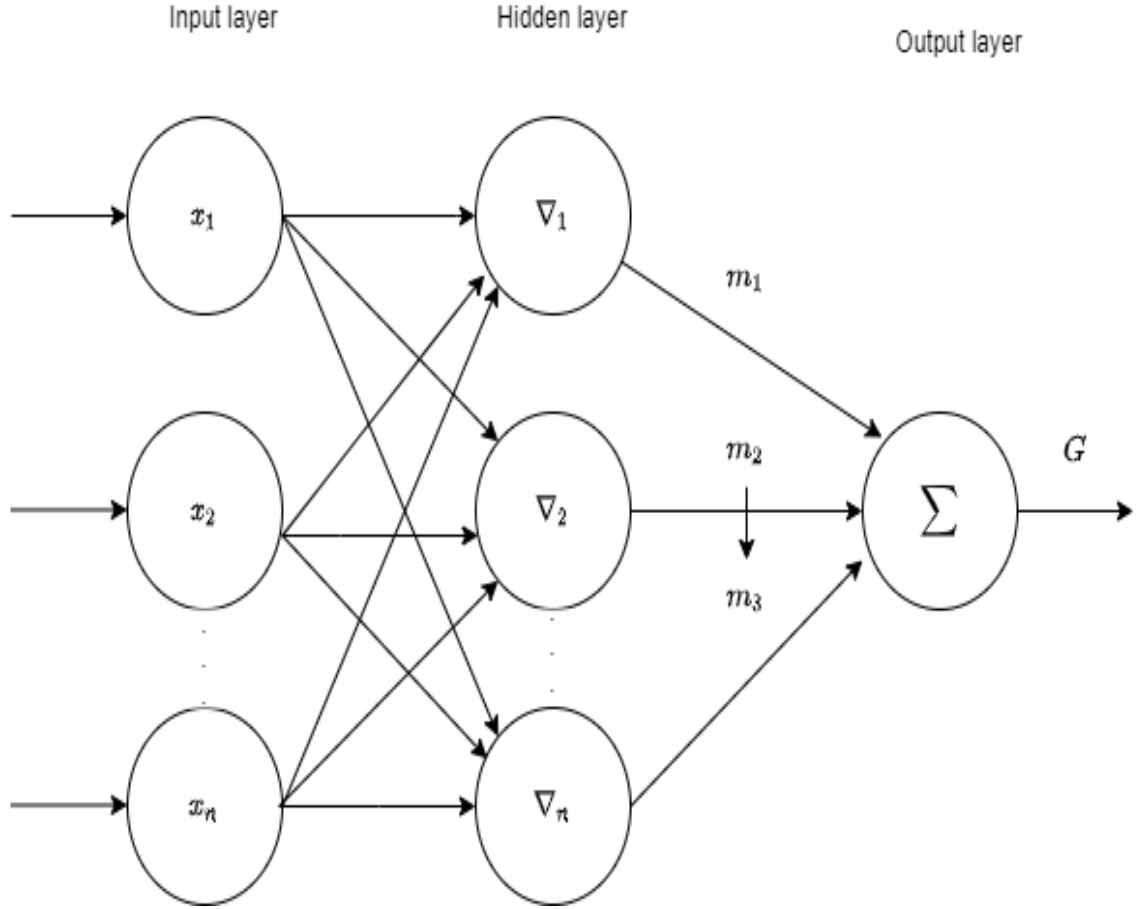
$$M = \begin{pmatrix} M_1 \\ \dots \\ M_m \end{pmatrix} \text{ and } \epsilon = [\epsilon_1, \dots, \epsilon_m]^T$$


Figure 2.2: RBFNN Network Architecture

In neural adaptive control, the following results holds [27];

Fact 2.3.1

The NN estimation error is bounded by $\|\epsilon\| \leq \epsilon_Z$ on a smooth compact set $\Theta \subset R^N$, where ϵ is a fixed bound [30].

Fact 2.3.2

Weierstrass higher-order approximation theorem. Select the activation functions $\nabla(x)$ as a complete independent basis. Then the NN estimation error ϵ converges uniformly to zero on Θ as the number of neurons $\eta_i \rightarrow \infty$, $i = 1, N$

CHAPTER 3

ADAPTIVE FORMATION CONTROL OF MULTI-AGENT QUADROTOR UAVS CONVEYING LOAD WITH OBSTACLE AVOIDANCE

3.1 Abstract

Quadrotor Unmanned Aerial Vehicles (UAVs) are generally underactuated systems and when load is attached for transportation purposes, the system complexity increases. Therefore, the need to appropriately control such systems becomes paramount as they usually navigate in cluttered environments. In this work, we conceptual-

ize the problem of cooperative tracking control for a Multi-agent UAV load system (MUAVLs) whereby each UAV is divided into global position and local attitude subsystems. To ensure that formation is maintained in a desired path, Neural Network Graph-theoretic Distributed Adaptive Control (NNGDAC) is used for the position subsystem with a modified virtual force artificial potential field for obstacle avoidance. Another Adaptive Feedback Linearization (AFBL) controller is also designed for the attitude subsystem which is verified by simulation results.

3.2 Introduction

Over the past few years, unmanned aerial vehicles (UAVs) have been employed in numerous fields for various applications springing from both civilian and military purposes. Examples of such applications are delivery, surveillance, fumigation, traffic monitoring, construction purposes for example pick and place objects, rescue missions, patrolling forests in case of fire outbreak, warfare, and other risky missions [2]. However, the more adapted they are to an environment the more versatile they become. The major advantages of UAVs is that it does not require a particular airfield base and they are free from rugged terrains experienced by ground robots.

A UAV is generally an underactuated system having four inputs but with six degrees of freedom comprising of position and attitude orientation. However, the degrees of freedom increases when two or more UAVs are combined to carry a load as a multi-agent system. Multi-agent UAV-load (MUAVLs) systems are those with more than one UAV concurrently conveying an attached or suspended load. These systems

are highly non-linear in nature and are difficult to characterize due to the complexity their aerodynamics [5]. However, they poses some advantages over single UAV-load system due to their redundancy and ability to carry heavier payloads. Such a system requires a controller for each UAV, a formation strategy and collision avoidance which is paramount for execution of clinical tasks. This is indeed a difficult task given the nature of the system. However, several efforts have been made to address the problems associated with controlling such a system. For example, some linear control techniques such as Proportional, Integral and Differential (PID) [31], [32], [19] have been used to tackle the control complexity. In [31], a null space-based approach was utilized for the formation of two UAVs, whereby a multi-objective task such as collision avoidance, wind perturbation and load weight distribution were catered for with the help of PID/Adaptive and Kinematic formation controller. In [32] similar authors presented an extension with four UAVs. Cooperative transport based on PID control for the system of a four UAV arrangement, whereby the cable force computation is formulated as an optimization problem which was demonstrated in [19]. However, PID controllers are not robust to inherent disturbances that is caused by the load.

Linear Quadratic Regulator (LQR) [33], [34] and Model Predictive Control (MPC) [35] have been used with different MUAVLs system structure for transportation purposes. These methods involves linearization of the system which has some limitations. However, such control methods have been applied. For a MUAVLs system with two UAVs based on Lagrangian model, a combination of LQR/Feedback Linearization (FBL) controllers were used in [36], whereby visual and inertial cues are used as sensing methods to avoid explicit communication between the collaborating robots. Based

on Udwadia–Kalaba modeling method, a LQR-PID was designed for a formulation of MUAVs involving four UAVs by the authors in [23], whereby swing suppression was considered and formation is maintained while guiding the load through a desired path.

The nonlinear control strategy applied are extensively FBL [37]. This strategy was implemented for MUAVs [1], [21], [38], [39]. In [21], a system of 4 UAVs connected to a single load whereby the load’s movable center of mass was considered in a leader follower formation scheme. A coordinate free formation based on was employed in [38] in which a fictitious repulsion force for collision avoidance was introduced between two UAVs cooperatively transporting a load with the aid of a PID and geometric controller. However, repulsive forces could potentially cause oscillation in movement between connected agents. In [39], an MPC based control for a decentralized dual UAV-load system utilizing a magnetic gripper to perform search, pick up, and relocate objects with minimum communication was adopted by means of blob detection, inverse 3D-projection, Kalman filtering and visual-servoing. For a two UAV system, FBL was used for trajectory tracking, load swing suppression and obstacle avoidance whereby potential field is used to maintain inter-agent distance [1]. However, FBL may not be robust against disturbances [40] which are in fact inevitable .

A passivity based formation control strategy with internal feedback control was employed in [41] for three MUAVL. Similar control technique was utilized by the same authors [42], but environmental wind disturbance was considered. In an experimental setup [43], coordinated three MUAVs independently to detect, track, and pick-up moving and static objects using monocular camera images and an EPM gripper whereby a reactive collision avoidance between agents was implemented. In [44],

a cooperative control law is developed to control the motion of two MUAVLs and load swing with the using two PID controllers. In a slung-load dynamics obtained by Newtonian approach with spherical coordinates the authors in [45] implemented parameter-robust Linear quadratic Gaussian / Loop Transfer Recovery (LQG/LTR) to control the position and attitude of all the vehicles and payloads of a dual MUAVLs to showcase the controller’s robustness against variation of payload mass.

Using three MUAVLs in [46], wrench analysis techniques used in traditional cable-driven parallel robots to account for the constraints of quadrotor actuation and dynamics in a bid to demonstrate and evaluate the design and operating configurations. A geometric feedback controller based on relative and inertial formation for 6 UAVs was adopted to track the yaw angle, cable orientation and a reference trajectory for the load’s position and orientation in [20], however, geometric control has only been applied to cases where the number of are greater than two. In order to avoid singularities and complexities associated with local parameters, a coordinate free dynamical model was used. Another cascade control with decoupled attitude from the rest of the system was used in [22] but obstacle avoidance was not considered.

Load disturbance affects the UAVs which is already input handicapped, and concurrently containing load swing increases its complication. According to [47], it is mandatory to use some form of hierarchical control to handle the disturbances generated by the interaction of the vehicles and the load while they are moving. Thus, the main contribution of this includes;

1. Building a relationship between the position error of the MUAVLs based on the

NNGDAC to generate inter-agent collision free trajectory.

2. Decoupling the MUAVs into two subsystems, translational and rotational and designing a NNGDAC which is robust to load disturbance while maintaining inter-agent distance for the translational subsystem. An AFBL is also utilized to control the rotational subsystem.
3. Obstacle avoidance using a modified artificial potential field with a virtual force.

In summary, the following objectives are to be achieved;

1. Maintain inter-agent collision free formation pattern.
2. Track the desired trajectory.
3. Load disturbance rejection/Load swing suppression.
4. Obstacle avoidance.

Our approach ensures oscillation free movement between the two UAVs carrying load unlike the methods in [31] in which undesirable oscillation between agents is glaring which can lead to collision, destruction and hence termination of a mission. In [1], a simplified model of a UAV was utilized in a MUAVs but potential field method was used to maintain inter-agent collision avoidance. However, this may lead to oscillation due to the conflict that results between attractive/repulsive forces. To ensure formation behaviors are robust against undesired side effect of the repulsive forces, H_∞ analysis was implemented by considering repulsive forces as the disturbance inputs [48] but oscillation between agents was still glaring in addition to the fact that

a linearized system was utilized. However, UAVs were not utilized neither did the authors consider load swings. Conventional flocking algorithms [1] induces oscillation as evident in the results presented in [49], however load disturbances or obstacle avoidance were not considered also.

3.3 Directed Graph Theory

Consider a simple directed graph $G = (V, E)$ with a nonempty finite set of vertices or nodes (whereby each quadrotor translational subsystem for each is a vertice ζ_{ij}) $V = \zeta_{ij}$ and a finite set of edges $E \subseteq V \times V$. The laplacian matrix is given by $L = D - A$, where the diagonal in-degree matrix D is given by $D = \text{diag}\{d_i\}$ with $d_i = \sum_j a_{ij}$ and the adjacency matrix A , as $A = [a_{ij}]$ with $a_{ij} = 1$ if $(v_i, v_j) \in E$ and $a_{ij} = 0$ otherwise. Consider the graph represented Fig 2., $L = \begin{pmatrix} 0 & 0 \\ -1 & 1 \end{pmatrix}$.

Remark 3.3.1 *When the graph is strongly connected, its Laplacian matrix L is an irreducible singular Z - matrix and $\text{rank}(L) = N - 1$ [27].*

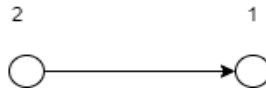


Figure 3.1: Graph of both agents

3.4 Control Design

It is desired to maintain inter-agent distance and avoid inter-agent collision. However, the multi-system is underactuated and has strong coupling. Cooperatively carrying

a load inline helps to suppress swing in the direction of movement when the load is between the leader and follower [47]. The control block diagram is shown in Fig. 3.2, which could be scaled to accommodate more than two UAVs.

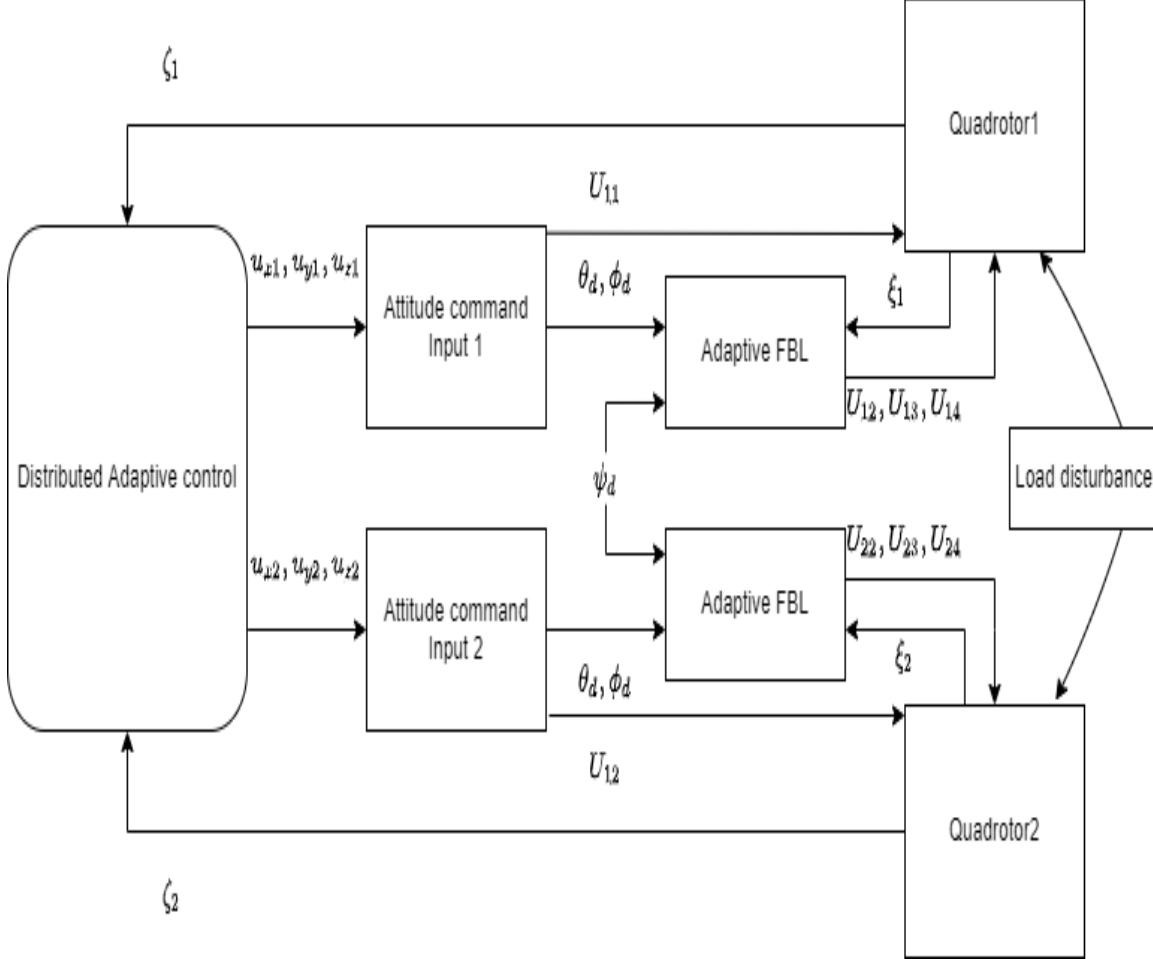


Figure 3.2: Control Schematic

3.4.1 NNGDAC for Trajectory Tracking

To generate the desired acceleration trajectory in the presence of external and load disturbances whereby, inter-agent collision is avoided, it becomes intuitive to adopt a DAFBL. This concept stems from [26], where a proportional-differential control

methodology was used for a single quadrotor uav without load and [50], [51], [52] where multi-UAV is considered without load and obstacle avoidance also. Recall that the translational axis constitute the network which is affected by the load dynamics. Let $\ddot{x}_{ji} = \ddot{\zeta}_{ji}$ be the graph dynamics for any one of the quadrotors. Consequently, in order to generate the virtual inputs, we therefore formulate the global dynamics of both quadrotor system to be governed by the Brunovsky form;

$$\begin{aligned}\dot{x}_{1i} &= x_{2i} \\ \dot{x}_{2i} &= \mathbf{h}(x) + u_{\zeta_i} + ds\end{aligned}\tag{3.1}$$

where the state vector is given by $x = [x_{1i} \ x_{2i}]^T$, position vector is given by $x_{1i} = [x_{11} \ x_{12} \ \dots \ x_{1N}]^T \in R^N$, the velocity vector as $x_{2i} = [x_{21} \ x_{22} \ \dots \ x_{2N}]^T \in R^N$, the global dynamics $\mathbf{h}(x) = [h_1(x_1) \ h_2(x_2) \ \dots \ h_N(x_N)]^T \in R^N$. $u_{\zeta_i} = [u_1 \ u_2 \ \dots \ u_N]^T \in R^N$, $ds_i = [ds_1 \ ds_2 \ \dots \ ds_N]^T \in R^N$ input and disturbance respectively.

The external load disturbances is ds and unknown nonlinearities is $h(x)$ and $u_{\zeta_i} = (u_x, u_y, u_z)$ represents the this distributive adaptive auxiliary inputs. Whereas the step command or reference generator captured by;

$$\begin{aligned}\dot{x}_{1r} &= x_{2r} \\ \dot{x}_{2r} &= h_r(x_r, t)\end{aligned}\tag{3.2}$$

where $x_{1r} = [x_{1r} \ x_{2r}]^T \in R^2$. It is desirable for both UAVs to maintain the same altitude. Since $R^T = R^{-1}$, from (1), the total thrust for each UAV will be now given

by;

$$R(m + m_i/2)(\ddot{x}_i + g \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}) = T \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (3.3)$$

It is desired that the control protocol synchronizes the states so as to maintain a safe distance between agents, consider the following assumptions [27], [53]:

Assumption 3.4.1 *The load disturbance ds_i is bounded for all i . Thus the overall disturbance vector Ds is also bounded by $\|Ds\| \leq Ds_Z$ with Ds_Z being a fixed bound.*

Assumption 3.4.2 *Unknown ideal NN weight matrix M is bounded by $\|M\|_H \leq M_Z$.*

Assumption 3.4.3 *NN activation functions ∇ are bounded by $\forall i$, so that one can write for the overall network that $\|\nabla\| \leq \nabla_Z$*

Assumption 3.4.4 *The unknown consensus variable dynamics $\|(h_r(x_r, t))\| \leq H_Z, \forall t$ respectively.*

Assumption 3.4.5 *The target trajectory is bounded so that $\|x_r(t)\| < X_r(t), \|x_{2r}(t)\| < X_{2r}(t), \forall t$.*

Theorem 3.4.1 *Distributed Adaptive Control Protocol for Synchronization. Consider the networked systems given by (3.1) under the Assumptions 4.1 - 4.5. The communication digraph being strongly connected. Select the auxiliary control signal so that the local node control protocols are given by:*

$$u_{\zeta_i} = kq_i - \hat{h}(x_i) + \frac{\rho_i}{d_i + b_i} e_2 \quad (3.4)$$

k is the control gain, the adaptive tuning law is taken as;

$$\dot{\hat{M}}_j = -H_i \nabla_i r_i (ds_i + b_i) - \delta H_i \hat{M}_i \quad (3.5)$$

where the local neighborhood synchronization position and velocity errors for each UAV are given by [54];

$$\begin{aligned} e_{1i} &= \sum_{j \in N_i} a_{ij} (x_{1j} - x_{1i}) + b_i (x_{1r} - x_{1i}) - \eta_{(x,y)}, \\ e_{2i} &= \sum_{j \in N_i} a_{ij} (x_{2j} - x_{2i}) + b_i (x_{2r} - x_{2i}) \end{aligned} \quad (3.6)$$

respectively, with the pinning gain $b_i \geq 0$, and $b_i > 0$ for at least one i and $\eta_{(x,y)} = \text{norm}(\zeta_i)$ specifies inter-agent distance in 2-D. The consensus disagreement error vector is given by;

$$\varphi = \begin{bmatrix} \varphi & \dot{\varphi} \end{bmatrix}^T = \begin{bmatrix} x_{1i} - \underline{1}x_{1r} & x_{2i} - \underline{1}x_{2r} \end{bmatrix}^T$$

where $\underline{1} \in R^N$ is the vector of ones. The global error dynamics may be described as;

$$\begin{aligned} e_1 &= -(\tilde{L}) \begin{pmatrix} x_{1i} - \underline{1}x_{1r} \end{pmatrix} = -(\tilde{L})\varphi \\ e_2 &= -(\tilde{L}) \begin{pmatrix} x_{2i} - \underline{1}x_{2r} \end{pmatrix} = -(\tilde{L})\dot{\varphi} \end{aligned} \quad (3.7)$$

where $\tilde{L} = L + B$, $B = \text{diag}(b_i)$ is a diagonal matrix consisting the pinning gains and $e_i \in R^N$ and $e_{2i} \in R^N$, $\forall i$.

Lemma 3.4.1 *For a strongly connected graph where $B \neq 0$, let*

$$\|\varphi\| \leq \frac{\|e_1\|}{\underline{\sigma}(\tilde{L})}, \quad \text{and} \quad \|\dot{\varphi}\| \leq \frac{\|e_2\|}{\underline{\sigma}(\tilde{L})}$$

where $\underline{\sigma}(\tilde{L})$ is the minimum singular value of $(\tilde{L})$ and $e = \eta$ if the nodes synchronizes.

Lemma 3.4.2 *The velocity vector bounded by*

$$\|e_2\| \leq \|r\| + \bar{\sigma}(\boldsymbol{\rho}) \|e_1\|$$

To minimize the consensus disagreement error and ensure synchronization is reached we will define the sliding mode tracking error given by:

$$q_i = e_{2i} + \rho e_{1i} \tag{3.8}$$

where, $\rho_i = \text{diag}(\rho) > 0, \forall i$. Now differentiating (3.8), yields

$$\dot{q}_i = e_{22i} + \rho_i \dot{e}_{1i} \tag{3.9}$$

Differentiating (4.42) yields;

$$e_{21} = -(\tilde{L}) \left(\dot{x}_{2i} - \underline{1}x_{2r} \right)$$

$$e_{22} = -(\tilde{L}) \left(\dot{x}_{2i} - \underline{1}h_r(x_r, t) \right)$$

Therefore,

$$\begin{aligned} \dot{q}_i &= -(\tilde{L})(h(x) + u_{\zeta_{ij}} + ds_i) \\ &\quad + (\tilde{L})h_r(x_r, t) + \rho_i e_{2i} \end{aligned} \tag{3.10}$$

We assume that the unknown nonlinearities in are smooth and thus can be approximated on a compact set $Y \in R$ by equation (2.9), this implies that;

$$h(x) = M^T \nabla(x) + \epsilon \tag{3.11}$$

we therefore, select the local node's approximation as;

$$\hat{h}(x) = \hat{M}^T \nabla(x) \tag{3.12}$$

Therefore, the global error dynamics becomes;

$$\dot{q}_i = - \left(\tilde{L} \right) \left(\hat{h}(x) + u_{\zeta_{ij}}(t) + Ds \right) + \left(\tilde{L} \right) \underline{1}h_r(x_r, t) + \boldsymbol{\rho}e_2 \tag{3.13}$$

so, considering equation (3.4), the global control input becomes;

$$u_{\zeta_{ij}} = kq - \hat{M}\nabla(x) + \frac{\boldsymbol{\rho}}{D+B}e_2$$

$$\dot{q} = -\left(\tilde{L}\right)\left(\tilde{h}(x) + kq + Ds\right) - \left(\tilde{L}\right)\frac{\boldsymbol{\rho}_{ij}}{d_{1j} + b_{ij}}e_2 + \left(\tilde{L}\right)\underline{1}h_r(x_r, t) + \boldsymbol{\rho}e_2 \quad (3.14)$$

where $\tilde{h}(x) = h(x) - \hat{h}(x) = \tilde{M}\nabla(x)$ which gives current weight estimate for each individual weight, whereby the weight estimation error gives;

$$\tilde{M} = \text{diag}(M_1 - \hat{M}_1, M_2 - \hat{M}_2, \dots, M_N - \hat{M}_N)^T$$

recall that $L = D - A$, therefore,

$$\dot{q} = -\left(\tilde{L}\right)\left(\tilde{h}(x) + kq + Ds\right) + \left(\tilde{L}\right)\underline{1}h_r(x_r, t) + A\left(\tilde{D}\right)^{-1}\boldsymbol{\rho}e_2 \quad (3.15)$$

where $\tilde{D} = D + B$. Consider the Lyapunov function;

$$V = \frac{1}{2}q^T P q + \frac{1}{2}\tilde{M}^T H^{-1} \tilde{M} + \frac{1}{2}(e_1)^T e_1 \quad (3.16)$$

where $P = P^T > 0$ and $H^{-1} = H^{-T}$ is a constant matrix therefore the derivative of the Lyapunov function becomes;

$$\dot{V} = q^T P \dot{q} + \text{tr} \left\{ \tilde{M}^T H^{-1} \dot{\tilde{M}} \right\} + (e_1)^T e_2 \quad (3.17)$$

Therefore, substituting (4.14), and (3.15), in (4.22)

$$\begin{aligned}\dot{V} = & -q^T P(\tilde{L}) \left(\tilde{M}^T \nabla(x) + \epsilon + Ds + kq \right) + q^T P(\tilde{L}) \underline{1} h_r(x_r, t) + q^T P A(\tilde{D})^{-1} \rho e_2 \\ & + tr \left\{ \tilde{M}^T H^{-1} \dot{\tilde{M}} \right\} + (e_1)^T e_2\end{aligned}\quad (3.18)$$

$$\begin{aligned}\dot{V} = & -kq^T P(\tilde{L}) q - q^T P(\tilde{L}) \left\{ \epsilon + Ds - \underline{1} h_r(x_r, t) \right\} + q^T P A(\tilde{D})^{-1} \rho e_2 \\ & + tr \left[\tilde{M}^T \left(H^{-1} \dot{\tilde{M}} - \nabla(x) q^T P(\tilde{L}) \right) \right] + (e_1)^T q - (e_1)^T \rho e_1\end{aligned}\quad (3.19)$$

from (3.8),

$$\begin{aligned}\dot{V} = & -kq^T P(\tilde{L}) q - q^T P(\tilde{L}) \left\{ \epsilon + Ds - \underline{1} h_r(x_r, t) \right\} + q^T P A(\tilde{D})^{-1} \rho (q - \rho e_1) \\ & + tr \left[\tilde{M}^T \left(H^{-1} \dot{\tilde{M}} - \nabla(x) q^T P(\tilde{L}) \right) \right] + (e_1)^T q - (e_1)^T \rho e_1\end{aligned}\quad (3.20)$$

but $\tilde{L} = \tilde{D} - A$

$$\begin{aligned}\dot{V} = & -kq^T P(\tilde{L}) q - q^T P(\tilde{L}) \left\{ \epsilon + Ds - \underline{1} h_r(x_r, t) \right\} \\ & + tr \left[\tilde{M}^T \left(H^{-1} \dot{\tilde{M}} - \nabla(x) q^T P(\tilde{D}) \right) \right] \\ & + tr \left[\tilde{M}^T \nabla(x) q^T P A \right] + q^T P A(\tilde{D})^{-1} \rho q - q^T P A(\tilde{D})^{-1} \rho^2 e_1 \\ & + (e_1)^T q - (e_1)^T \rho e_1\end{aligned}\quad (3.21)$$

Lemma 3.4.3 [55]. *Since $\tilde{L}$ nonsingular Z matrix, the following holds*

$$q = \begin{bmatrix} q_1 & q_2 & \cdots & q_N \end{bmatrix}^T = \left(\tilde{L} \right)^{-1} \underline{1}$$

$$P = \text{diag} \{p_i\} \equiv \text{diag} \{1/q_i\}$$

Then $P > 0$ and the symmetric positive definite matrix Q is given by;

$$Q = P(\tilde{L}) + (\tilde{L})^T P \quad (3.22)$$

recall that L is irreducible and $b_i > 0$, so from Lemma 4.3,

$$\begin{aligned} \dot{V} = & -\frac{1}{2}kq^T Qq - q^T P \left(\tilde{L} \right) \left\{ \epsilon + Ds - \underline{1}h_r(x_r, t) \right\} \\ & + \text{tr} \left[\tilde{M}^T \left(H^{-1} \dot{\tilde{M}} - \nabla(x) q^T P \left(\tilde{D} \right) \right) \right] \\ & + \text{tr} \left[\tilde{M}^T \nabla(x) q^T P A \right] + q^T P A \left(\tilde{D} \right)^{-1} \boldsymbol{\rho} q \\ & - q^T P A \left(\tilde{D} \right)^{-1} \boldsymbol{\rho}^2 e_1 + (e_1)^T q - (e_1)^T \boldsymbol{\rho} e_1 \end{aligned} \quad (3.23)$$

where $Q = Q^T > 0$. Now applying (3.5) and taking the norm of both sides yields

$$\begin{aligned}
\dot{V} \leq & -\frac{1}{2}k\underline{\sigma}(Q) \|q\|^2 + \bar{\sigma}(P) \bar{\sigma}(\tilde{L}) H_Z \|q\| + \delta M_Z \|\tilde{M}\|_H - \delta \|\tilde{M}\|_H^2 \\
& + \phi_Z \bar{\sigma}(P) \bar{\sigma}(A) \|\tilde{M}\|_H \|q\| + \frac{\bar{\sigma}(P) \bar{\sigma}(A) \bar{\sigma}(\rho)}{\underline{\sigma}(\tilde{D})} \|q\|^2 \\
& + \left(1 + \frac{\bar{\sigma}(P) \bar{\sigma}(A) \bar{\sigma}(\rho^2)}{\underline{\sigma}(\tilde{D})}\right) \|q\| \|e_1\| - \underline{\sigma}(\rho) \|e_1\|^2
\end{aligned} \tag{3.24}$$

where $T_Z = Ds_Z + \epsilon_Z + H_Z$, maximum and minimum singular values of a matrix Z is denoted by $\bar{\sigma}(Z)$ and $\underline{\sigma}(Z)$ respectively and $\|Z\|_N = \sqrt{\text{tr}\{Z^T Z\}}$ with $\text{tr}\{\cdot\}$.

$$\begin{aligned}
\dot{V} \leq & - \begin{bmatrix} \|e_1\| & \|q\| & \|\tilde{M}\|_H \end{bmatrix} \cdots \\
& \cdots \begin{bmatrix} \underline{\sigma}(\rho) & \frac{1}{2} \left(1 + \frac{\bar{\sigma}(P)\bar{\sigma}(A)\bar{\sigma}(\rho^2)}{\underline{\sigma}(\tilde{D})}\right) & 0 \\ \frac{1}{2} \left(1 + \frac{\bar{\sigma}(P)\bar{\sigma}(A)\bar{\sigma}(\rho^2)}{\underline{\sigma}(\tilde{D})}\right) & \left(\frac{1}{2}k\underline{\sigma}(Q) - \frac{\bar{\sigma}(P)\bar{\sigma}(A)\bar{\sigma}(\rho)}{\underline{\sigma}(\tilde{D})}\right) & \frac{1}{2}\phi_L \bar{\sigma}(P) \bar{\sigma}(A) \\ 0 & \frac{1}{2}\phi_L \bar{\sigma}(P) \bar{\sigma}(A) & \delta \end{bmatrix} \begin{bmatrix} \|e_1\| \\ \|q\| \\ \|\tilde{M}\|_H \end{bmatrix} \cdots \\
& \cdots + \begin{bmatrix} 0 & \bar{\sigma}(P) \bar{\sigma}(\tilde{L}) T_Z & \delta M_Z \end{bmatrix} \begin{bmatrix} \|e_1\| \\ \|q\| \\ \|\tilde{M}\|_H \end{bmatrix}
\end{aligned} \tag{3.25}$$

which can be re-written as;

$$\dot{V} \leq -s^T C s + c^T s \quad (3.26)$$

As we can see $\dot{V} \leq 0$ iff $C \geq 0$, so

$$\|s\| > \frac{\|c\|}{\underline{\sigma}(C)} \quad (3.27)$$

Based on the Lyapunov equation, for $\dot{V} \leq 0$, therefore (4.27) becomes

$$\dot{V} \leq - \underbrace{\begin{bmatrix} \|e_1\| & \|q\| & \|\tilde{M}\|_H \end{bmatrix}}_C \begin{bmatrix} \rho & 1 & 0 \\ 1 & \rho & \gamma \\ 0 & \gamma & \delta \end{bmatrix} \begin{bmatrix} \|e_1\| \\ \|q\| \\ \|\tilde{M}\|_H \end{bmatrix} + \begin{bmatrix} 0 & \bar{\sigma}(P) & \bar{\sigma}(\tilde{L}) & T_Z & \delta W_M \end{bmatrix} \begin{bmatrix} \|e_1\| \\ \|q\| \\ \|\tilde{M}\|_H \end{bmatrix}$$

Since singular values are equivalent to eigen values, for symmetric positive definite matrix, $C \geq 0$ we select, $\boldsymbol{\rho} = \rho I, \rho = \sqrt{\frac{\alpha(\tilde{D})}{\bar{\sigma}(P)\bar{\sigma}(A)}}$, $k = \frac{2}{\alpha(Q)} \left(\frac{1}{\rho} + \rho \right) > 0$, and $\gamma = \frac{1}{2} \nabla_m \bar{\sigma}(P) \bar{\sigma}(A)$.

According to Geršhgorin circle's theorem; $\underline{\sigma}(C) \geq \delta - \gamma$ with $0 < \gamma \leq \delta \leq \rho - 1$. Hence, $s(t)$ is UUB. Consequently, $\|s\|_1 \geq \|s\|_2 \geq \dots \geq \|s\|_\infty$ with sufficient

conditions;

$$\|q\| > \frac{T_Z \bar{\sigma}(P) \bar{\sigma}(\tilde{L}) + \delta M_Z}{\delta - \frac{1}{2} \nabla_m \bar{\sigma}(P) \bar{\sigma}(A)} \quad (3.28)$$

or

$$\|e_1\| > \frac{T_Z \bar{\sigma}(P) \bar{\sigma}(\tilde{L}) + \delta M_Z}{\delta - \frac{1}{2} \nabla_m \bar{\sigma}(P) \bar{\sigma}(A)} \quad (3.29)$$

or

$$\|\tilde{M}\| > \frac{T_Z \bar{\sigma}(P) \bar{\sigma}(\tilde{L}) + \delta M_Z}{\delta - \frac{1}{2} \nabla_m \bar{\sigma}(P) \bar{\sigma}(A)} \quad (3.30)$$

which also shows UUB of $q(t)$, $e_1(t)$, $\tilde{M}(t)$. Therefore, from Lemma 4.1, the boundedness of q and e_1 implies bounded e_2 . Now Lemma 4.1 shows that the consensus error vector $\varphi(t)$ is UUB. Hence $xr(t)$ is cooperative UUB.

3.4.2 Attitude Control Design

Adaptive control methods have been applied for solving such problems relating uncertainty of parameters in several dynamic model, [56], [57], [58], [59]. Considering the coupling nature of UAVs, it becomes intuitive to apply adaptive control methods to mitigate the effect of such uncertainties which might affect the attitude dynamics during flight [40]. Consequently, an AFBL is utilized to control of each UAV attitude

subsystem ξ_i . Consider the attitude subsystem

$$\ddot{\xi}_i = f(\xi) + gu \quad (3.31)$$

let, $u = g^{-1}(-f(\xi) + \rho + \chi)$. Substituting u in (3.31) gives

$$\ddot{\xi}_i = \rho_s + \chi \quad (3.32)$$

where χ is the lumped uncertainties induced. The error dynamics is given by;

$$e_\xi = \dot{\xi}_d - \dot{\xi} \quad (3.33)$$

let

$$\tilde{\chi} = \hat{\chi} - \chi \quad (3.34)$$

be the unknown parameter error which is the error between the lumped uncertainty (χ) , and its estimated value ($\hat{\chi}$), an appropriate Lyapunov function can be defined as:

$$V = \frac{1}{2}e_\xi^2 + \frac{1}{2}\nu\tilde{\chi}^2 \quad (3.35)$$

where ν is the adaptation gain. Therefore;

$$\dot{V} = e_\xi \dot{e}_\xi + \nu \tilde{\chi} \dot{\tilde{\chi}}$$

let the virtual input $\rho = \ddot{\xi}_d - \dot{\hat{\chi}} + k e_\xi$. Therefore,

$$\dot{V} = -k e_\xi^2 + \tilde{\chi} (e_\xi + \nu \dot{\tilde{\chi}})$$

for $\dot{V} \leq 0$, $k > 0$ and the adaptation gain is thus,

$$\dot{\tilde{\chi}} = -\nu^{-1} e_\xi \tag{3.36}$$

3.5 Obstacle Avoidance

Obstacle avoidance is a key feature for UAVs moving in a cluttered environment. However, conventional potential field methods used for obstacle avoidance developed for ground robots, are not suitable for aerial vehicles due to their fast movement and inherent instability [60]. We therefore utilize a modified repulsive potential with virtual force E whenever there is an obstacle in the path of the MUAVS, defined as [61];

$$O_a = \sum_{i=1}^2 E_i \tag{3.37}$$

where

$$E = \begin{cases} E_{rep}(\zeta) + E_{vir}(\zeta) & \rho \leq \rho_{obs} \\ 0 & \rho > \rho_{obs} \end{cases}$$

where

$$E_{rep}(\zeta) = -K_e \left(1 - \frac{\rho}{\rho_{obs}}\right) \left(\frac{\zeta_{obs} - \zeta}{\rho^3}\right)$$

$$E_{vir}(\zeta) = -K_{vir} \frac{1}{\rho}$$

where $-K_e$ and $-K_{vir}$ are constants. ρ_{obs} is the quadrotor minimal distance which has a repulsive effect must be greater than the inter-agent distance, i.e ($\rho_{obs} > \eta_{(x,y)}$) to avoid conflict. The distance between the quadrotor and the obstacle is given by;

$$\rho = \sqrt{(\zeta - \zeta_{obs})^2}$$

3.6 Simulation Results and Discussion

We utilized UAV parameter values for Parrot AR.Drone given in table 2.1 [1]. To demonstrate the effectiveness of the control algorithm, we present simulation results for the system firstly without obstacle avoidance. Both UAVs are kept apart with a initial positions $\zeta = [0, 0, 0]$ and $\zeta = [1, 0, 0]$ for the leader and follower respectively while final was position specified as $\zeta = [15, 15, 15]$.

Fig. 3.3 shows position of the MUAVL during trajectory tracking without activat-

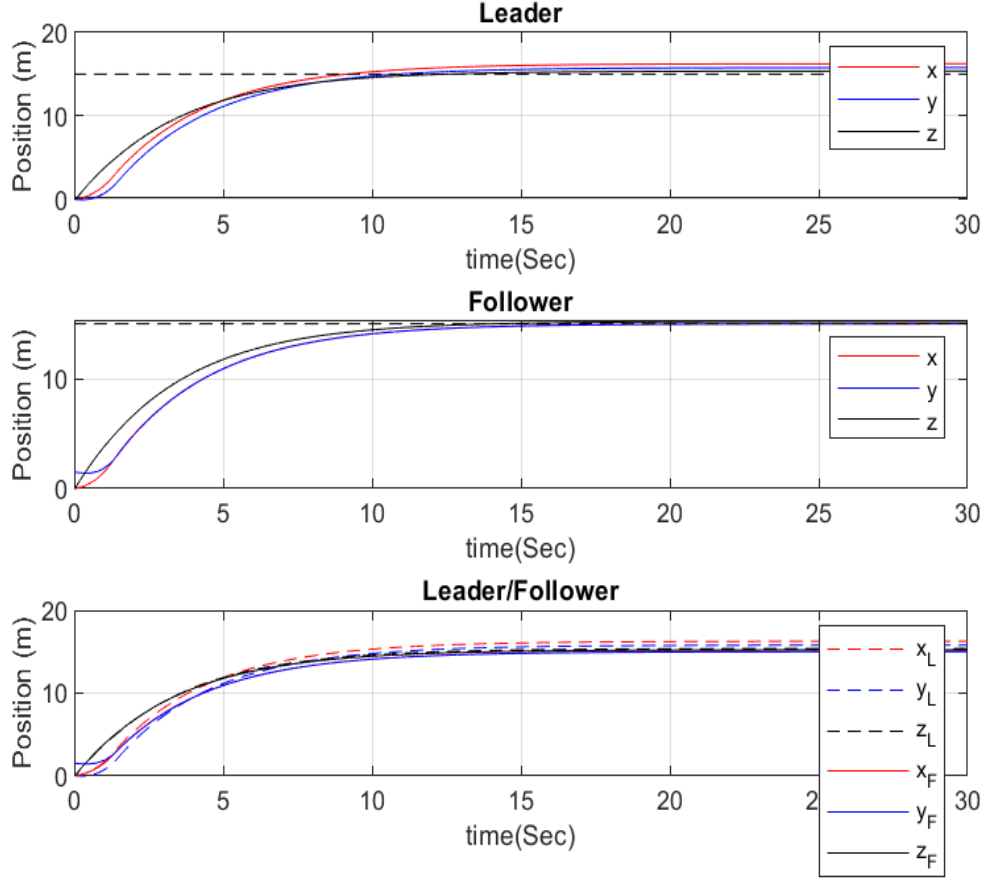


Figure 3.3: Trajectory of leader-follower

ing obstacle avoidance. Evidently, our proposed strategy can effectively maintain as safe distance between agent while containing the disturbance and hence load swing. Attitude tracking is also achieved, Fig. 3.4.

Obviously, there is a negligible orientation tracking error which could be improved upon in future. Fig. 3.5 shows that inter-agent distance between the leader and follower is maintained. The load angles are shown in Fig. 3.6, with $\beta_1 = 30^\circ$, and $\beta_2 = 33.6^\circ$ of the follower to the horizontal. The discrepancy emanating from the a slight difference in height which is also negligibly small and does not compromise the aim of this work. However, with $\alpha = 48.6^\circ$ to the vertical, due to the fact that the

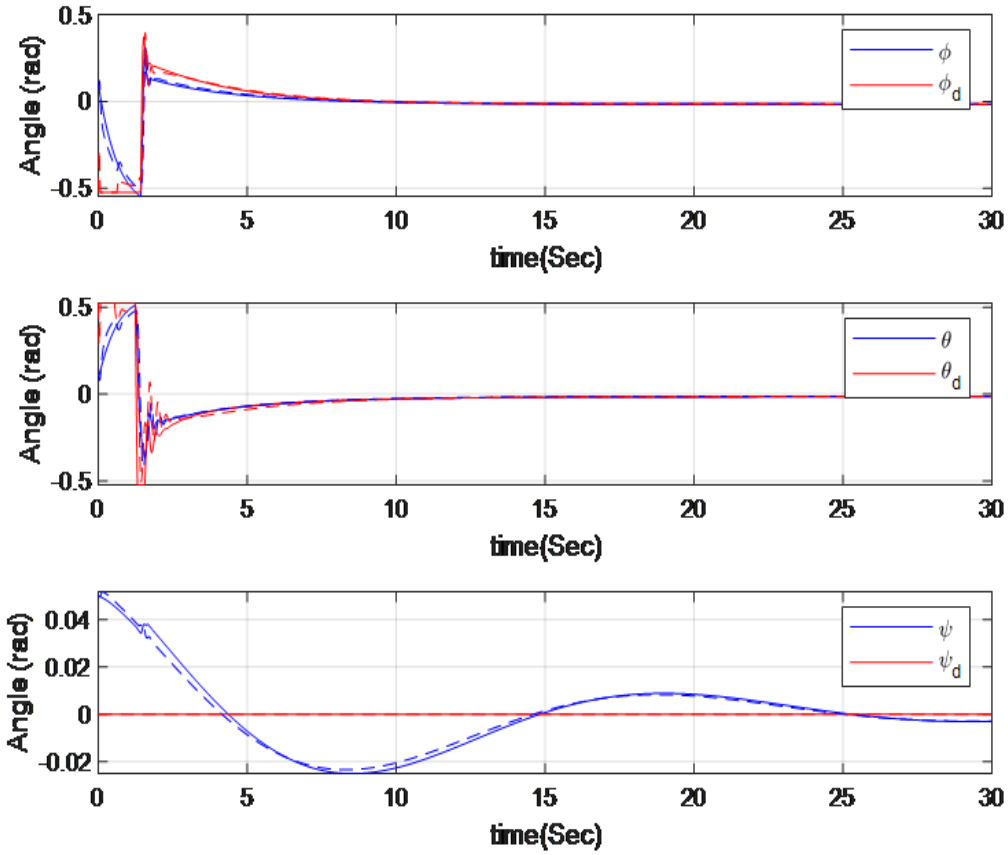


Figure 3.4: Leader-Follower Orientation Angles

follower is not directly behind the leader UAV. A 3-D plot is shown for visual purpose, Fig. 3.7.

To demonstrate obstacle avoidance, an obstacle is placed at a point centered at $\zeta_{obs} = [8.2, 7.4, 9]$ in the path of the MUAVLs. Fig. 3.8 shows the position trajectory tracking when the obstacle avoidance is activated. Note that the leader deviates slightly while the follower also deviates sufficiently enough such that the inter-agent distance is not compromised. Evident in Fig. 3.9, the inter-agent distance between the leader and follower are maintained. Attitude orientation angles of the leader and follower are shown in Fig. 3.10 with a 3-D plot of the position in Fig. 3.11 for visual

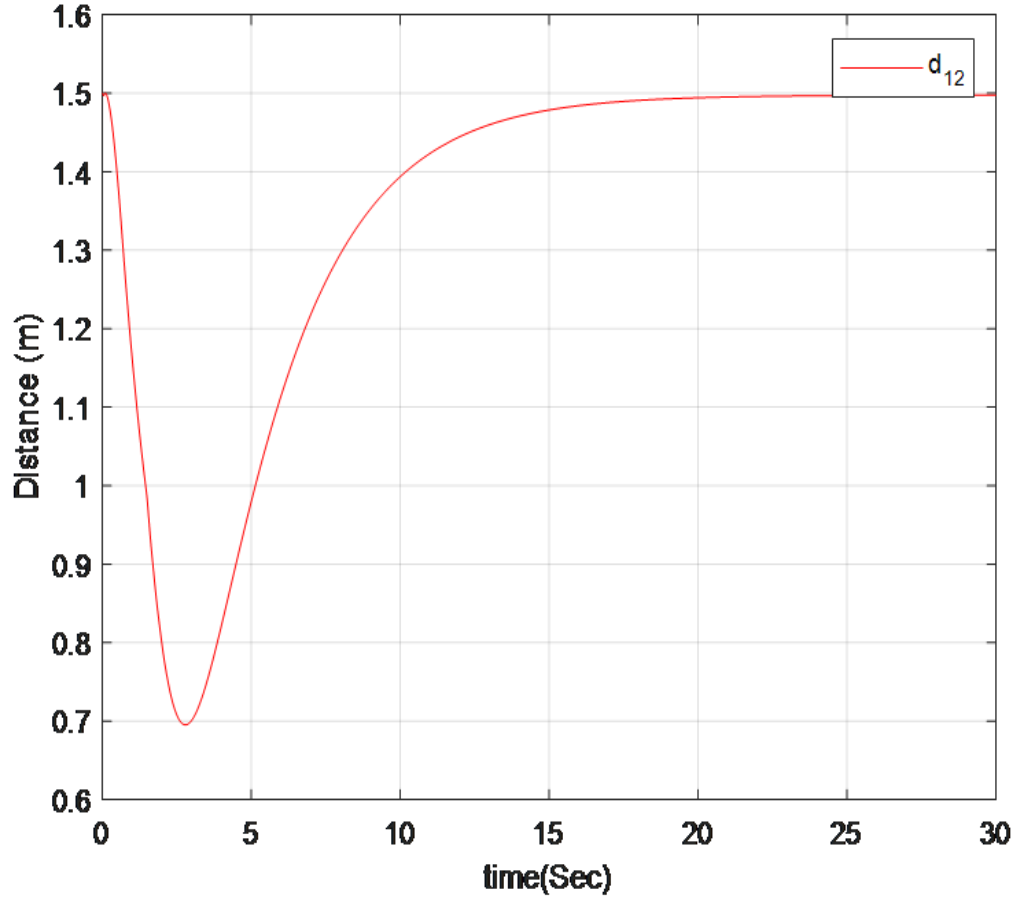


Figure 3.5: Inter-agent distance

purpose. As can be seen in Fig. 3.12, the load angles are maintained after a slight disturbance due to obstacle avoidance.

3.7 Conclusion

A Neural Network Graph-theoretic Distributed Adaptive Control (NNGDAC) algorithm which is equipped with a modified virtual force artificial potential field for obstacle avoidance is used for tracking a Multi-agent UAV Load system (MUAVLs) in the presence of load disturbances. A local Adaptive Feedback Linearization (AFBL)

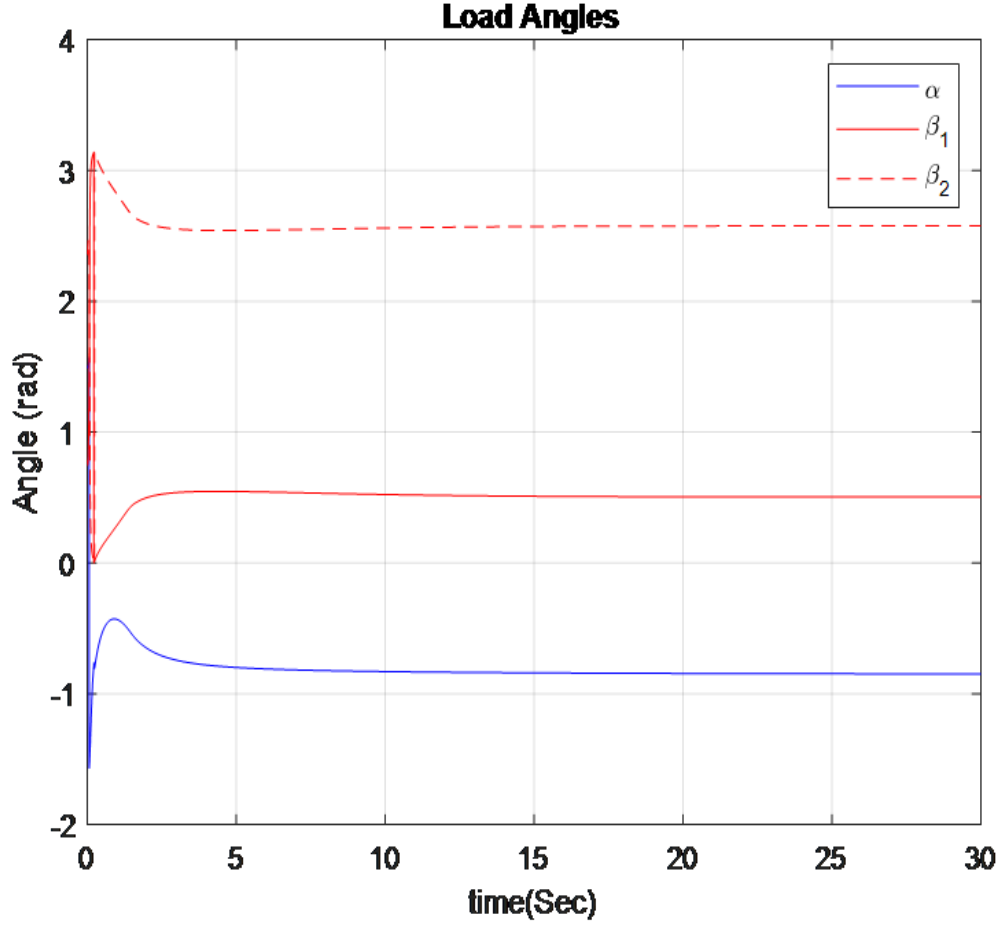


Figure 3.6: Load Orientation Angles

controller is also designed for the rotational axis which is verified by simulation results. However, tilt-wing/rotor UAVs are generally fully actuated, therefore, there is need to investigate how additional input could be utilized to cater for inherent problems associated with MUAVs to reduce control complexity. Our future work includes investigating actuator fault in the development of a fault tolerant controller.

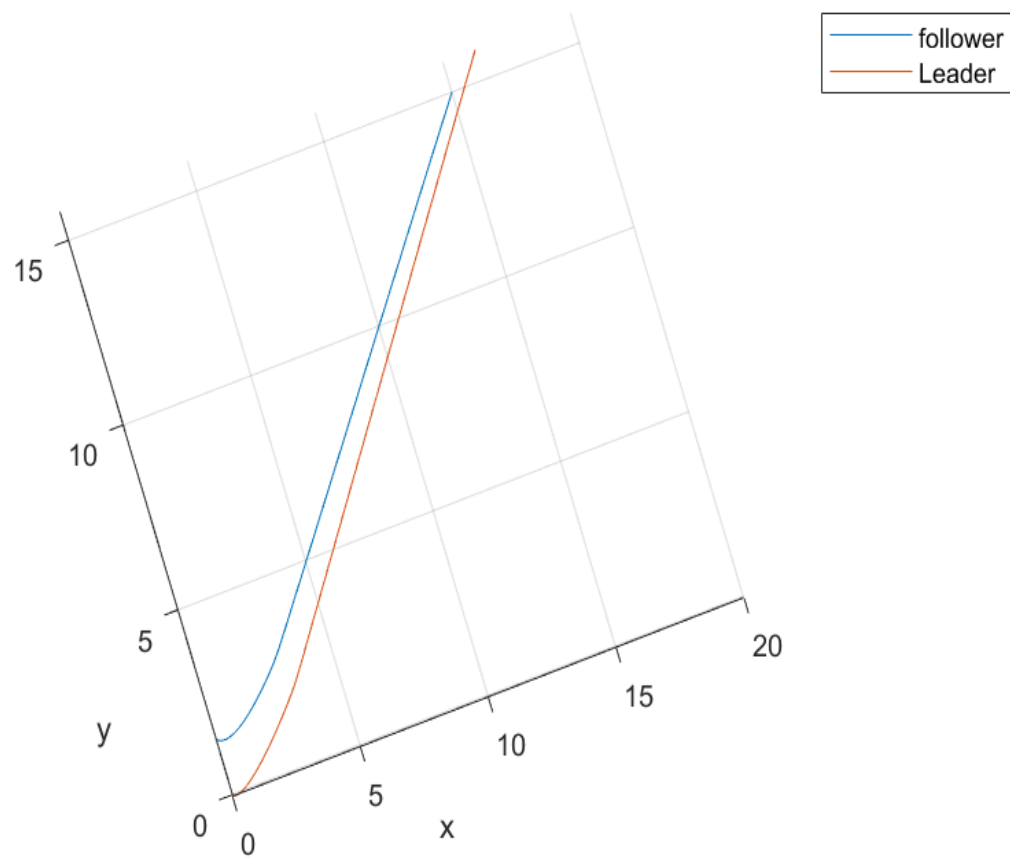


Figure 3.7: 3-D Plot

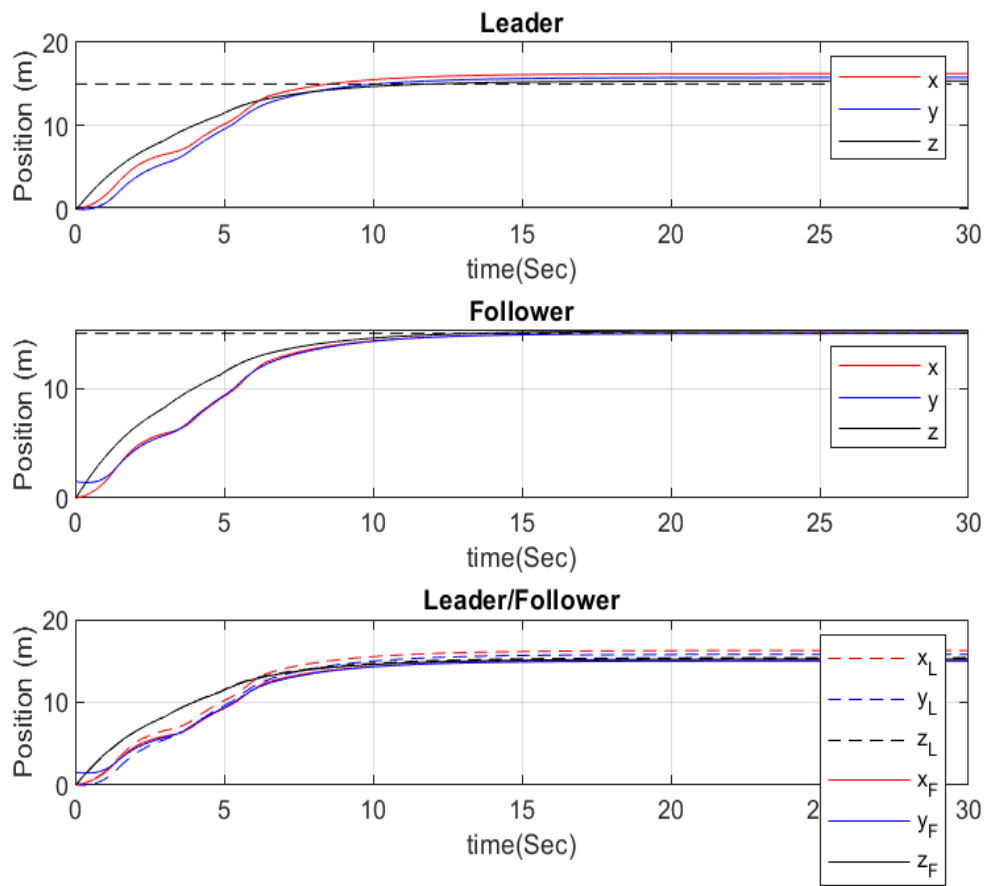


Figure 3.8: Trajectory of leader-follower

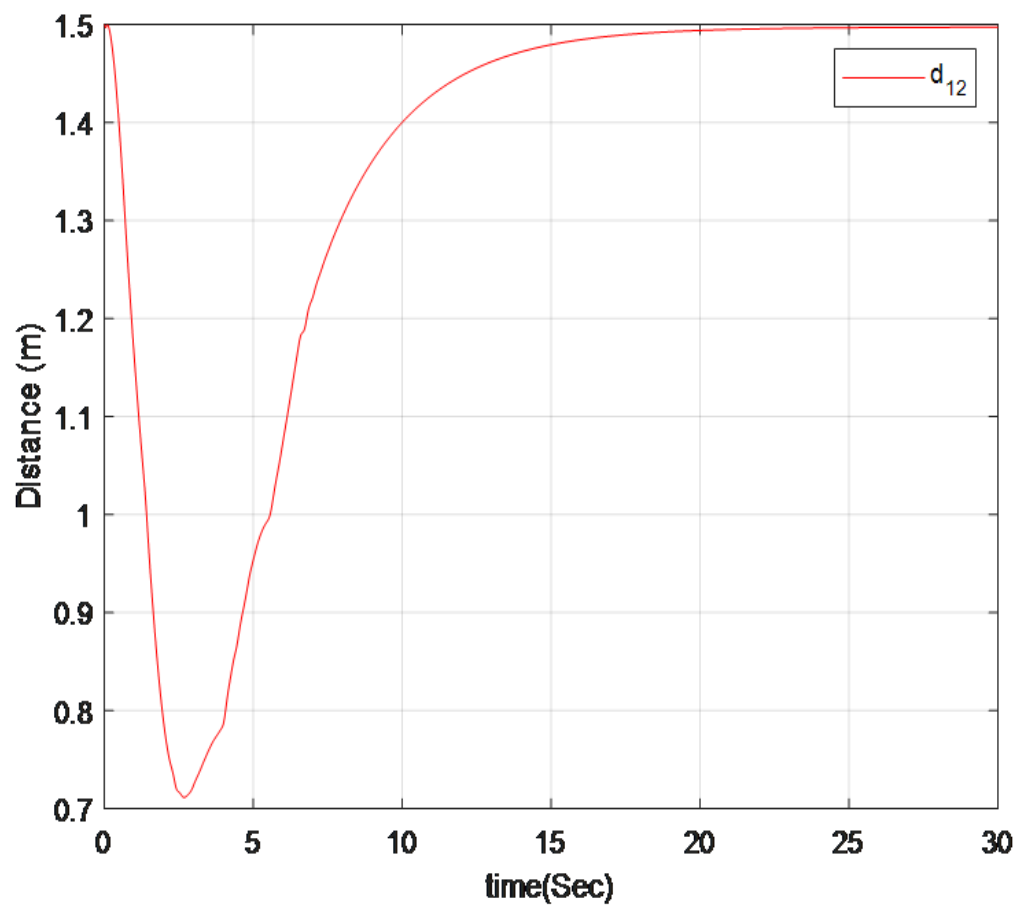


Figure 3.9: Inter-agent distance

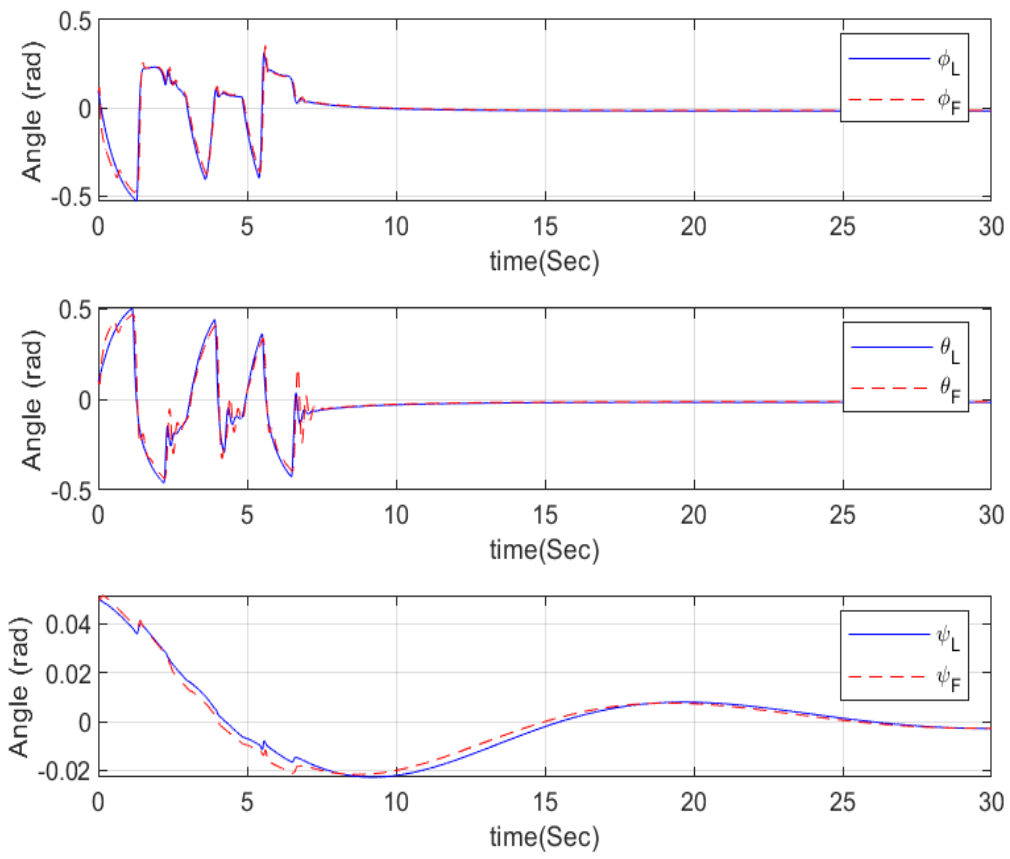


Figure 3.10: Leader-Follower Orientation Angles

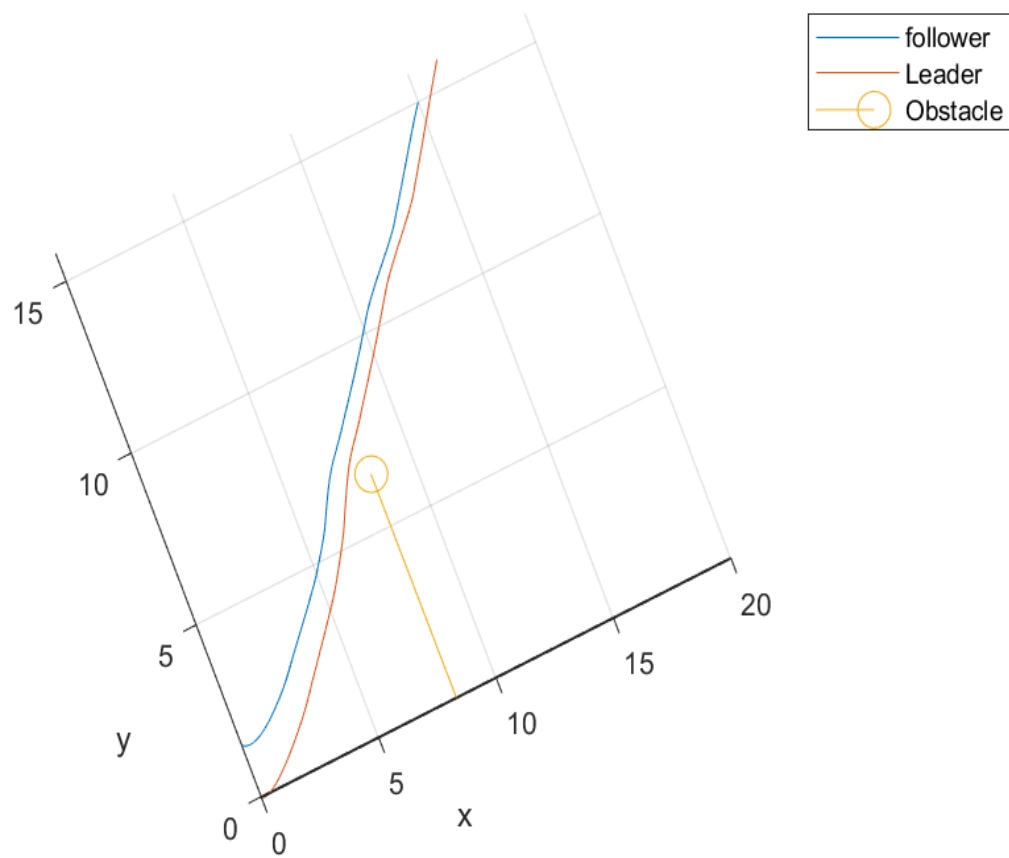


Figure 3.11: 3-D Plot

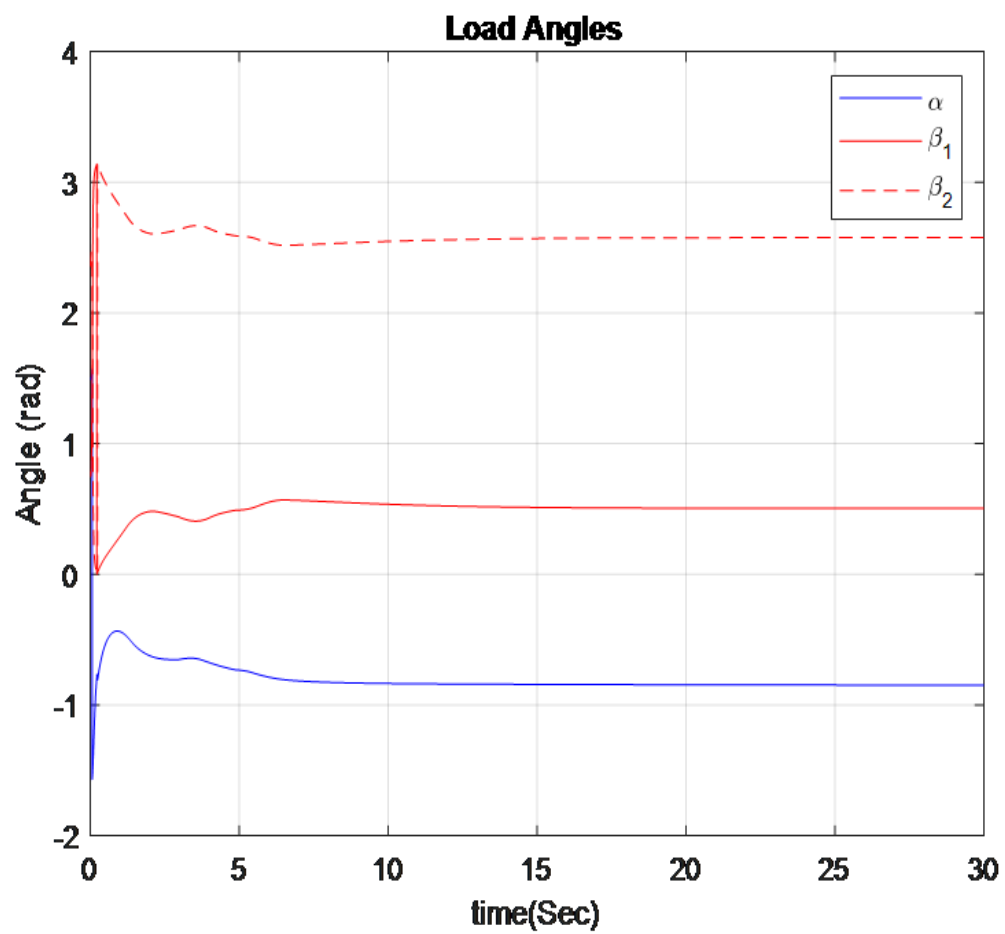


Figure 3.12: Load Orientation Angles

CHAPTER 4

BACKSTEPPING ADAPTIVE FORMATION CONTROL OF MULTI-AGENT QUADROTOR UAVS CONVEYING LOAD

4.1 Abstract

Quadrotor Unmanned Aerial Vehicles (UAVs) are highly nonlinear and underactuated in nature as they possess fewer control inputs than control variables. A combination of multiple UAVs conveying single load is complex but it offers some advantages due to its complimentary nature, as such, heavier loads can be conveyed compared to using single UAVs. Consequently, the need to avoid inter-agent collision necessitates the use of multi-agent control strategies in the presence of load disturbances. Therefore,

in this work a Multi-agent UAV-Load system (MUAVLs) comprising dual-UAV with a single load is broken into altitude/position and attitude subsystem dynamics. To ensure that formation is maintained in a desired path, using rigid graph theory, an Adaptive Backstepping Multi-agent Control (ABMC), based on Lyapunov theory is designed for the position subsystem in the presence of load disturbances. Furthermore, another Backstepping Finite-time Sliding Mode Control (BFSMC) is designed for the attitude subsystem which is verified by simulation.

4.2 Introduction

Over the past few years, unmanned aerial vehicles (UAVs) have been employed in numerous fields for various applications springing from both civilian and military purposes. Examples of such applications are delivery, surveillance, fumigation, traffic monitoring, construction purposes for example pick and place objects, rescue missions, patrolling forests in case of fire outbreak, warfare, and other risky missions[2]. However, the more adapted they are to an environment the more versatile they become. The major advantages of UAVs are that they do not require a particular airfield base and they are free from rugged terrains experienced by ground robots.

A UAV is generally an underactuated system having four inputs but with six degrees of freedom. However, the degrees of freedom increases when two or more UAV is combined to carry a load as a multi-agent. A multi-agent UAV-Load (MUAVLs) systems are those with more than one UAV conveying an attached or suspended load. These systems are highly non-linear in nature and are difficult to characterize due

to the complexity of their aerodynamics [5]. However, they possess some advantages over single UAV-load system due to their redundancy and ability to carry heavier payloads. Nevertheless, such a system requires a controller for each UAV, a formation strategy/collision avoidance due to interactions between both agents which can be modelled by either a directed or undirected graph. Fewer measurements and higher interactions among agents is associated with distance-based which is described by graph rigidity in contrast to the predominantly used displacement and position based formation control, modeled by connectedness (Graph Laplacian) [62].

However, progress is being made to address the control problems associated with a MUAVLs. For example, some linear control techniques such as Proportional, Integral and Differential (PID) [31], [32], [19] was used to tackle the control complexity. Linear Quadratic Regulator (LQR) [33], [34], Model Predictive Control (MPC) [35], a combination of LQR/Feedback Linearization (FBL) [36], and LQR-PID in [23], have also been used with different MUAVLs structure for load transportation purposes. However, in addition to the limitation of linearizing a system, the performance of PID controllers generally deteriorates with disturbances.

However, other control techniques have been developed such as a passivity based formation control strategy with internal feedback control was employed in [41]. Similar control technique was utilized by the same authors [42], but environmental wind disturbance was considered. In an experimental setup [43], coordinated three MUAVLs independently to detect, track, and pick-up moving and static objects using monocular camera images and an EPM gripper whereby a reactive collision avoidance between agents was implemented. In a Newtonian based slung-load dynamics obtained by ap-

proach with spherical coordinates, the authors in [45] implemented parameter-robust Linear quadratic Gaussian / Loop Transfer Recovery (LQG/LTR) to control the position and attitude of all the vehicles and payloads of a dual MUAVs to showcase the controller's robustness against variation of payload mass. Using three MUAVs in [46], wrench analysis techniques used in traditional cable-driven parallel robots to account for the constraints of quadrotor actuation and dynamics in a bid to demonstrate and evaluate the design and operating configurations. A geometric feedback controller based on relative and inertial formation for 6 UAVs was adopted to track the yaw angle, cable orientation and a reference trajectory for the load's position and orientation in [20], whereby, a coordinate free dynamical model in order to avoid singularities and complexities associated with local parameters. Another cascade control with decoupled attitude from the rest of the system was used in [22].

The nonlinear control strategy applied are extensively FBL for multiple UAVs with suspended load [21], [38], [39], [1], [44]. However, FBL may not be robust against disturbances [40] which are in fact inevitable especially when dealing with case of MUAVs. Furthermore, load disturbance affects the UAVs which is already input handicapped, and concurrently containing load swing increases its complication. According to [47], it is mandatory to use some form of hierarchical control to handle the disturbances generated by the interaction of the vehicles and the load while they are moving. This implies the suitability of nonlinear control techniques considering the nonlinear nature of the MAUVs. Nonlinear control techniques are attractive due to their ease of realization, faster response and good transient. However, some nonlinear control techniques such as Backstepping Control (BS) and Sliding Mode

Control (SMC) are yet to be adopted in the control MUAVs. Recently, combining the functionality of both control methods is gaining attention due to its robustness [63], [64], [65]. It is important to mention that the combination of both controllers is superior to classical sliding mode control, integral backstepping and second order sliding mode controls [66].

1. Relative control of MUAVs based on the (ABMC) to generate inter-agent collision free trajectory.
2. Decoupling the MUAVs into two subsystems, translational and rotational and designing a ABMC which is robust to load disturbance while maintaining inter-agent distance for the translational subsystem. A BFSMC is also utilized to control the rotational subsystem.

In summary, the following objectives are to be achieved;

1. Maintain inter-agent collision free formation pattern.
2. Track the desired trajectory.
3. Load disturbance rejection/Load swing suppression.

Our approach ensures oscillation free movement between the two UAVs carrying load unlike the methods in [31],[1], [48], or conventional flocking algorithms [67]. To ensure formation behaviors to be robust to the undesired side effect of the repulsive force, without load attachment, H_∞ analysis was implemented by considering repulsive forces as the disturbance inputs [48] but oscillation between agents was still glaring.

However, in [1] an incomplete model of the UAV was utilized, with repulsive potential field which is unsuitable and causes oscillation between agents, in addition to the fact that feedback linearization controller used is not robust against disturbances.

4.3 Undirected Graph Theory

Consider a undirected graph $G = (V, E)$ with a nonempty finite set of vertices or nodes (whereby each UAV translational subsystem is a vertex ζ_{ij}) V with a finite set of edges $E \subseteq V \times V$ specified by the inter-agent distance. A d-dimensional framework F is a pair (G, f) where $f = (f_1, \dots, f_n) \in R^d$, $d \in [2, 3]$ is the position of vertex i in 2 or 3 dimensional space [68]. Consider the MUAVLs Figure 2.1, where the two UAVs are represented by a class of Laman graph, Figure 4.1, implying connectivity which can be established by LiDAR technology or by some other means. More details on graph rigidity can be found in [69],[11].

Lemma 4.3.1 [11] *A framework in 2D, with $N \geq 2$ is infinitesimally rigid, iff $\text{rank}(S_x) = 2N - 3$, where S_x denotes the rigidity matrix of graph G .*

Lemma 4.3.2 [70] *For a vector $h_r \in R^2$ and identity vector 1_N , then $S_x(1_N \otimes h_r) = 0_{|E|}$.*

Lemma 4.3.3 *For infinitesimally and minimally rigid framework in 2D, the diagonal elements of $\bar{S}_x \bar{S}_x^T$ are equal to one.*

Proof. [Proof of Lemma 3] Motivated by [71], for a normalized rigidity matrix, let $\bar{S}_x(i, :)$ be an arbitrary row given by $[0, \dots, \bar{S}_{2m-1,n}, \bar{S}_{2m,n}, \dots, 0]$, where the consecu-

tive elements are given by $\bar{S}_{2m-1,n} = x_{mn}/\sqrt{x_{mn}^2 + y_{mn}^2}$ and $\bar{S}_{2m,n} = y_{mn}/\sqrt{x_{mn}^2 + y_{mn}^2}$ respectively. It follows that $\bar{S}_x(i,:) \bar{S}_x^T(i,:) = (\bar{S}_{2m-1,n}^2 + \bar{S}_{2m,n}^2) = 1$ ■

Theorem 4.3.1 *Furthermore, if interaction between the UAVs is modelled by an undirected, infinitesimally and minimally rigid graph depicted in Figure (4.1), then normalized rigidity matrix has a minimum singular value upper bounded by 1.*

Proof. [Proof of Theorem 1] For an N vertices normalized rigidity matrix, according to Lemma 1 - 3 , where $\lambda_i(S_x)$ denotes the minimum i^{th} eigen value. Considering any matrix $\sum Z_i = tr(Z)$ then $\sum \lambda_i \bar{S}_x = (2N - 3)tr(S_x)$. Since $\bar{S}$ is positive definite, then, $(2N - 3)\underline{\lambda}\bar{S} \leq (2N - 3)$, hence $\underline{\lambda}\bar{S}_x \leq 1$ ■



Figure 4.1: Graph representation of both UAV

4.4 Control Design

It is desired to maintain inter-agent distance and avoid inter-agent collision. However, the multi-system is underactuated and has strong coupling. Cooperatively carrying a load inline helps to suppress swing in the direction of movement when the load is between the leader and follower [47]. The control block diagram is shown in Fig. 4.2, which could be scaled to accommodate more than two UAVs.

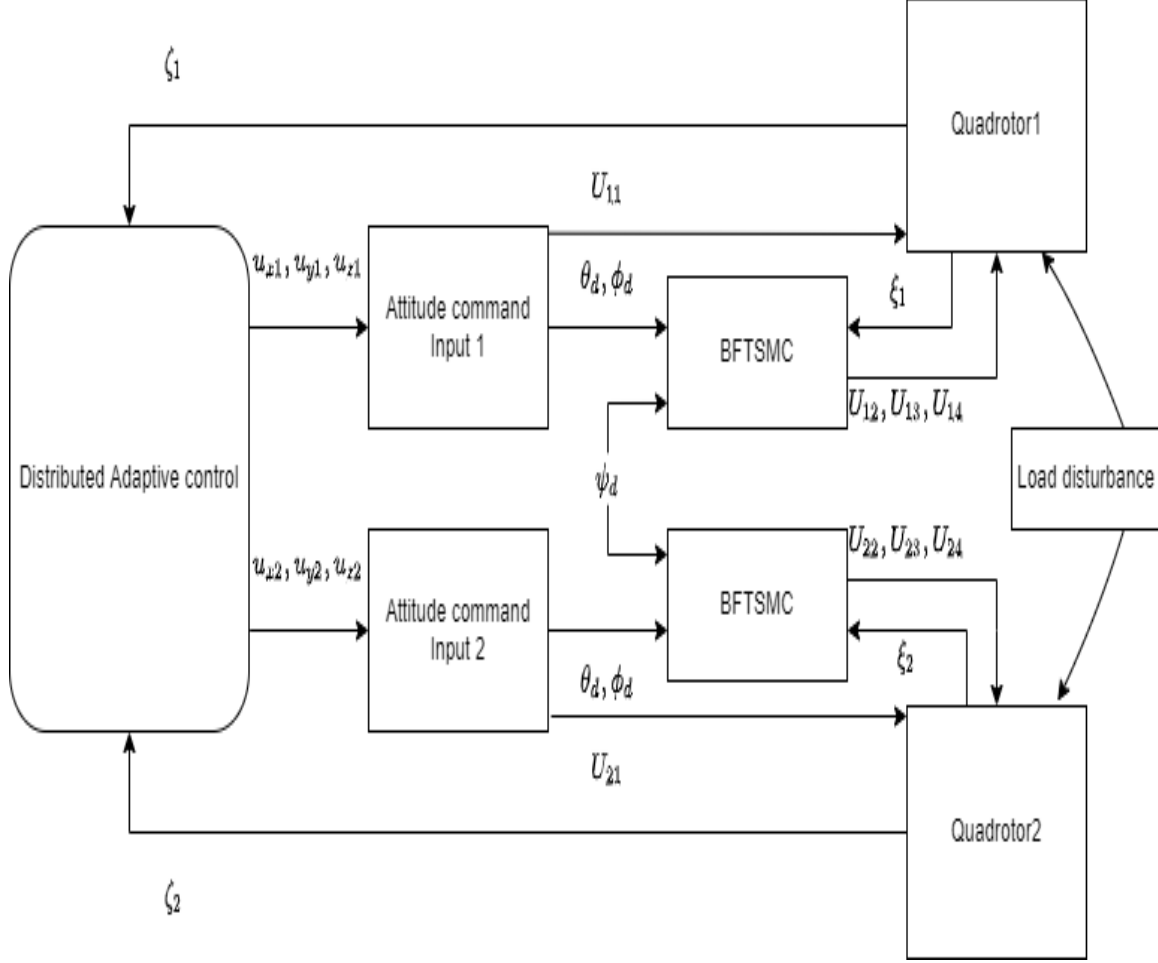


Figure 4.2: Control Schematic

4.4.1 Distributed Backstepping Control (DBSC) for Trajectory Tracking

To generate the desired acceleration trajectory in the presence of external and load disturbances whereby, inter-agent collision is avoided, it becomes intuitive to adopt a DBSC based on graph rigidity framework. Translational dynamic may be considered as a double integrator system, a concept stems from [26], where a proportional-differential control methodology was used for a single quadrotor UAV without load and [50], [51] where multi-UAV is considered without load and obstacle avoidance also. We consider

the translational axis constitutes an unknown nonlinearity which is affected by the load dynamics. Let $\ddot{x}_{ji} = \ddot{\zeta}_{ji}$ be the graph dynamics for any one of the quadrotors. Consequently, in order to generate the virtual inputs, we therefore formulate the global dynamics of both quadrotor system to be governed by the Brunovsky form;

$$\begin{aligned}\dot{x}1_i &= x2_i \\ \dot{x}2_i &= \mathbf{h}(x) + u_{\zeta_i} + Ds\end{aligned}\tag{4.1}$$

where the state vector is given by $x = [x1_i \ x2_i]^T$, position vector is given by $x1_i = [x1_1 \ x1_2 \dots x1_N]^T \in R^N$, the velocity vector as $x2_i = [x2_1 \ x2_2 \dots x2_N]^T \in R^N$, the global dynamics $\mathbf{h}(x) = [h_1(x) \ h_2(x) \dots h_N(x)]^T \in R^N$. $u_{\zeta_i} = [u_1 \ u_2 \dots u_N]^T \in R^N$, $ds_i = [ds_1 \ ds_2 \dots ds_N]^T \in R^N$ input and disturbance respectively. The external load disturbances is ds and unknown nonlinearities is $h(x)$ and $u_{\zeta_i} = (u_x, u_y, u_z)$ represents the this distributive adaptive auxiliary inputs. Whereas the step command or reference generator captured by;

$$\begin{aligned}\dot{x}1_1 &= x2_r \\ \dot{x}2_r &= h_r(x_r, t)\end{aligned}\tag{4.2}$$

where $x_r = [x1_r \ x2_r]^T \in R^2$. It is desirable for both UAVs to maintain the same altitude. Since $R^T = R^{-1}$, from (1), the total thrust for each UAV will be now given

by;

$$R(m + m_i/2)(\ddot{x}_i + g \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}) = T \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (4.3)$$

It is desired that the control protocol synchronizes the states so as to maintain a safe distance between agents, consider the following assumptions [27]:

Assumption 4.4.1 *The load disturbance ds_i is bounded for all i . Thus the overall disturbance vector ds_i is also bounded by $\|Ds\| \leq D_Z$ with D_Z being a fixed bound.*

Assumption 4.4.2 *Unknown ideal NN weight matrix M is bounded by $\|M\|_H \leq M_Z$*

.

Assumption 4.4.3 *NN activation functions ∇ are bounded by $\forall i$, so that one can write for the overall network that $\|\nabla\| \leq \nabla_Z$*

Assumption 4.4.4 *The target trajectory is bounded so that $\|x1_r(t)\| < X_0(r), \|x2_r(t)\| < X_{2t}(t), \forall t$.*

recall that the subscript i, j denote agent neighbors. $x1$ is position and $\dot{x} = x2$ is the velocity. Then, the distance error for the MUAVLs given modeled by an undirected graph is given by [11]

$$e_{ij} = \|x1_{ij}\| - d_{ij} \quad (4.4)$$

where $x1_{ij} = x1_i - x1_j$ specifies interagent distance. According to Figure 4.1, agent 1 is the leader tracks the desired target, whereas it is expected that the distance between UAV 1 and UAV 2 converges to a the desired distance d_{ij} . Hence the tracking error $e_r = x1_r - x1_i$ with $e_r = [e1_r, e2_r]^T$ in x and y direction so that $\dot{e}_r = x2_r$. Differentiating 4.4 gives the distance error dynamics which can be given as;

$$\dot{e}_{ij} = \frac{x1_{ij}^T(\dot{x}1_i - \dot{x}1_j)}{\|x1_{ij}\|} = \frac{x1_{ij}^T(x2_i - x2_j)}{e_{ij} + d_{ij}} \quad (4.5)$$

we choose the Lyapunov function as;

$$V_1 = \frac{1}{2} \sum_{ij \in N} e_{ij}^2 \quad (4.6)$$

Therefore;

$$\dot{V}_1 = \sum_{ij \in N} \Xi(e) \frac{x1_{ij}^T(x2_i - x2_j)}{e_{ij} + d_{ij}} = \Xi(e) S_x \mathbf{x}_2$$

with $\Xi(e) = (\dots, e_{ij}, \dots) \in R^N$ for $(i, j) \in E$. Using backstepping technique [70], let $\mathbf{c} = \mathbf{x}_2 - \sigma$, where σ is an auxiliary variable given by;

$$\sigma = v_\sigma + \mathbf{1} \otimes (x2_r + K_e e_r) \quad (4.7)$$

where $v_\sigma = -k_v S_x^T \Xi(e)$, and k_v, k_e are positive constants. S_x^T is given by $S_x^T =$

$\sum_{ij \in N} \frac{x1_{ij}}{\|x1_{ij}\|}$. Therefore,

$$\mathbf{c}_i = x2_i + k_v \sum_{ij \in N} \frac{x1_{ij}}{\|x1_{ij}\|} (e_{ij}) - (x2_r + K_e e_r) \quad (4.8)$$

v_σ ensures that the desired formation is achieved, while $x2_r + K_e e_r$ helps to maintain tracking of the target by the leader and followers. Let us define a second Lyapunov function;

$$V = V_1 + V_2 \quad (4.9)$$

where $V_2 = \frac{1}{2} \mathbf{c}^T \mathbf{c}$, therefore

$$V = V_1 + \frac{1}{2} \mathbf{c}^T \mathbf{c}$$

and

$$\begin{aligned} \dot{V} &= \Xi(e) S_x \mathbf{x}_2 + \mathbf{c}^T \dot{\mathbf{c}} \\ &= \Xi(e) S_x (\mathbf{c} + \sigma) + \mathbf{c}^T [\dot{\mathbf{x}}_2 - \dot{\sigma}] \\ &= \Xi(e) S_x \sigma + \mathbf{c}^T [\Xi(e) S_x + \dot{\mathbf{x}}_2 - \dot{\sigma}] \\ &= -k_v \Xi(e) S_x S_x^T \Xi(e) + \mathbf{c}^T [\Xi(e) S_x + \mathbf{h}(x) + u_\zeta + Ds - \dot{\sigma}] \\ &= -k_v \Xi(e) S_x S_x^T \Xi(e) + \sum_{i=1}^N c_i^T \left[\frac{x1_{ij}}{\|x1_{ij}\|} (e_{ij}) + h_i(x) + u_{\zeta_i} + ds_i - \dot{\sigma}_i \right] \end{aligned} \quad (4.10)$$

From Assumption 1, and Young's inequalities, we can have;

$$c_i^T ds_i \leq \frac{1}{2} + \frac{\|c_i\|^2 D z_i^2}{2} \quad (4.11)$$

substituting (4.11) into (4.10) results in

$$\dot{V} \leq -k_v \Xi(e) S_x S_x^T \Xi(e) + \sum_{i=1}^N c_i^T \left[\frac{x_{1ij}}{\|x_{1ij}\|} (e_{ij}) + h_i(x) + u_{\zeta_i} + \frac{\|c_i\|^2 D z_i^2}{2} - \dot{\sigma}_i \right] + \frac{N}{2} \quad (4.12)$$

$$\dot{V} \leq -k_v \Xi(e) S_x S_x^T \Xi(e) + \sum_{i=1}^N c_i^T \left[\frac{x_{1ij}}{\|x_{1ij}\|} (e_{ij}) + J(x_i, c_i) + u_{\zeta_i} - \dot{\sigma}_i \right] + \frac{N}{2} \quad (4.13)$$

where $J(x_i, c_i) = h_i(x) + \frac{\|c_i\| D z_i}{2}$ which can be approximated by equation (2.9).

This implies that;

$$J(x_i, c_i) = M^T \nabla(x_i, c_i) + \epsilon \quad (4.14)$$

we therefore, select the local node's approximation as;

$$\hat{J}(x_i, c_i) = \hat{M}^T \nabla(x_i, c_i) \quad (4.15)$$

where $M - \hat{M} = \tilde{M}$ gives the estimate error for each individual weight, whereby

the weight estimation error matrix is;

$$\tilde{M} = \text{diag}(M_1 - \hat{M}_1, M_2 - \hat{M}_2, \dots, M_N - \hat{M}_N)^T$$

We therefore propose the control law;

$$u = -k_s c_i - \hat{J}^T(x_i, c_i) - \sum_{ij \in N} \frac{x1_{ij}}{\|x1_{ij}\|} (e_{ij}) + \rho \quad (4.16)$$

where ρ is given by;

$$\rho = -k_\sigma \sum_{ij \in N} \frac{(x2_{ij}e_{ij} + \dot{e}_{ij}x1_{ij})\|x1_{ij}\|^2 - x1_{ij}^T x2_{ij} x1_{ij} e_{ij}}{\|x1_{ij}\|^3} - q \text{sign}(c_i) + K_s \dot{x}2_r \quad (4.17)$$

where $q \geq N\|\dot{x}2_r\|_\infty$ and the adaptive tuning law is given by;

$$\tilde{M}_i = -H_i \nabla(x_i, c_i) c_i^T + \kappa_i H_i \hat{M}_i \quad (4.18)$$

where $\kappa_i > 0$ is a constant and $H_i = \mu_i I_{\delta_i}$ is a positive matrix, μ_i is a postive constant,

and I_{δ_i} is a square identity matrix of size $\delta_i \times \delta_i$.

Stability Analysis

By substituting (4.16) in (4.13), we get;

$$\begin{aligned} \dot{V} \leq & -sk_v\Xi(e)S_xS_x^T\Xi(e) + \sum_{i=1}^N c_i^T \left[\frac{x1_{ij}}{\|x1_{ij}\|}(e_{ij}) + J(x_i, c_i) - \right. \\ & \left. k_sc_i - \hat{J}^T\nabla(x_i, c_i) - \sum_{ij \in N} \frac{x1_{ij}}{\|x1_{ij}\|}(e_{ij}) + \rho - \dot{\sigma}_i \right] + \frac{N}{2} \end{aligned} \quad (4.19)$$

But, $J(x) - \hat{J}(x) = \tilde{M}$. Therefore,

$$\dot{V} \leq -k_v\Xi(e)S_xS_x^T\Xi(e) + \sum_{i=1}^N c_i^T [-k_sc_i + \rho - \dot{\sigma}_i + \sum_{ij \in N} \tilde{M}\nabla(x_i, c_i) + \epsilon(x_i, c_i)] + \frac{N}{2} \quad (4.20)$$

Further more; $\rho - \dot{\sigma}_i = \dot{v}_r - b\text{sign}(c_i)$ Hence;

$$\begin{aligned} \dot{V} \leq & -k_v\Xi(e)S_xS_x^T\Xi(e) + \sum_{i=1}^N [\|c_i\| \quad \| \epsilon(x_i, c_i) \| - c_i^T (k_sc_i - (\dot{v}_r \\ & + b\text{sign}(c_i)) + \sum_{ij \in N} \tilde{M}\nabla(x_i,))] + \frac{N}{2} \end{aligned} \quad (4.21)$$

Consider the Lyapunov function;

$$V = V_1 + V_2 + V_3 \quad (4.22)$$

where $V_3 = \frac{1}{2} \sum_{i=1}^N \tilde{M}^T H^{-1} \tilde{M}$. So, $\dot{V}_3 = \sum_{i=1}^N \text{tr}(\tilde{M}^T H^{-1} \dot{\tilde{M}})$ Therefore;

$$\begin{aligned} \dot{V} \leq & -k_v \Xi(e) S_x S_x^T \Xi(e) + \sum_{i=1}^N c_i^T [-k_s c_i - (\dot{v}_r + b \text{sign}(c_i))] \\ & + \sum_{ij \in N} c_i^T \tilde{M} \nabla(x_i, c_i)] + \frac{N}{2} + \sum_{i=1}^N \text{tr}(\tilde{M}^T H^{-1} \dot{\tilde{M}}) \end{aligned} \quad (4.23)$$

which can be re-written as;

$$\begin{aligned} \dot{V} \leq & -k_v \Xi(e) S_x S_x^T \Xi(e) + \sum_{i=1}^N c_i^T [-k_s c_i - (\dot{v}_r + b \text{sign}(c_i))] \\ & + \frac{N}{2} + \sum_{i=1}^N \text{tr}(\tilde{M}^T (H^{-1} \dot{\tilde{M}} + \nabla(x_i, c_i) c_i^T)) \end{aligned} \quad (4.24)$$

Selecting the control gain as;

$$c_i = \Pi \left(\frac{k_c}{2\Pi} + 1 \right) \quad (4.25)$$

where $-k_\sigma \leq -\frac{\Pi}{2}$, $\kappa_i \geq \underline{\Pi} \Upsilon$, $\underline{\Pi} = \min[\Pi_1, \dots, \Pi_N]$. Considering, the control gain (4.25), the adaptive tuning law (4.18) and using Young's inequality, (4.24) becomes;

$$\dot{V} \leq -\Pi V_1 - \Pi V_2 - \Pi \sum_{i=1}^N \frac{\Upsilon^{-1}}{2} \|\tilde{M}\|_H^2 + \frac{N}{2} + \frac{1}{2} \sum_{i=1}^N (\epsilon_z^2 + \kappa \tilde{M}_Z^2) \leq -\Pi V + T_Z, \quad (4.26)$$

where $T_Z = \frac{N}{2} + \frac{1}{2} \sum_{i=1}^N (\epsilon_z^2 + \kappa \tilde{M}_Z^2)$

According to Lemma 1.1 in [72], (4.26) implies

$$V(t) \leq \frac{T_z}{\underline{\Pi}} + (V(0) + \frac{T_z}{\underline{\Pi}} T_z) e^{-\underline{\Pi} t} \quad (4.27)$$

It shows that using the control law (4.16), the distance errors are uniformly ultimately bounded (UUB). Furthermore, considering (4.22), if $\dot{V}$ satisfies $\dot{V} \leq -\alpha_1 V + \alpha_2$, then for bounded set with initial conditions, the states and the NN weights are bounded and converges to a bounded set. Proof given in [71], [72].

4.4.2 Backstepping Finite Time SMC for Attitude Subsystem

To ensure asymptotic stability based on strong robustness for matched disturbances which may emanate from the load and inherently in the the system dynamic, a backstepping sliding mode control (BSMC) is designed. Let $\eta = [\phi, \theta, \psi]$ and $\dot{\xi} = [\dot{\phi}, \dot{\theta}, \dot{\psi}]$;

$$\begin{aligned} \dot{\eta} &= \xi \\ \dot{\xi}_{11} &= f(\xi) + \hat{g}u \end{aligned} \quad (4.28)$$

The design of backstepping control based on Lyapunov follows; let the tracking error between the actual orientation and the desired trajectory (η_d) be given by;

$$e_\eta = \eta - \eta_d \quad (4.29)$$

Differentiating (4.29), yields

$$\begin{aligned}\dot{e}_\eta &= \dot{\eta} - \dot{\eta}_d \\ &= \xi - \dot{\eta}_d\end{aligned}\tag{4.30}$$

an appropriate Lyapunov function can be defined as:

$$V_1 = \frac{1}{2}e_\eta^2\tag{4.31}$$

Therefore;

$$\dot{V}_1 = e_\eta \dot{e}_\eta = e_\eta(\xi - \dot{\eta}_d)\tag{4.32}$$

if ξ is considered a virtual control input, then the desired value which is known as the stabilization function may given by

$$\alpha^* = \dot{\eta}_d - k_1 e_\eta\tag{4.33}$$

hence substituting (4.33) in (4.32) yields $\dot{V} = -k_1 e_\eta^2 \leq 0$ which implies asymptotic stability. Let the deviation of the virtual control from its actual value be give by;

$$e_{\eta_2} = \xi - \alpha^*\tag{4.34}$$

so,

$$\dot{e}_{\eta_2} = \dot{\xi} - \dot{\alpha}^* \quad (4.35)$$

differentiating and substituting (4.33), and (4.28) into (4.35) gives;

$$\dot{e}_{\eta_2} = f(\xi) + gu - \ddot{\eta} + k_1 \dot{e}_{\eta} \quad (4.36)$$

Furthermore, we proceed with the design of nonsingular terminal sliding mode control in two stages, first the sliding mode surface and then the reaching law. Consider a nonsingular terminal sliding mode surface given by [73];

$$s = e_{\eta_2} + \varpropto \int e_{\eta_2}^{p/q} \quad (4.37)$$

where $\varpropto > 0$, p and q are positive and $1 < p/q < 2$. Therefore;

$$\dot{s} = \dot{e}_{\eta_2} + \varpropto e_{\eta_2}^{p/q} \quad (4.38)$$

Selecting the exponential reaching law of sliding mode control as;

$$\dot{s} = -k_2 \text{sgn}(s) - k_3 s \quad (4.39)$$

$$\dot{e}_{\eta_2} = -k_2 \text{sgn}(s) - k_3 s - \varpropto e_{\eta_2}^{p/q} \quad (4.40)$$

From (4.41) and (4.36), the controller is derived as;

$$u = \frac{1}{\hat{g}}(-f(\xi) + \ddot{\eta} - k_1\dot{e}_\eta - k_2\text{sgn}(s) - k_3s - \alpha e_{\eta_2}^{p/q}) \quad (4.41)$$

According to [58], on the sliding surface $\dot{s} = 0$, the error dynamics is given by;

$$\dot{e}_{\eta_2} = -\alpha e_{\eta_2}^{p/q} \quad (4.42)$$

Solving (4.42) results in;

$$T_f = \frac{|e_{\eta_2}|^{(1-p/q)}}{\alpha(1-p/q)} \quad (4.43)$$

This implies that the sliding surface converges in finite time T_f . If the second Lyapunov function is chosen as;

$$V_2 = V_1 + \frac{1}{2}s^2 \quad (4.44)$$

the derivative becomes

$$\begin{aligned} \dot{V}_2 &= -k_1e_\eta^2 + s\dot{s} \\ &= -k_1e_\eta^2 + s(\dot{e}_{\eta_2} + \alpha e_{\eta_2}^{p/q}) \end{aligned} \quad (4.45)$$

substituting (4.36) and (4.41) in (4.45) gives;

$$\dot{V}_2 = -k_1e_\eta^2 - s(k_2\text{sgn}(s) - k_3s) \quad (4.46)$$

which can be simplified as

$$\dot{V}_2 \leq -||k_1|||e_\eta||^2 - ||k_2|||s| - ||k_3|||s||^2 \quad (4.47)$$

Thus $\dot{V}_2 \leq 0$ so, (4.41) will stabilize the system.

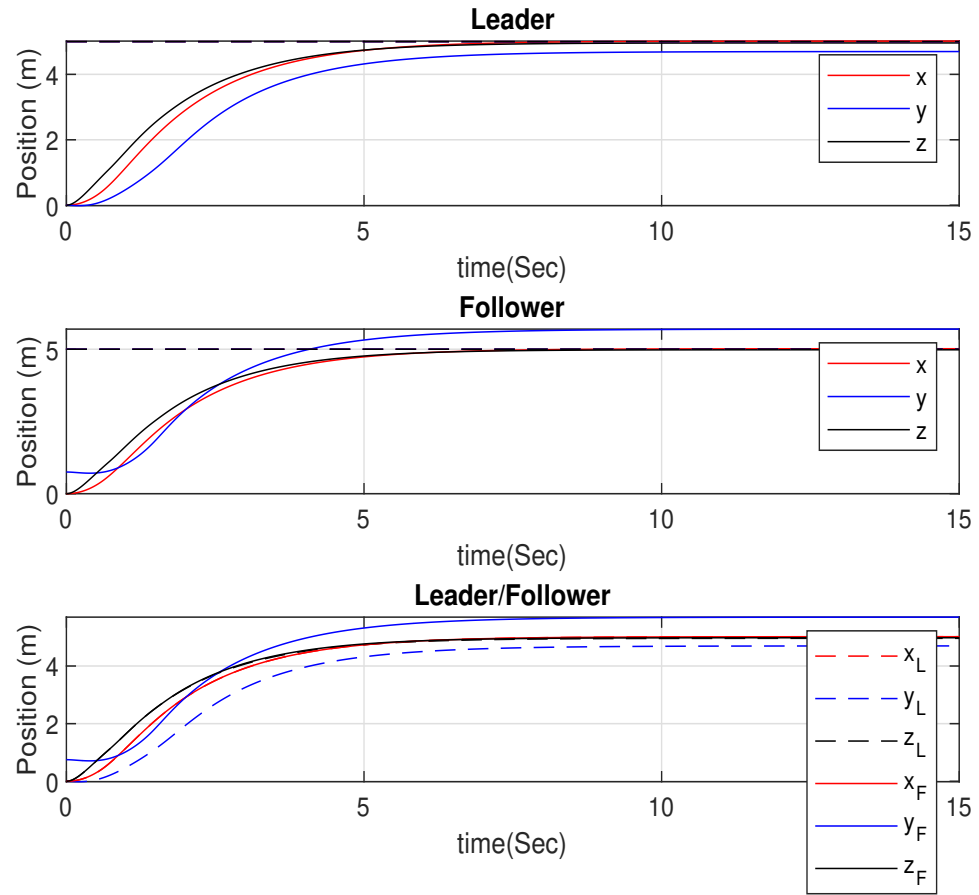


Figure 4.3: Trajectory of leader-follower

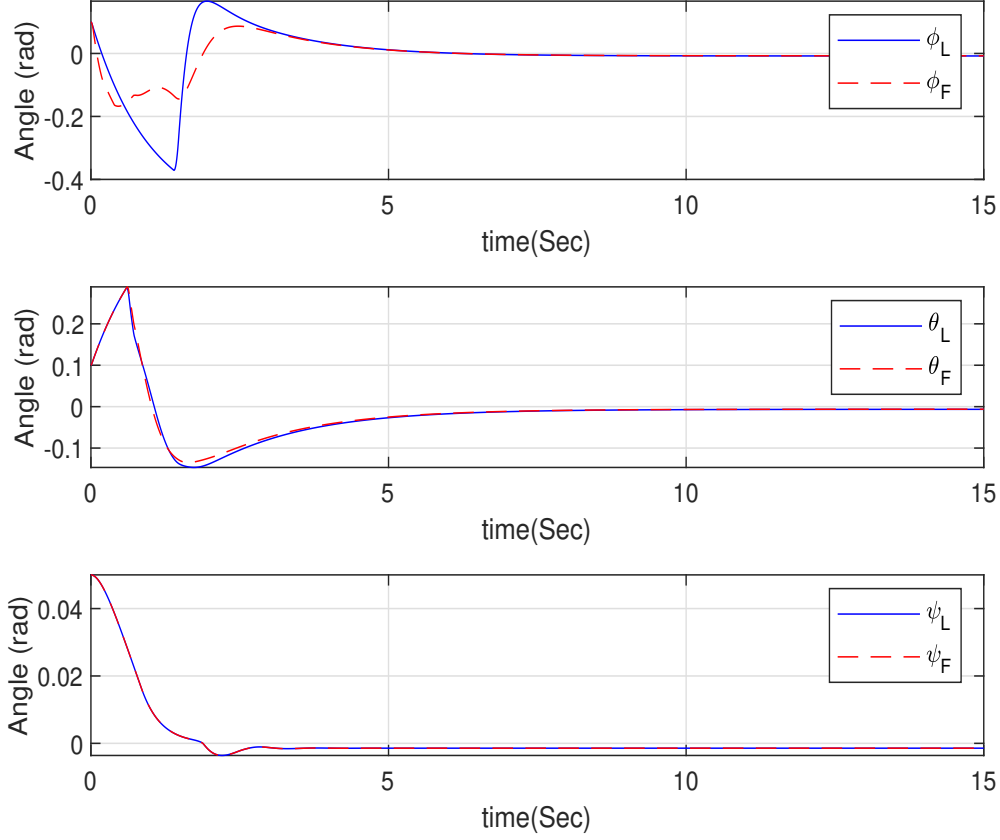


Figure 4.4: Leader-Follower Orientation Angles

4.5 Simulation Results and Discussion

In this work we utilized UAV parameter values for Parrot AR.Drone given in table 2.1 [1]. To demonstrate the effectiveness of the control structure, we present simulation results for the MUAVLs. Due to the nature of the MUAVLs it is important to avoid inter-agent collision. Also, maintaining the same altitude is paramount to ensure that each UAV is not engaged with unnecessarily large load since the aim is to convey a heavier beyond the capability of a single UAV. Both UAVs are kept apart with a initial positions $\zeta = [0, 0, 0]$ and $\zeta = [0.75, 0, 0]$ for the leader and follower respectively while

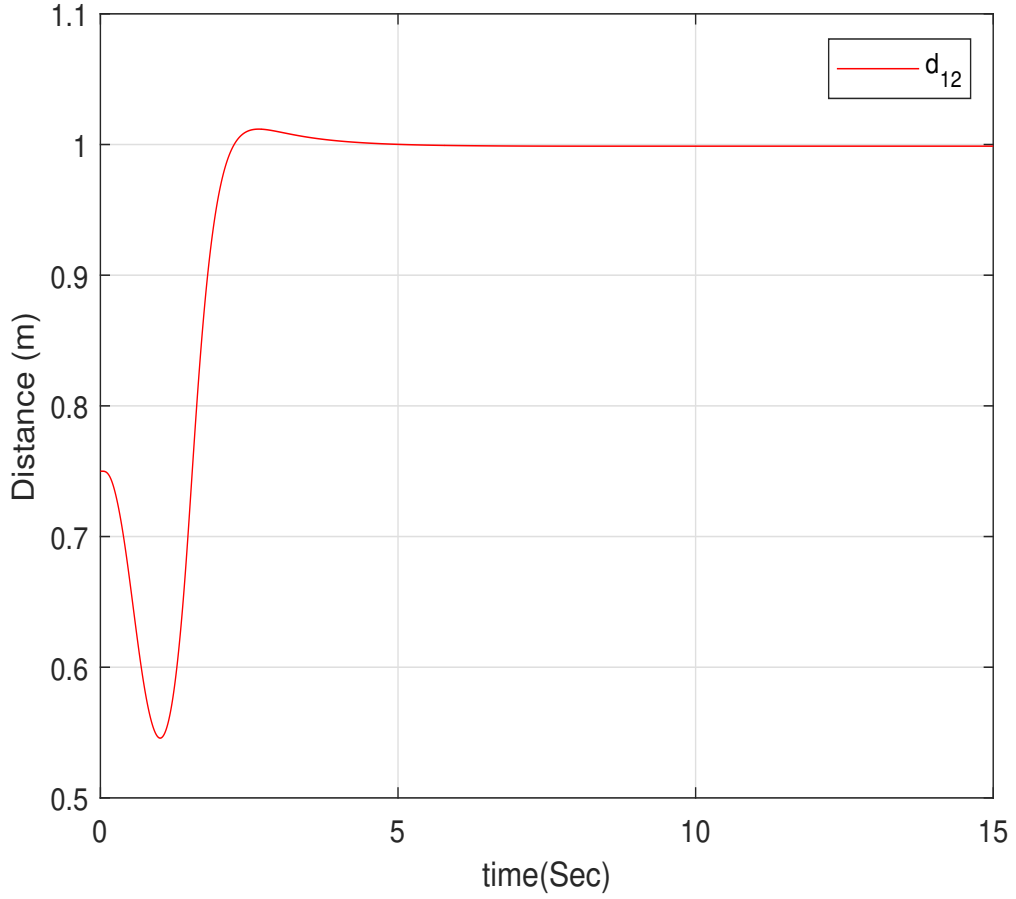


Figure 4.5: Inter-agent Distance

final was position specified as $\zeta = [5, 5, 5]$. Therefore, it is evident in Figure 4.3 that our control technique is capable of fulfilling the aforementioned requirements as the altitude is maintained while enforcing a fair distance between agents in the presence of load disturbance.

Figure 4.4 shows the orientation angles of the leader and follower which depicts the effectiveness of the attitude controller. Obviously, there is a minute orientation tracking error which could be improved upon in future. Figure 4.5 which represents the distance between agents position also portrays that a safe inter-agent distance between the leader and follower is sufficiently maintained. The load angles are shown

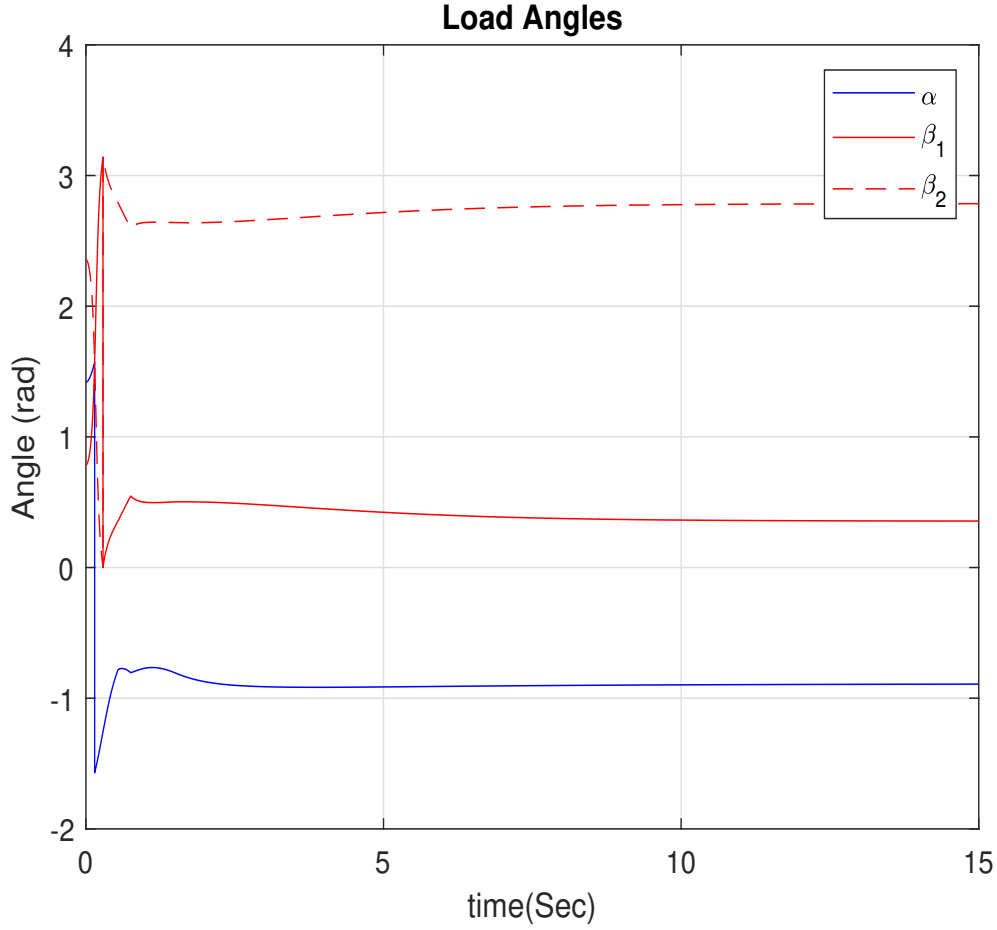


Figure 4.6: Load Orientation Angles

in Figure 4.6, with $\beta_1 = 16.75^\circ$, and $\beta_2 = 18^\circ$ of the follower to the horizontal. The negligible discrepancy emanated is a consequence minor difference in height. We hope to totally eliminate this minute difference in our future work. However, $\alpha = 45^\circ$ to the vertical is also maintained. Finally, Figure 4.7 shows the 3-D plot for visual purpose.

4.6 Conclusion

A multi-agent framework for relative control of MUAVLs based on ABMC was developed generate inter-agent collision free trajectory in the presence of load disturbances.

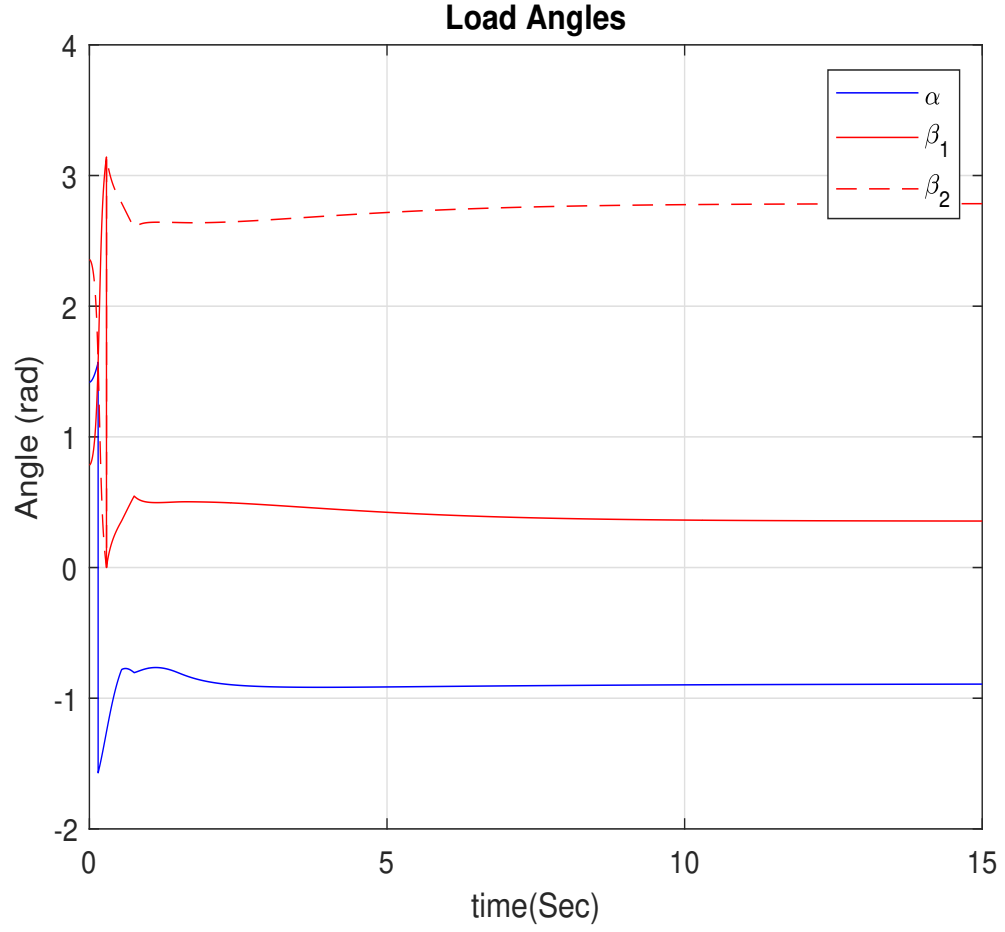


Figure 4.7: 3-D Plot

A BFSMC was designed for the attitude subsystem. The stability analysis of the overall system is given based on the Lyapunov theory and simulation results shows the effectiveness of our control strategy. However, in future, we will investigate actuator fault in the development of an active fault-tolerant controller for the MUAVLs.

CHAPTER 5

CONCLUSION/FUTURE WORK

This work mainly consists of controlling MUAVs described in chapters 3 and 4.

In chapter 3, A Neural Network Graph-theoretic Distributed Adaptive Control (NNGDAC) algorithm which is equipped with a modified virtual force artificial potential field for obstacle avoidance is used for tracking a Multi-agent UAV Load system (MUAVs) in the presence of load disturbances. A local Adaptive Feedback Linearization (AFBL) controller is also designed for the rotational axis.

In chapter 4, a multi-agent framework for relative control of MUAVs based on ABPMC was developed generate inter-agent collision free trajectory in the presence of load disturbances. A BPMC was designed for the attitude subsystem. The stability analysis of the overall system is given based on the Lyapunov theory and simulation results shows the effectiveness of our control strategy. Both designs were verified by simulation results.

However, tilt-wing/rotor UAVs are generally fully actuated, therefore, there is need to investigate how additional input could be utilized to cater for inherent problems associated with MUAVs to reduce control complexity. Our future work includes

investigating how actuator fault may affect a mission. Also, an aerodynamic load would be considered. The leader and follower can estimate the position and velocity of a moving target in an experimental implementation using Light Detection and Ranging (LiDAR) technology or vision based technique which are also applicable for dynamic obstacle avoidance. External disturbances such as wind gust rejection together with the performance analysis of our methods compared to future research works will be worth investigating.

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