I, Shraddha Barawkar, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

It is entitled:
Collaborative Transportation of a Common Payload using Two UAVs Based on Force Feedback Control

Student’s name: Shraddha Barawkar

This work and its defense approved by:

Committee chair: Manish Kumar, Ph.D.

Committee member: Kelly Cohen, Ph.D.

Committee member: Tamara Lorenz, Ph.D.
Collaborative Transportation of a Common Payload using Two UAVs based on Force Feedback Control

by

Shraddha Barawkar

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Dr. Manish Kumar
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Abstract

This research presents a novel approach to perform the task of collaborative transportation by using multiple quadcopter Unmanned Aerial Vehicles (UAVs). Collaborative transportation of a common payload would allow bulky, heavy payloads to be carried via multiple small-sized UAVs enabling their applications such as in emergency evacuations. However, from a control perspective, physical interactions between the UAVs and the payload during collaborative transportation present challenges in terms of stability and accurate trajectory tracking. In this paper, a leader-follower approach is implemented. The leader UAV uses a Proportional, Integral and Derivative (PID) controller to reach the desired goal point or follow a predefined trajectory. Traditionally, a Position Feedback Controller (PFC) has been used in literature to control the follower UAV. PFC takes the feedback of leader UAVs position to obtain the desired trajectory for the follower UAV which is then tracked using a traditional PID controller. Such control schemes have been shown in literature to work effectively in indoor environments using reliable and accurate positional information obtained from motion tracking cameras. However, the research focuses on outdoor application, that requires usage of Global Positioning System (GPS) to receive the positional information of the leader UAV. GPS has inherent errors of order of magnitude that can destabilize the system. The control scheme proposed in this research addresses this major limitation. In this research, a Force Feedback Controller (FFC) is used to control the follower UAV. The FFC provides control based on the interaction forces and torques acting at the follower UAV due to leader UAVs motion. Two control schemes are implemented to develop this FFC. They are Fuzzy Logic (FL) and admittance control respectively. FL emulates human behavior during such collaborative lift. Admittance controller simulates a virtual spring mass damper system, to generate a desired trajectory for the follower UAV. This generated trajectory complies with the contact forces acting on the follower UAV and it is then tracked by a traditional PID controller. With the proposed control schemes, the follower UAV can be controlled without using leaders positional feedback and the system can be implemented for real-world applications. Results of numerical simulations showing the effectiveness of the proposed controller for way-point navigation and complex trajectory tracking are presented. The results are compared to the benchmarked PFC implemented for the system.
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Chapter 1

Introduction

1.1 Motivation and Objective

The field of robotics has been evolving in the last five decades. Particularly, the progress made in the areas of computing, sensing, and communication has propelled the field of robotics tremendously in the last decade. This is witnessed from the numerous applications of robots in medical, civilian and other crucial applications. The main objective in all these applications consists of robot assisting humans to perform tasks more efficiently. Recently, the unmanned aerial technology, the topic of this thesis, is gaining immense popularity in the robotics industry. This is evidenced by the development of a wide range of applications tremendous using unmanned aerial vehicles (UAVs). For example, UAVs are planned to be used for package delivery, monitoring and fighting wildfires [4, 5], wildlife research [6], 3D mapping [7], search and rescue operations [8] and
disaster management. UAV technology has a potential to bring about a transformative change to the way natural disasters are handled today. Natural disasters cause huge loss to life and property. Mitigation of these effects following a disaster is extremely challenging due to a number of socio-technical problems including destruction of infrastructure and shortage of resources. Robots, in general, and UAVs, in particular, have immense potential to solve this problem. They provide a safe, reliable, and inexpensive means to gather information as well as provide aid to people. The research reported in this thesis is particularly motivated by the roles such systems can play in search and rescue operations after the occurrence of a disaster. Robotic researchers have indeed been developing ways to use robots for mitigating the catastrophic damages caused by disasters. For example, distributed search and rescue by robots is discussed in [9]. A team of humans and rescue robots was utilized for earthquake hit in Mirandola, Italy for disaster management [10]. Traditionally, manned helicopters have been performing rescue evacuations during a disaster. However, search and rescue tasks can be made faster, cheaper, and more efficient by using UAVs. UAVs possess tremendous potential in this context and hence unmanned aerial technology should be exploited for disaster management. To perform rescue tasks for multiple persons, the UAV is expected to possess high payload capacity. Currently, military UAVs like Global HAWK, Orion [11], MQ1, UNITED 40 (smart eye 2) [11] possess high payload capacity along with long endurance capacity. However, their use might not be economically feasible, especially during large-scale application such as disaster management. Additionally, the above-mentioned UAVs are fixed wing aircraft that would make the rescue operations difficult to perform. Small UAVs provide tremendous
Figure 1.1: Schematic diagram of people being transported by UAVs collaboratively

promise for rescue and emergency operations. However small UAVs have low payload capacity. This necessitates the use of multiple small UAVs to lift a common heavy payload. Several technological gaps and challenges need to be addressed, to implement such a system in real world for rescue tasks. These include unavailability of reliable and safe control methodology for collaborative lift by multiple UAVs and inability to handle uncertainties in sensor measurements. The overall objective of this research is to develop a fully deployable, safe, and reliable collaborative multi-UAV system which can provide autonomous air lift for rescue evacuations during large-scale disasters. A schematic diagram for this system is shown in Fig. 1.1. Additionally, the proposed system will find wider use in applications such as heavy package delivery, transportation means as aerial cars, specific applications in industries and many more. Its multi-functional use also serves as the motivation of this research. The research reported in this thesis provide details of the two control methods to perform collaborative lift and transportation by two UAVs. These methods employed are fuzzy logic based force feedback controller and admittance based force feedback controller to achieve our objective.
1.2 Background Research

In this section, the current state-of-the-art in the field of collaborative transportation using multiple robots is briefly discussed to motivate our approach. The collaborative transportation using multiple robots becomes a complicated, interesting and challenging problem to solve primarily because of contact dynamics. Due to this fact, this field has captivated the attention of many robotic researchers since a long time. Researchers have been trying to solve issues related to collaborative transportation since last two decades. The research in this field is inspired by the mechanisms such as those employed by biological entities like ants to transport food particles collaboratively [12]. Extensive research has been performed on collaborative transportation using mobile ground robots. Cooperative towing with multiple ground robots is discussed in [13]. Design of the Army-Ant cooperative lifting robot is discussed in [14]. In yet another study, a force amplifying, multiple ground robot transport system is demonstrated [15]. Researchers have been trying to extend such studies (applied on ground robots) to aerial robots. However, highly nonlinear, unstable dynamics of aerial platforms along with the role of gravity makes this translation complicated. Despite these challenges, researchers were successful in their endeavors. For example, research in [16], provides a control and path planning algorithm for multiple aerial manipulators for cooperative transportation. Cabled payload transportation using multiple robot system is demonstrated in [17, 18]. Inverse kinematics of multiple UAVs cooperatively transporting a cable suspended payload is proposed in [19].
1.3 Research Contribution

This research uses the leader follower (LF) approach which is a popular approach implemented for swarm robotics, in general, and collaborative transportation, in particular. For example, in [20] a LF based control approach is utilized for multiple mobile robots. Control of flight formation of multi-UAV helicopters is implemented by using LF method [21]. Control of multiple robots using LF approach, requires the positional information of leader robot or UAV. The positional information of UAVs is obtained using motion tracking cameras in indoor environments and Global Positioning System (GPS) for outdoor environments. Such control schemes are known as position feedback schemes or controllers in this research. Most of the approaches in literature employ motion tracking cameras for testing and validation of control schemes. These cameras provide positional accuracy to the order of decimal of millimeters. A system, required to be used outdoors, needs to rely on GPS for positional information. However, commercially available traditional GPS sensors, possess inherent errors of 1 to 2 meters in magnitude. This magnitude of error would result in destabilization of the whole system. Even the use of differential GPS, providing accuracy in the order of centimeters would make the system unstable. Such magnitudes of error in position estimation leads to development of large interaction forces and moments during collaborative transportation. This will then lead to instability of the whole system.

A novel force feedback controller is proposed in this research to address the above limitation. In this approach, the leader UAV implements PID controller to follow a pre-defined
path. The follower UAV, on the other hand, is guided by the interaction contact force and torques acting on it. The FFC is based on the principle of minimization of force and torques [22, 23]. Hence, when contact forces and torques are exerted on the follower UAV, due to leader UAVs motion, the follower tracks the leader by moving in a manner that minimizes the forces and torques to achieve collaborative transportation. Work in [22, 23] illustrates the implementation of FFC using Fuzzy logic for controlling multiple collaborating industrial robots. However, UAVs possess highly nonlinear and unstable dynamics. Hence the above-mentioned concepts do not find a trivial extension to UAVs. However, regardless of the challenges offered, researchers are trying to use passive force control for collaborative transportation as can be seen from work discussed in [3]. The control strategy in [3] implements force control. However, it employs visual inertial navigation system to estimate the force for implementation of the control scheme. This limits its application only to indoor environments. In this research, a simple FFC is implemented assuming the availability of force/torque feedback from sensors located at the contact of follower UAV and the payload. The follower UAV tracks leader UAV, based on the interaction forces and torques acting on it. In this respect, the proposed concept is like one discussed in [3]. However, work in [3] can only be implemented indoors. Whereas, the control methods discussed in this research allow implementation of our system in outdoor environments without relying on error prone GPS to control the follower. Motivation of our research emerges from the practical limitations offered by real world scenarios.

The developed control scheme is independent of geometry of payload, payload position, cable tension and constraints, grasping point location and mechanism implemented. As
mentioned above, the most important merit of this scheme is that the follower UAV can be controlled without the use of GPS. This makes it suitable for real world application. The leader UAV can, however, utilize GPS signal or can be operated remotely in GPS denied environments. Usually, control of a leader-follower based swarming system requires communication between leader and followers. However, in the proposed scheme, this drawback is eliminated. Here, no digital communication is required between UAVs. Additionally, more number of UAVs can be incorporated to share the payload weight without modifying the underlying control architecture. The proposed control scheme also provides fault tolerance if one or more UAVs fail while in operation.

Two methods to implement FFC are proposed here. The first method utilizes fuzzy logic to develop the FFC. While, the second method uses admittance control to develop and implement the FFC. The admittance control concept is implemented in a manner similar to presented in [3]. The following sections provides a brief introduction of both the methods.

1.4 Research Summary and Thesis Overview

In this section, we briefly describe the control strategies implemented for collaborative transportation in this thesis.

Fuzzy logic is an interesting mathematical tool which emulates human behavior to solve problems. It is linguistic in nature, due to which complex problems can be solved in an intuitive sense. FL is used to implement a controller of the follower UAV for collaborative
transportation. Two benefits are offered by FL in context with collaborative transportation. It allows the development of rule-base based on human expertise. This is very useful, since humans perform collaborative transportation task very efficiently. Fuzzy logic has special ability to handle sensor uncertainties. This makes it robust to noisy force and torque sensors used to implement the FFC. This allows us to use light weight and inexpensive sensors. FL-FFC is implemented along each coordinate axis. It works on the principle of minimization of forces and torques to achieve synchronous collaborative motion. This principle is well discussed and presented in [22, 23].

The second approach makes use of admittance based controller for the implementation of FFC. Interaction of robots with environment has been a research interest for many roboticists. A hybrid position/force control of robot manipulators interacting with environment is well presented in [24]. Stability of manipulators during contact operations is discussed in [25]. Researchers have also been trying to implement aerial manipulation since long time. Control of multiple manipulators of a multiple cooperative UAV system using trajectory compliant interaction is presented in [26]. Admittance control of a manipulator arm attached to a quadcopter is discussed in [27]. Admittance controller is a special type of controller which controls the follower UAV based on the contact/interaction forces acting at the follower UAV. Therefore, input to this controller is contact force and output is the desired motion or position [28]. The leader UAV follows a traditional PID controller. Main objective consists of minimization of contact forces at the follower UAV (due to leader UAV), for collaborative transportation of a common payload. The admittance controller implements a virtual spring mass damper system along each
coordinate axis. The desired trajectory complying with contact forces is generated by simulating the virtual spring mass damper system. The control scheme offers the same benefits as of FL-FFC. Simulation results of the system using admittance control are discussed in later chapters. The proposed controls scheme is based on the method discussed in [3]. However, it may be noted that the research in [3], makes use of visual inertial navigation system. On the contrary, the research proposed in the thesis avoids usage of GPS or visual inertial navigation system for follower control. Additionally, the proposed controls scheme is implemented by a novel dynamic model to evaluate forces acting at the follower UAV. In real world application, we assume utilization of force / torque sensors for implementing these control schemes. The results of both these techniques are compared with the benchmarked position feedback controller (PFC) that assumes availability of positional information of leader to the follower. Such a controller is expected to provide best possible results since it assumes complete knowledge of leader’s position, and the follower controller could simply replicate the leader controller to achieve a synchronized motion.
Chapter 2

Literature Survey

This Chapter provides an overview of existing body of work in cooperative transportation. The Chapter first presents a survey of work carried out on ground robots transporting a common payload. This followed by survey on cooperative transportation using multiple UAVs. Finally, work carried out in the area of Force Control, which is the method utilized in this thesis, is presented.

2.1 Collaborative transportation - ground robots

In [13], cooperative towing of a payload carried out by multiple ground mobile robots is presented. The towing is performed in a single plane. The robots transport the payload via cables attached to the payload, allowing manipulation in planar environment. A quasi static model is presented for performing manipulation of this system. Equations of
motion are then derived. These equations help in computing the payloads motion when the motion of the robots is provided. The constraints, during this process, include dry friction and tension constraints. Stable equilibrium conditions are evaluated for one, two and three or more mobile robots transporting the payload. When uncertainties in support forces are observed at the payload, it becomes difficult to implement planning of the payload in spite of the knowledge of the positions or motions of the robots. This paper develops abstractions which are independent of the above limitation. These abstractions are later on employed to develop an algorithm for motion planning of the system. Geometric and kinematic abstractions are developed to generate controls to achieve motion of the payload along a prescribed path. The research discussed until now, inspires us to perform stability analysis which we plan to do in future work. However, as can be seen, many studies in literature have geometric and kinematic constraints. The proposed control scheme in this thesis is independent of these constraints. It is very simple and effective as compared to the current studies in literature. Going further, a force-amplifying N-robot transport system (Force-ANTS) is discussed comprehensively in [15], for performing collaborative, planar, common payload manipulation and transportation without employing communication between robots. The novelty of this work is that, it carries out the designated control scheme without requiring communication between the robots. It indicates the use of local estimates of the payloads motion (at the points of attachment, instead of communicating with each other) to implement the controls scheme. It employs, a leader follower scheme, in which the leader can be a human or a robot, applying very small force which acts as a guide for other robots. The followers then align
their forces with the leaders forces and amplifies them. Two objects are considered for analysis in [15], which are, small objects in which kinetic friction plays a dominant role. The second one is a large object, in which viscous friction and inertia play vital roles. Simulation and experimentation is performed in this work. A human-robot collaboration case is also conducted in this research. In the proposed scheme [15], only the leader has the knowledge of the payloads desired positions and trajectory. Whereas the followers just align and amplify their forces according to leaders estimates. It is indicated that followers attain exponential rates of convergence of forces with leaders forces which is an added advantage of the control scheme. Two types of Force-ANTS is examined in this research viz. Constant Boost-Force-ANTS and Proportional Force-ANTS systems. This scheme uses force sensors to implement the control algorithms. This scheme is similar to the control scheme proposed in this thesis with few differences. There is no amplification of forces by followers in our research, and we have used this capability for aerial robots which are more complex and difficult to control as compared to ground robots.

2.2 Collaborative transportation by multiple UAVs

Researches have been trying to extend the successful concepts of collaborative transportation using ground robots to aerial robots. In this section current state of the art in multi robot, especially multi UAVs collaborative transportation is discussed. Research in [1] discusses multi quadrotor cooperative transport and grasping. It assumes rigid connections between the UAVs and the payload. In this paper the UAVs are modeled
individually as well as a group. It presents individual robot control laws, stabilizing the payload in all three coordinate directions. It also demonstrates autonomous grasping capabilities of UAVs. Consider the Fig. 2.1, shown. The dynamic model of this system consists of modeling the individual UAVs or basically writing the equations of motions for individual UAVs. The equations of motion for the payload are then obtained after combining the equations of motion of individual UAVs. The control vectors consists of the body thrust force (which is summation of all thrust forces of UAVs) and the body moments about X, Y and Z axis. It is assumed in the paper that the UAVs are heavier than the mass of the payload, which might not be true in all cases.

The research in [1] uses a combination of centralized and decentralized control. In centralized scheme, the state estimates of UAVs are combined to achieve the estimate of the body, following which the control vector is evaluated. The pose, orientation and velocity are all evaluated using the centralized scheme. However, the angular velocity is evaluated onboard of each UAV, hence terms requiring the angular velocity are evaluated by a
decentralized scheme. In this thesis, however, we employ a centralized scheme to control the system using a leader follower approach. Additionally, the research in [1] requires the attachment of UAVs in a horizontal plane which is parallel to payload. The results in [1] show weak performance of this technique along X axis.

Research in [17] demonstrates collaborative transportation of a payload suspended by cables via multiple aerial robots. Robot configurations are developed, ensuring static equilibrium of the payload (at a certain position) and satisfaction of constraints on cable tensions. Stability analysis of payload for these configurations are also performed. The conditions for static equilibrium of a payload are developed. The analysis later on is carried out for 3 robots for simplification. The developed conditions are then analyzed for stability and tension models. Based on the conditions, various robot configurations to achieve a desired position of the payload are attained. A closed form analytical solution is developed for tension constraints and stability for different configurations of payload. In the whole study, point robots are considered. Experimental verification of all these configurations is also provided in this paper. The paper evaluates two problems with respect to 3-D manipulation with cables. The first problem consists of computing the positions of all the robots that respect cable constraints and equilibrium conditions given a desired position and orientation of the payload. This forms an inverse problem. The second problem consists of evaluating the payloads position and orientation, satisfying cable and equilibrium constraints, given the actual positions of the robots. Stability analysis is carried out by computing the change of potential energy of the static system. In
the whole analysis it is assumed that the system has only three degrees of freedom, provided the cables are in tension. Second problem provides a definite number of solutions of payloads pose and orientation. The one which is most stable is considered as the desired exact solution. In the whole analysis, the quadrotors are are assumed to be point robots. However in reality the UAVs are not point robots and hence the paper additionally, to consider this fact, develops a model for transformation from desired applied forces to the four control inputs, which are the three orientation angles and the vertical thrust, which is then required by the hardware system. In experimentation, a quadrotor was allowed to fail. This paper shows that in spite of a failure, the system quickly recovers and attains a desired position. The work done in [17], requires the satisfaction of cable tension and geometric (to avoids collisions) constraints. However the proposed control scheme of this paper, is independent of these assumptions.

Research in [18], considers payload dynamics and development of dynamic model for rigid body as well as point load payloads. It proves that the systems are differentially flat when cable tensions are positive. Differential flatness property is then used to compute trajectories for payload and quadrotor robots, which are feasible from dynamics point of view. Work in this paper demonstrates that these concepts are better than other works which consider quasi static models and ignore payload dynamics. The case where zero cable tension is observed, is also considered and such systems are also proved to be hybrid differentially flat systems in this work. Research in [18], discusses the differential flatness concepts for both point mass as well as rigid body payloads. It discusses different lemmas for these systems based on differentially flat properties. The research proposed in [18]
addresses the limitations of under actuation constraints on UAVs. Work in [19] presents the inverse kinematics problem of a cabled cooperative transportation by multiple UAVs. It presents the solution to compute the positions of the UAVs where the position of and orientation of the payload is known. This problem has infinite solutions when three or more robots are employed. However, when three or more robots are there, the problem has finite solutions, provided the tensions in the cables are specified. In all these papers and current literature seen till now, cable tension acts as a constraint and must be a known parameter to control the system. This can lead to instability of the system when when incorrect cable tensions are recorded or estimated. However this is not a drawback when the control scheme proposed in the thesis is employed. Dialytic elimination analytic algorithm is presented to solve inverse kinematics problem. The work also presents case studies in the presence of an equilateral triangular payload and a general payload. A numerical procedure is also developed to evaluate the cable tensions which are within the allowable limits. This paper also performs stability analysis by evaluating the Hessian matrix which consists of all possible sets of second order derivatives of the potential energy function.

2.3 Force Control

Force feedback control is most widely used for industrial robots and robotic manipulators for manufacturing applications where force control is also required in addition to position control. Researchers have been trying to implement hybrid position/force control, where
either position or force control is required along one of the co-ordinate axis. In context with force control, research in [22], implements force and moments control for multiple co-operative robots manipulating a work-piece collaboratively. Sensors are used to estimate the forces and torques at points of attachments of robots. The control strategy presented in this paper, is based on the principle of minimization of forces and torques acting at the robots to achieve collaborative operations. It makes use of two six degrees-of-freedom robots. It applies fuzzy logic to implement the force control for these robots. The force and torque measurements along/about each axis are provided by the force/torque sensors mounted at robots. This data is then fed to a fuzzy controller. This scheme uses the leader-follower approach. Hence, one robot acts as the leader and the other one acts as the follower. This paper also, with the help of data of force torque sensors, estimates the external force acting on the end effector. The force/torque sensors provide measurements which includes the manipulator and end effector dynamics. This paper employs Kalman filtering to estimate the external force acting at the end effector. In order to do so, it utilizes the dynamics of the end effector. To tune the fuzzy logic parameters of the control scheme presented in [22], a neural network is implemented in [23]. Model predictive control is used to generate an optimum signal. This optimum signal is then used to train the neural network by using back propagation technique. The research, proposed in this thesis, is inspired and motivated from the above discussed control strategy. Fuzzy logic is used to demonstrate force feedback controller. The rules for the fuzzy logic force feedback controller are developed based on the principle of minimization of forces and torques to achieve collaborative motion. The principle has been discussed in depth, in
later chapters. Work in [22] utilizes the same principle. The interesting work in [18], for industrial robots, is applied in this thesis for two UAVs.

*Admittance Interaction Control:* Interaction control has been a focus of interest amongst many robotics researchers. Researchers have been trying to extend the control concepts on robots interacting with environment, since last decade. Many times either a force control or position control is required at a particular coordinate axis. For example, in manufacturing tasks, a force is required to be maintained at a particular position on the workpiece. Thus, here a hybrid position and force control is required for the robotic manipulator. There are two types of interaction or compliance controls: viz admittance and impedance control. Admittance control takes contact force as input and provides motion as output, whereas impedance control takes motion as input and provides force as output. Choosing one of these completely depends on the application of the control schemes. These concepts have been applied to various fields and extensive research has been performed. Research in [29] discusses the application of impedance control for robotic manipulation. Research in [24], presents hybrid position/force control for robotic manipulators. The hybrid technique discussed in [24], consists of combining the force information and position information of the manipulator. This is then used for maintaining the force and position constraints at the end effector of the manipulator. Both force and position sensors are utilized to carry out the control process. Research in [25] discusses the stability of manipulators interacting with the environment. Contact tasks requiring contact force as well as position control of manipulators are very complex to control. During contact tasks, the high forces acting at the end effector can destabilize
a manipulator, if not taken care of. Hence control of right amount of force as well as position are very important when it comes to controlling a robotic manipulator. In [25], a simple impedance control was implemented. It is demonstrated that implementing an impedance control to a manipulator guarantees stability of the manipulator. This stability is observed for many variations of stable environments considered for a manipulator. Rather than just regulating an output of the system, the controller tries to change the systems dynamic impedance (or stiffness) when the system has to respond to a change in environmental conditions. A structure of the environmental dynamics is proposed here along with limitations of system interactions. Dynamic behavior of the manipulator is then presented along with the impedance control implementation. Insensitivity to kinematic errors is presented, resulting from the application of impedance control.

Researchers have also being trying to implement these interaction control concepts for aerial robots. Aerial manipulation is currently being studied by many researchers. For example [27] presents the control of manipulator attached to a multirotor. This is developed for outdoor application. The manipulator arm has seven degrees of freedom. A back-stepping based controller is used for the eight rotor multicopter and an admittance based control is implemented for the control of the manipulator. Research in [27] provides the benefit of providing a higher payload capacity to the system as compared to the other UAV manipulator systems for outdoor applications. During the movement of the arm, the dynamics of the whole multirotor changes. The motion of the arm also causes the change in mass distribution, hence change in the center of gravity of the system. This might lead to instability of UAV, and hence these facts must be considered. A nonlinear
controller which considers the complete dynamics of the arm as well as the above constraints is utilized in [27]. It helps in dampening the oscillations of the system, during arm movement. In addition to this controller, an admittance controller is also proposed in this paper for the manipulator.

Research in [26], proposes control of multi-quadrotor manipulator systems. In order to achieve this control application, it implements a hierarchical control. The hierarchical framework includes three layers. They are the design of desired behavior of object, the optimal force distribution using multi quadrotors, and the individual quadrotor manipulator control. The object behavior design consists of computing the desired wrench of the payload depending on the application like compliant interaction and trajectory tracking. The optimal cooperative force distribution layer, assigns the contact force to each quadrotor manipulator system. It requires minimization of a cost function. It also considers the friction constraints to avoid slipping. The individual quadrotor system control consists of implementing an admittance control for each manipulator. The advantage offered by the control scheme is that, in order to perform different tasks, only specific control block needs to be changed rather than modifying the whole controller.

Physical human-quadrotor interaction based on admittance control strategy is demonstrated in [30]. It consists of application of physical human vehicle interaction. Admittance control consists of simulating a spring mass damper system. In this way, the damping, the stiffness and the inertia can be controlled intuitively based on the desired task. In the proposed work forces acting on the quadcopter are evaluated from the attitude and position information of the quadcopter. These then act as the inputs to
admittance controller. The admittance controller takes force as input and provides a reference trajectory (or motion) of the quadrotor. This reference trajectory is then tracked by a traditional PID controller. A near hover analysis is performed on the quadcopter. The unscented Kalman filter is utilized to estimate the external forces and torques acting on the UAV. It is also utilized to estimate the state of the quadrotor. Similar steps are used to implement admittance control in this thesis.

Collaborative transportation using multiple micro aerial vehicles is discussed in [3]. It implements an admittance based control strategy to achieve the control task. The control scheme is independent of shape of payload. It does not require prior knowledge of location of grasping point for carrying out the control strategy. It also avoids communication between the aerial vehicles. The work in [3], uses a leader follower approach, and an admittance based control strategy is implemented for the follower. The work in [3], uses Unscented Kalman filter to estimate the forces acting on the follower. The filter uses information from visual inertial navigation system. The proposed control scheme in this thesis is similar to the work performed in [3]. However, control strategy of [3] relies on visual inertial navigation system to carry out the control scheme. In order to implement such schemes outdoors, GPS is required. GPS has inherent errors which can lead to faulty estimation of forces, and hence can lead to instability. On the other hand, the work proposed in this thesis allows the implementation of these systems in real world, without relying on GPS for the control of the follower UAV. This serves as the merit of our research. Additionally, research in this thesis provides a novel dynamic model to evaluate the forces and torques for simulation purposes.
Chapter 3

Overview of Control Approaches

This chapter introduces three control approaches used in this thesis: i) Leader-follower approach; ii) Fuzzy logic control approach; and iii) Admittance based control approach. The chapter provides theoretical details and previous works carried out based on these control approaches.

3.1 Leader-follower approach

A leader-follower (LF) approach is a mechanism in which one of the entities (of the whole swarm) acts as a leader and others just act as mere followers. The followers may follow the leader based on its position (termed as position feedback) or force (termed as force feedback) or both. The leader follower scheme is being studied since time immemorial. This scheme has been extended in swarm robotics, as a part of control strategy.
inspiration of this scheme is taken from nature. For example, hierarchical group behavior of pigeon flocks is well discussed in [31]. It discusses how the spatial position of pigeons in a flock determines its position in the hierarchy. Research in [32] discusses the presence of leader and follower ants in the process of nest building. It indicates active and non-active, as two types of ants. Active ones start the process of nest building first, whereas non-active ants follow them. The ant starting or initiating the process of nest building is declared as the leader ant. In birds, a leader follower singing is experienced in red-winged blackbirds, is discussed in [33].

However, such scheme also exists amongst humans, in companies, in research groups, in academics and in many other places. Hierarchical organization is almost found everywhere. Researchers have been trying to study these traits and make them more effective. For example, concepts of authentic leadership and eudaemonic well-being to understand leader-follower outcomes has been presented in [34]. This gives outline of the four component model using these concepts and also describes its outcomes on leader and followers for their well-being. Additionally, research in [35] gives an insight into quality of leader-follower exchanges. It indicates that this quality is governed highly by personal and interpersonal attributes. Another interesting example of leader-follower approach is its use in simulation of virtual human crowds discussed in [36]. These few examples show implementation of the leader-follower mechanism in nature. Inspired from the application of this approach in nature, extensive research using LF approach for swarm robotics control has been performed since the past decade. Additionally, researchers have also being trying to improve formation control strategies based on this LF approach. For example,
presents LF approach with additional input constraints applied to the robots. This scheme has also been extended in ocean engineering. For example, simulations using LF based formation control for underwater vehicles are discussed in [38]. Additionally adaptive LF control of multiple manipulator systems is examined in [39]. In this research, adaptive control is utilized to take care of uncertain and nonlinear dynamics of multiple manipulator systems. In context of quadcopters or UAVs, LF scheme is demonstrated in [40]. Research in [40] proposes a linear control law in LF formation control of quadcopters which makes it different from other studies. An interesting concept of changeable leaders has been discussed in [41]. According to studies in this paper, a leader-follower formation saturated control for multiple quadrotors using switching topology strategy can achieve better consensus due to changing leaders. Researchers have been trying to improve existing LF approaches using different arrangements, theories, and principles. This makes LF an emerging as well as a developing concept in swarm robotics. In the research proposed in this thesis, we utilize the LF approach to control two UAVs performing collaborative transportation task of a common payload for implementing the novel force feedback controller (FFC). In this concept, one of the UAV acts as a leader and other UAV act as a follower. For simplicity, only two UAVs are considered. The follower UAV tracks the leader UAV based on the contact or interaction forces or torques acting on it due to leaders motion. This is the reason why it is termed as force feedback controller. Existing studies have demonstrated the capability of multi-UAV cooperative transportation. However, most of the studies utilize position feedback controller (PFC) to implement it. In PFC, the follower UAV tracks the leader UAV based on the current position of the
leader UAV. This scheme can be performed indoors using motion tracking cameras that provide very accurate positional feedback. However, for outdoor environment, GPS is utilized which has inherent noise in its measurements of leaders position. This erroneous measurements lead to instability of the entire system. In contrast, the FFC allows the implementation of this system indoors as well as outdoors, without relying on GPS for measurements to control the follower.

A centralized control scheme is the one in which a central entity or leader controls the entire swarm. Now, one may think that if more number of UAVs are present, a LF approach may lead to increased the communication load (between the leader and followers) to communicate the leaders estimate or position at each instant to the followers, which is a drawback of the centralized control scheme. However, this drawback can be addressed by utilizing the FFC using LF approach. This is due to the fact that no communication between the leader and the followers is required when FFC is used, since each follower will move according to the force and torque exerted at its point of contact, which is provided by the respective force and torque sensors. Additionally one may think, that leaders failure can lead to failure or crashing of the whole system, which is again a drawback of the centralized control scheme. However if, the leader fails, one of the follower UAVs can be made the leader UAV. This has not been demonstrated in the proposed research, however, existing studies have implemented it such as the studies performed in [41]. Hence, LF approach is implemented to demonstrate the novel FFC in this research.
3.2 Force Feedback Control

Flocking behavior in nature has been studied since a long time by scientists and researchers. Collective behavior is observed in bird flocks, insect swarms, fish schools, mammal groups or herds. Scientists and researchers have been trying to understand and examine these biological behaviors. Animals and birds in groups try to maintain a certain position in the flock or group. They do this by comparing their position and velocities with their nearest neighbors to maintain the flocking mechanism. There exists an attractive force amongst the birds to ensure a certain distance is maintained, to remain the part of flock. Additionally, a repulsive force also exists, which ensures separation if a bird comes too close to its neighbor. At the equilibrium distance, the forces of attraction and repulsion will cancel out each other and the force acting on the entity will be zero. This determines the average distance of between entities in the swarm, which it should maintain from the neighbor [42]. As can be seen, force feedback or force control is largely observed in nature. Motivated from these mechanisms, researchers have been trying to extend these concepts on robots. These concepts have been extended on industrial robots. Research in [22] uses a force feedback controller, by utilizing fuzzy logic to control the internal forces generated when multiple robots carry a common object. It also utilizes a LF approach to achieve effective control. A comprehensive study has been made in [22]. Additionally, research in [43] illustrates learning of force control policies or strategies for manipulation, compliant with the environment. The normal position control policy is utilized. A force/torque profile is added to this policy, which leads to control of force/torque
along-with control of position trajectories. It demonstrates the success of these strategies for robust manipulation tasks. Research in [33] implements a hybrid force/position control for robot manipulators using neural network based adaptive control scheme. Another work in [44], illustrates the contact force optimization for posture and balance control of biped robots. The force control scheme has also been extended to UAVs. For example impedance based control, which provides a relation between generated contact forces and the output motion, is developed for a UAV with a manipulator arm [45]. Admittance based control, in which force is the input to the controller and the desired motion is the output, is implemented on a quadcopter for physical human quadcopter interaction [30]. In this way, researchers have been trying to implement force control for aerial platforms too. Here, we implement a force feedback control scheme similar to the work proposed in [22, 23], applied for industrial robots, for multi-robot cooperative work of handling a payload. However, extending such concepts on UAVs increases its complexity due to the role of gravity and presence of nonlinear and unstable dynamics of the aerial platforms. In multiple robot control, there arises a choice of choosing a control strategy. The control strategy can either be a position control or force control. In order to implement a position control, in a LF scheme, the follower is required to follow the leader based on its position. However, an incorrect position information of the leader robot can lead to the follower attaining an incorrect position instead of the desired or allocated position. As a result of this, contact forces are generated which can get transmitted from one robot to another and then cause instability in the system. This situation does not arise indoors when visual inertial navigation systems with high accuracy is used. However, this situation can
be encountered outdoors when GPS, having inherent errors of approximately 1 to 2 meters, can provide incorrect measurement of leaders position. Hence, rather than position control, force control is implemented. We do the same and implement force control for collaborative transportation task. However in this case only force control is desirable. In other applications like the ones involving manufacturing tasks, both a designated force as well as a desired trajectory is required. In these scenarios it is preferable to opt for a hybrid position/force control rather than individual controls. In this research, to address all the above mentioned drawbacks, a force feedback scheme is implemented for multi-UAV transportation task. Using force feedback by using force or torque sensors for estimation, instead of position feedback allows the real world application of such systems, without relying on GPS with errors for feedback to control the follower. It also provides the capability of implementation of such systems in GPS denied environments. Additionally, due to the FFC, control scheme is independent of the geometry of payload, constraints such as cable tensions, location of grasping position and payloads position. This differentiates it from existing methods in literature. Additionally, the control scheme implemented using force feedback does not involve communication between the leader and the follower UAVs as discussed in the previous section. The proposed control scheme can also be implemented irrespective of the number of UAVs utilized. Additional UAVs would act as followers and follow the leader UAV based on contact forces or torques at their locations. This also provides fault tolerance to the system which suggests that the system will still work even if one of the UAV fails. All these serve as the merits of this research.
3.2.1 Principle of minimization of contact forces/torques

In order to achieve collaborative motion by multiple UAVs, the contact forces at points of attachment of UAVs should be minimized. This principle is used for industrial robots, and is well presented in [22, 23]. It is implemented for UAVs in this research. Consider two people lifting a table together as shown in Fig. 3.1. The table has to be moved in direction D. In order to do so, person A becomes the leader and the person B becomes the follower. Now if person A exerts the force in direction D shown by $F_A$, then a pull contact or interactive force will be generated at the follower B. Now, if the follower wants to move with person A, it must minimize this contact force $F_B$ acting on it. To do so he moves left towards direction D, thus minimizing the contact force $F_B$. This same can be applied for torques as well. This forms the basic principle of force/torque minimization to achieve collaborative transportation of common payload. This principle has been applied.
to develop the force feedback controller using fuzzy logic as well as admittance control in this thesis. The example of humans was considered since humans perform the task of collaborative transportation intuitively and effectively. The same phenomenon is observed in biological entities too. For example ants use the same principle for transporting food particles in a cooperative manner.

3.3 Fuzzy logic control

3.3.1 Introduction

Human brain is more complex with around millions (or even more than that) neurons firing together. It is well said by few people, that humans have immense mental capability. This is witnessed by the tasks possessing uncertainty, chaos, ambiguity, randomness and others [22] which humans perform with ease due to their immense mental capabilities. However, current mathematical models do not address and implement these capabilities in algorithms [22]. Professor L. A. Zadeh of University of California Berkeley invented fuzzy set theory to solve the complex problems in the presence of above mentioned characteristics. The book [46], discusses selected papers by Prof. L.A.Zadeh. Fuzzy Logic was invented to get a mathematical model for problems involving uncertainties, randomness and chaos. The term fuzzy means, something which is approximate or in between. Thus FL provides an approximate solution to the problem [22]. Additionally it helps in incorporating human logic to solve the mathematical problem, as the rules of fuzzy logic
are linguistic in nature. Hence human logic can be implemented to develop the rule base. FL basically emulates human behavior to solve complex problems. Sometimes the mathematical model of the problem is unknown, however the desired results or the outcomes of the problem are known. This is to say that, we know how to control it, however we lack certain mathematic formulae, due to hidden nonlinear dynamics of the system, to evaluate them. In these cases fuzzy logic can be used to develop the controller. Fuzzy logic is robust in nature and allows the use of imprecise and noisy signals to provide the desired output [47]. Hence FL can be used to control nonlinear systems which cannot be modeled mathematically. Hence this methods main underlying focus is to solve the problem instead of understanding its working [47].

3.3.2 Fuzzy Logic Basics

3.3.2.1 Fuzzy sets

A fuzzy set is a set or a class having a number of objects. This set has a characteristic membership function, which determines the amount of membership or grade the object has in a given class. The membership value of an object can vary from 0 to 1 (including values between 0 and 1). Consider an example of a fuzzy set of people, with random heights. There are three MFs in this category, which are short, medium and tall. A person with height 4.5 feet can be considered as the limit for short people, 5.5 feet can be considered as the limit for medium height people, and a person of height 6 feet can be considered as the limit for tall people. These represent the upper limits, and people with
these height are assigned the membership value as 1 in short, medium and tall categories respectively. However a person with height 5.6 feet (between medium and tall) will receive membership value from medium as well as from tall category. In this way ambiguity is taken care of, using fuzzy logic. Such variations are often seen in nature where randomness and uncertainty is present. A Traditional or classical set on the other hand, is a set in which the objects of that class have membership value either 0 or 1, that is there is a person of certain height can either be tall, short or medium. Hence a person with height 5.6 will still be considered of medium height though he also belongs to tall category to some extent. Considering this example, we now understand the difference between fuzzy sets and traditional or classical sets. Hence consider if A is a set of variables $x$, then,

$$MF_A(x) = 0 \text{ OR } MF_A(x) = 1, \text{ for a traditional set and,}$$

$$0 \leq MF_A(x) \leq 1, \text{ for a fuzzy set}$$

where $MF_A$ denotes the membership function value of elements in set A. Additionally, one might confuse probability concepts with fuzzy concepts. However both differ to some extent. Probability function indicates that, the addition or integral of its function should be unity. For example if $P_A$ denotes the probability of an event $A$, $P_B$ of B then,

$$P_A + P_B = 1$$

However this might not be true for fuzzy sets. The integral or the addition of the membership function values may not always be unity. This fact can be clearer after understanding the rules of combining MFs and understanding properties of MFs [48]. Additionally probabilistic approach indicates the chance of the object in a particular
event [22]. For example a person of height 5.6ft has a chance of 30\% being tall. This indicates he has 70\% chance of not being tall. However FL will give a membership value to such person of 1 for medium and maybe over 0.1 for tall.

### 3.3.2.2 Fuzzy Logic Operations

Classical set theory consists of binary logic operators. They are OR for union, AND for intersection and NOT for complement. Operations using these operators follow certain mathematical relations. However fuzzy logic operators are different [22]. Consider two fuzzy sets A and B with their membership function as $f_A(x)$ and $f_B(x)$ respectively. Then the operators as defined by Prof. L. A. Zadeh are as follows,

1. Union: OR operator

   $$C = A \cup B$$
   $$f_c(x) = \max[f_A(x), f_B(x)]$$

2. Intersection: AND operator

   $$C = A \cap B$$
   $$f_c(x) = \min[f_A(x), f_B(x)]$$

3. Complement: NOT operator

   $$f_A'(x) = 1 - f_A(x)$$

Where C is the new resulting fuzzy set in variable ’x’ and $f_C(x)$ is its corresponding membership function [48].
There are overall three steps to solve a problem using Fuzzy Logic. They are:

1. Fuzzification
2. Fuzzy inferencing
3. Defuzzification

In between steps 1 and 2, an additional step is there which generation of rule matrix. These steps are discussed in the following paragraphs.

**Fuzzification**

Fuzzification is the process of fuzzifying the inputs. The input given to a fuzzy logic controller is a number which is known as crisp input. This crisp input must be converted to a fuzzy number or parameter. In other words it means adding uncertainty or ambiguity to this crisp input and converting it to a fuzzy parameter. This can be performed by utilizing a fuzzifier function that provides some fuzziness to a crisp set. It is similar to a membership function, however it is designed to provide an organized and controlled uncertainty to the elements viz. the inputs and outputs [22]. Another method is to build membership functions manually which overlap, such that a degree of uncertainty is induced over the entire crisp set. The spread or pattern of these functions may or may not be symmetric. Depending on the application, the membership functions can be triangular, sinusoidal, trapezoidal or of other forms. Various options can be used to achieve optimum results.

**Fuzzy Rules**

Fuzzy logic controller provides output, by implementing the fuzzy rules which are linguistic IF THEN statements connecting the inputs, fuzzy logic operators and the outputs
of the controller. Any FL rule compromises of two parts which are antecedent and consequent, known as situation and action blocks respectively. The antecedent part of the rule is everything before THEN, whereas the consequent is the part after THEN. The linguistic nature of fuzzy rules allows developing rules based on human common sense. They are developed based on the knowledge of how the system would respond in certain scenarios provided by different combinations of inputs. There are two types of rules Mamdani fuzzy rules and Takagi-Sugeno fuzzy rules. For example, if \( x_1, x_2 \) are inputs, \( x_3 \) is output, \( A \) and \( B \) are input membership functions and \( C \) is the output membership function. Then,

\[
\text{IF } x_1 \text{ is } A \text{ OR } x_2 \text{ is } B \text{ THEN } x_3 \text{ is } C
\]

represents the Mamdani fuzzy rule. Now consider another rule,

\[
\text{IF } x_1 \text{ is } A \text{ OR } x_2 \text{ is } B \text{ THEN } x_3 = f(x_1, x_2)
\]

represents the Takagi Sugeno fuzzy rule. Where \( f \) represents the function in \( x \) [dr.km-th]. Both these rules only differ in the consequent part of the rules. Mamdani system takes the output as a membership function whereas Sugeno system output can be linear or a constant function in \( x \).

**Fuzzy Inferencing**

When certain crisp inputs are applied to a fuzzy controller, certain rules get fired based on the membership value each input carries. The outcomes of all the rules getting satisfied are combined to give the entire area covered in output membership function. Refer Fig. 3.2 for the outcome. This process of determining the outcomes from the input information
Figure 3.2: Fuzzy inferencing: MAX-MIN method [2]

and a set of fuzzy rules is termed as fuzzy inferencing. MAX-DOT, AVERAGE, MAX-
PRODUCT, MAX-MIN, ROOT-SUM-SQUARE(RSS) are some of the most commonly
used fuzzy inference methods. Fig. uses the MAX-MIN Fuzzy inference method[22].

Defuzzification

Defuzzification is a process of converting the fuzzy set achieved in Fuzzy inference method
to a crisp real number denoting the output. The defuzzifier is a mathematical formula
utilized in fuzzy controller to convert the fuzzy set into real number. This step is very
relevant because the output of fuzzy controller cannot be a fuzzy set, it must be a number.
Defuzzification is performed for each output of the system. Various methods are employed
to achieve this process. The centroid method is one of the relevant methods. It computes the centroid of the area covered under the output fuzzy membership function, which is the outcome of combination of various rules. The x-coordinate corresponding to the centroid then becomes the crisp output. Other methods are maxima methods which consist of mean of maximum, Left right maxima and possibility of maximum [22]. The formula utilized for centroid method is,

\[ x_{CG} = \frac{\sum x f_A(x)}{\sum f_A(x)} \]

Where \( f_A \) denotes the membership function of output \( A \) and \( x_{CG} \) is the \( x \) coordinate of center of gravity(CG) of the area denoting the crisp output.

### 3.3.2.3 Fuzzy Logic controller for multiple UAVs collaborating together to transport a common payload

In this research, for the follower UAV, to implement the force feedback controller, a fuzzy logic controller is developed. The follower UAV tracks the leader UAV in accordance with the interaction contact forces and torques acting on the follower UAV, due to leader UAVs motion. Along each coordinate axis a single FL-FFC is implemented. Each components of contact force and torque are provided as inputs and the desired control is taken as output. The rule base for these are developed based on intuitive human logic using the principle of minimization of forces and torques to achieve collaborative transportation. This principle has been discussed, by using the example of a table being transported by
two humans cooperatively, in force feedback section. Based on the same example and principle, the rule base is developed. The main objective becomes controlling the follower UAV by using the contact forces and torques exerted at it. Developing the rule base was a challenge. Initially only three membership functions were assumed for the input torque $\tau$, force $F$ and output motion of the FL-FFC. However in order to achieve an effective control, the FL-FFC was further developed using five membership functions for inputs and outputs. For simulation purposes the contact forces and torques are evaluated by the novel dynamic model developed in this research. This is shown and discussed in the dynamics chapter. It is to be noted that the contact forces and torques will be provided by the force and torque sensors in real world application of the system.

**Development of rule base for FL-FFC in X direction**

Let input 1 be $Force_X$ and input 2 be $torque_Y$ for the follower UAV. The contact force in $X$ direction will determine how much the UAV should move in that direction. In order for a quadcopter or a UAV to move in $X$ direction, it must pitch or tilt about $Y$ axis. Hence the output considered for FL-FFC in $X$ direction is the desired pitch angle for the follower UAV. Five membership functions viz. NL (negative large), NM (negative medium), Z (Zero), PM (positive medium), PL (positive large) are used for inputs and outputs. Now if,

\[
Force_X = NL
\]

\[
torque_Y = NL
\]

This means that both the contact force as well as the contact torque are large along negative $X$ direction, hence, the output motion or desired pitch is,
\[ \theta^{\text{des}} = NL \]

Hence the UAV must move along \( X \) direction by an amount NL(negative large) to minimize the large contact force and torque acting at the follower UAV, to move collaboratively with the leader UAV. Hence the principle of minimization of force/torque (discussed earlier) is implemented to develop the rule base. Suppose now if the,

\[ \text{Force}_X = NL \]

\[ \text{torque}_Y = PM \]

then,

\[ \theta^{\text{des}} = NM \]

This is done because, now in order to minimize the force, the UAV must move in negative X direction by large amount. On the other hand in order to minimize contact \( \text{torque}_Y \) it must move in positive X direction by medium amount. To consider both the effects, the consequent of the rule becomes negative medium. This serves as the advantage for employing five membership functions instead of three membership functions like: \( N \) (negative), \( Z \) (Zero), \( P \) (Positive). For example if,

\[ \text{Force}_X = N \]

and,

\[ \text{torque}_Y = P \]

then

\[ \theta^{\text{des}} = Z \]

However this rule does no tell the magnitude of negativity of force and magnitude of
positivity of torque. On the other hand, the previous rule gives additional information of the existing magnitude of the force and torque acting at the follower UAV.

For FL-FFC in Y direction, the inputs are $F_{\text{force}Y}$ and $\tau_{\text{torque}X}$, which are the force along Y direction and torque about X direction and output is the desired roll angle. Whereas, for FL-FFC in Z direction, the input is only force along Z direction and output is the desired acceleration along Z direction. These outputs from all the FL-FFCs determine the actual pose as well as attitude (angular position) of the follower UAV. The membership functions of all FL-FFCs were tuned manually to achieve optimum results. Additionally triangular MFs were used.

### 3.3.3 Advantages and Drawbacks of fuzzy logic control

Fuzzy logic is inherently robust. It does not require accurate and noise free inputs. The performance of fuzzy logic is effective even in presence of noisy inputs. This gives an added benefit to the research since cheaper and lighter force and torque sensors can be employed, which provides noisy measurements. The rules employed for FL-FFC can be changed anytime to improve the performance of FL-FFC. Fuzzy logic is very flexible in accommodating changes in the parameters or rules. It also provides a weight to the rules. For example if the rule has 0.3 weightage then, its chances of usage are less. The weight can vary from 0 to 1. Hence, critical rules can be given a higher weightage. Sometimes, some inputs need to be dominated as compared to other inputs. For example, FL can provide more response to force or torque. This varying dominance in inputs can be achieved by changing the fuzzy parameters of membership functions which results in change in
shape and position of MF in the Fuzzy inference system (FIS). In order to get optimum results manual tuning, to provide equal role to both force and torque was done. Nonlinear systems with complex dynamics can be controlled using fuzzy logic. The system can be controlled even without knowing the dynamics or mathematics involved behind its working. In this way fuzzy logic helps in solving intricate, complex control problems of nonlinear systems [47]. Additionally its linguistic form helps in solving complex behavior, with the inclusion of human knowledge and common sense to develop the rules. In this manner, it provides a better understanding of the working of the problem, rather than trying to understand the mathematics involved in the problem. Fuzzy controllers also pose many drawbacks. For example obtaining mathematical model of fuzzy controller is difficult. The difficulty increases for FL having multiple inputs and outputs. The mathematical model is required to perform stability analysis like implementing a Lyapunov based theory to evaluate the stability of FLC. Additionally, fuzzy logic employs large number of parameters. Hence its tuning becomes very difficult as compared to simple PID controllers in which only three parameters need to be tuned along each coordinate axis. Optimization solvers like Genetic Algorithm can be employed to tune FLC, however the process is very time consuming [22]. In this research the tuning of all parameters of FL-FFC was carried out manually, which was a challenge.
3.4 Admittance Control

3.4.1 Introduction

The concept of interaction control was proposed by Prof. Neville Hogan. Interaction control consists of controlling robots when they interact with the environment. For example a manipulator arm performing drilling operation is an example of a robot interacting with the environment, here to perform drilling operation. The control strategies employed to carry out these tasks autonomously, are known as interaction control strategies. The admittance control is a special type of interaction control. In manipulators, both force and position control is required. Admittance control takes input as force acting at the end effector and simulates a virtual spring mass system to generate the desired motion of the end effector. In this research it has been used to control the follower UAV only based on the interaction contact forces acting on it.

Additionally, in admittance control approach, spring, mass and damper form the passive elements of a system. These passive elements help in reducing the oscillations on a body. Such systems possess inherent passivity as they perform the role of dissipating the vibration or external energy acting on it [49]. In this research, the utilization of such virtual spring-mass-damper systems (possessing inherent passivity) to control the position of the follower UAV guarantee the stability of the position controller. This forms the merit of using an admittance controller for the collaborative transportation task.
3.4.2 Concepts

Interaction control is generally used in manipulation tasks where hybrid position/force control is required. The manipulator may require the use of either position or force control along a certain coordinate axis. Interaction control provides a relation between the force at the end effector and the position of the manipulator arm. Depending on the inputs or outputs to the control law, there are two types of interaction controls schemes:

1. Impedance control:

In this type of control, position is the input and the force is the output. This can be used in manufacturing applications for example in drilling operation, where a desired force is required at a certain position. The relation for impedance control is as follows,

\[ F = Kx \]

Where, F is the desired force required at the end effector and x is the current position of the end effector. K is termed as the impedance of the controller. Impedance can be considered as the resistance offered by a system.

2. Admittance control

In this type of interaction control, the input is the contact force acting at the end effector and output is the desired motion required at the end effector. For example, given a constant contact force, to perform milling operation to make a slot in a workpiece, a desired trajectory is required. The relation for admittance control is,

\[ x = F/K \]

Where, 1/K represents the admittance or the conductance of a system. It tells how much force should be admitted into the system to get the desired position. K represents
resistance or stiffness of the spring. This means a low resistance will represent high admittance, which indicates higher compliance with force to obtain the desired trajectory.

### 3.4.3 Admittance control for collaborative transportation

Admittance control is a special type of force feedback, interaction control, which provides a desired trajectory or desired motion for follower UAV based on the interaction contact forces generated at it due to the leaders motion. This is done by simulating a virtual spring mass damper system along each coordinate axis of the follower UAV. Refer Fig. 3.3. The equilibrium position of this virtual spring mass system will be the one in which, the springs are un-stretched and dampers are not activated. This is the desired equilibrium position, which the follower must attain to move collaboratively with the leader. An interaction contact force at the follower UAV, will lead to activation of this virtual spring mass damper system. In order to achieve collaborative motion with the leader, the
follower UAV must minimize the contact force and attain the equilibrium position again. Hence the interaction force acts as the external force on the virtual spring mass damper system. Based on this force and the current position of the follower UAV (spring in stretched form), the equilibrium position is evaluated. Hence, the governing control law for this type of controller is expressed as,

\[ m_v(\ddot{r}_T - \ddot{r}) + c(\dot{r}_T - \dot{r}) + K(r_T - r) = F \]  

(3.1)

Where, \( r_T \) is the desired generated trajectory and \( r \) is the current position of the follower UAV. \( m_v, c \) and \( K \) represent the mass, the damping ratio and the stiffness of the virtual spring mass damper system. The desired trajectory generated is then fed to a traditional PID controller for further tracking. This controller is again explained in later chapters. The contact forces are evaluated using the novel dynamic model proposed in this research.
Chapter 4

Dynamical Modeling of the System

4.1 Problem Formulation

The control task consists of lifting a common payload, in the form of a cylindrical rod of mass \( m_p \), with the help of two UAVs. Please refer to Fig. 4.1 for the schematic diagram of the overall system. First UAV acts as the leader and the second UAV acts as a follower. The leader UAV starts from the origin \( \{0, 0, 0\} \) in a three-dimensional (3D) space.

Two scenarios are considered, as control tasks, for the leader UAV. In first scenario, the leader UAV’s role consists of reaching a goal position represented by \( \{x_g, y_g, z_g\} \). Whereas, the second scenario is a task in which the leader UAV has to track a predefined trajectory denoted by \( r_T \) as shown in Fig. 4.1. In order to fulfill either of the scenarios, a control is provided by the leader UAV which is denoted by \( u_l \). This control consists of the desired roll \( (\phi_{l}^{des}) \), pitch \( (\theta_{l}^{des}) \), and yaw \( (\psi_{l}^{des}) \) angles, and desired acceleration \( (\ddot{r}_{Zl}^{des}) \) along \( Z_W \).
Figure 4.1: Schematic system diagram.

axis to allow the leader UAV to perform the tasks discussed above. Hence,

\[ u_l = (\phi_{l}^{des}, \theta_{l}^{des}, \psi_{l}^{des}, r_{zl}^{des}) \] (4.1)

Once the control objective for the leader UAV is defined, next objective consists of computing the control laws (or control) for the follower UAV based on the interaction contact forces and/or torques acting on it. Thus the problem consists of developing a force feedback control scheme that enables the follower UAV to track the leader UAV (in both the scenarios). The control for the follower UAV is denoted by \( u_f \) which consists of the desired roll \( (\phi_f^{des}) \), pitch \( (\theta_f^{des}) \), and yaw angles \( (\psi_f^{des}) \), and desired acceleration along \( Z_W \) axis \( (r_{zf}^{des}) \), to follow the leader UAV and reach the final position denoted by \( \{x_f, y_f, z_f\} \). Hence,

\[ u_f = (\phi_f^{des}, \theta_f^{des}, \psi_f^{des}, r_{zf}^{des}) \] (4.2)
The objective of the follower controller is to minimize the interaction forces developed at the point of contact with the payload.

It is assumed that the system has rigid connections, that is, both UAVs are rigidly attached to the payload. Hence, the angular acceleration of the entire system is the same, due to which the UAVs as well as the payload possess the same attitude at any time instant. Also, UAVs are assumed to have a constant yaw equal to zero (i.e., $\psi_{l}^{des} = \psi_{f}^{des} = 0$). It may be noted that this assumption does not affect the ability of the system to carry out the two tasks mentioned above.

## 4.2 Dynamics of the Overall System

The dynamics of the system has been developed based on the free body diagrams of the individual components of the system, as seen in Fig. 4.2. Let $X_W$, $Y_W$ and $Z_W$ be the axes in the world frame $W$ and $X_B$, $Y_B$ and $Z_B$ the corresponding axes in body frame $B$ of the leader UAV. It may be noted that body frames of the leader and the follower UAVs are aligned since they share the same orientation due to rigid connection in the system. The equation of motion of the leader is given by:

$$F_1 = R * \begin{bmatrix} 0 \\ 0 \\ F_l \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ m_l * g \end{bmatrix} - m_l * \ddot{r}_l$$  \hspace{1cm} (4.3)
where $F_1$ is the contact force acting on the payload at the point of contact with the leader UAV. It may be noted that, due to Newton’s third law, $F_1 = -F_0$, $F_3 = -F_2$, $\tau_1 = -\tau_l$, and $\tau_f = -\tau_2$. $F_l$ is the sum of all the rotor thrusts of the leader UAV. In equation (4.3), $m_l$, $r_l$, $R$ are the mass of the leader, the position of the leader, and the rotation matrix from leader’s body frame $B$ to the world frame $W$, respectively. The rotation matrix $R$ from the body to the world frame is given by:

$$R = \begin{bmatrix}
    c\psi c\theta - s\phi s\psi s\theta & -c\phi s\psi & c\psi s\theta + s\phi s\psi c\theta \\
    c\theta s\psi + c\psi s\phi s\theta & c\phi c\psi & s\psi s\theta - c\psi c\theta s\phi \\
    -c\phi s\theta & s\phi & c\phi c\theta 
\end{bmatrix}$$

(4.4)

where $\phi$, $\theta$ and $\psi$ represent the actual roll angle, pitch angle and yaw angle of the system, which forms the actual (or current) attitude of the system. Also, $c(.)$ and $s(.)$ represent the cosine and sine terms of roll, pitch and yaw angles [50]. The rotation matrices from the world to the body frames of all the three entities (leader, follower and payload) are the
same since they possess the same attitude. The equation governing the follower UAV’s translational motion is expressed as:

\[
F_2 = R \begin{bmatrix} 0 \\ 0 \\ F_f \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ m_f \ast g \end{bmatrix} - m_f \ast \ddot{r}_f \tag{4.5}
\]

where \( F_2 \) is the contact force at the payload end at the point of contact with the follower UAV. \( F_f, \) \( m_f \) and \( r_f \) represent the sum of rotor forces of the follower, the mass of the follower and the position of the follower, respectively. Similarly, the equation of translational motion of the payload can be written as:

\[
m_p \ast \ddot{r}_p = F_1 + F_2 - \begin{bmatrix} 0 \\ 0 \\ m_p \ast g \end{bmatrix} \tag{4.6}
\]

\( m_p \) is the mass of the payload and \( r_p \) is the position of the payload. The equations of motion corresponding to the rotational motion for the system are also evaluated. The rotational equations of motion for the leader and the follower UAV are given as

\[
\tau_1 = \begin{bmatrix} L_1 \ast (F'_2 - F'_4) \\ L_1 \ast (F'_3 - F'_1) \\ M_1l - M_2l + M_3l - M_4l \end{bmatrix} - \begin{bmatrix} p_l \\ q_l \\ r_l \end{bmatrix} \times I_l - I_l \ast \alpha_l \tag{4.7}
\]
\[
\tau_2 = \begin{bmatrix}
L_2 * (F_2^f - F_4^f) \\
L_2 * (F_3^f - F_1^f) \\
M_1^f - M_2^f + M_3^f - M_4^f
\end{bmatrix} - \begin{bmatrix}
p_f \\
q_f \\
r_f
\end{bmatrix} \times I_f \begin{bmatrix}
p_f \\
q_f \\
r_f
\end{bmatrix} - I_f * \alpha_f
\] (4.8)

where \(\tau_1\) and \(\tau_2\) are the contact torques at the payload ends at points of contact of the leader UAV and the follower UAV end respectively. \(L_1\) and \(L_2\) are the lengths of the arms (distance between UAV centre and rotor centre of the UAV) of the leader and the follower UAV. \(F_i^l\) and \(M_i^l\) are the forces and moments generated by the i’th rotor of the leader. \(F_i^f\) and \(M_i^f\) are the forces and moments generated by the i’th rotor of the follower. The angular velocity components in body frame are denoted by \(p, q\) and \(r\) with suffix \(l\) for leader UAV, \(f\) for follower UAV and \(p\) for payload. \(\alpha_i\), \(\alpha_f\) and \(\alpha_p\) denote the angular acceleration vector of the leader UAV, the follower UAV and the payload. The mass moments of inertia of the leader UAV, follower UAV, and the payload are represented as \(I_i, I_f,\) and \(I_p\). The rotational equation of motion of the payload is expressed as follows:

\[
I_p * \alpha_p = \tau_1 + \tau_2 - \begin{bmatrix}
p_p \\
q_p \\
r_p
\end{bmatrix} \times I_p \begin{bmatrix}
p_p \\
q_p \\
r_p
\end{bmatrix} + (r_1 \times F_1) + (r_2 \times F_2)
\] (4.9)

where,

\[
r_1 = r_1 - r_p
\] (4.10)

\[
r_2 = r_f - r_p
\] (4.11)
In equation 4.9, \( r_1 \) represents the vector from the payload center to the center of the leader UAV, and \( r_2 \) is the vector from the payload center to the center of the follower UAV. The expression \( (r_1 \times F_1) \) represents the moment due to the contact force at the point of contact of the payload and the leader UAV. While, \( (r_2 \times F_2) \) is the moment due to the contact force at the point of contact of payload and the follower UAV.

Additionally, the following equations are derived from the rigid body motion of the system. The following equations relate the linear acceleration at the payload ends (where UAVs are attached) with the linear acceleration at the center of gravity of the payload.

\[
\ddot{r}_l = \ddot{r}_p + (\alpha_p \times r_1) + (\omega_p \times (\omega_p \times r_1))
\] (4.12)

\[
\ddot{r}_f = \ddot{r}_p + (\alpha_p \times r_2) + (\omega_p \times (\omega_p \times r_2))
\] (4.13)

where,

\[
\omega_p = \begin{bmatrix}
p_p \\
q_p \\
\tau_p
\end{bmatrix}
\] (4.14)

Considering, the assumption of rigid connection between the leader and the payload, and the payload and the follower results in the same angular accelerations for the leader,
follower, and the payload. Hence:

$$\alpha_l = \alpha_f = \alpha_p \quad (4.15)$$

The purpose of developing this detailed dynamic model for the system is to develop a realistic simulation framework where accelerations (linear and angular) and the contact forces and torques can be found based on forces and moments generated by the UAVs. The interaction contact forces would then serve as the input to the controller designed for the follower UAV as discussed in the following section. Euler integration of the accelerations obtained from the above equations would be used to obtain the velocity and position, and simulate the system.
Chapter 5

Control Approaches

A leader-follower approach is utilized for collaborative transportation task using two UAVs. One of the UAV acts as the leader, and the second one acts as the follower UAV which follows the leader based on the contact forces and torques acting on it due to leader’s motion. The leader UAV starts from the origin \( \{0, 0, 0\} \) and is required to reach a desired goal point \( \{x_g, y_g, z_g\} \) in the first scenario and follow a predefined trajectory denoted by \( r_T \) in second scenario as discussed in Problem formulation section. The leader UAV controller design is based on a traditional PID controller as discussed in [50]. For the follower UAV, two control schemes are implemented that utilize contact forces and torques acting on the follower. The first scheme is a Fuzzy Logic based Force Feedback Controller (FL-FFC) that utilizes a Fuzzy Inference Engine (FIS), tuned manually based on human expertise, outputs the controls \( u_f \) using the contact forces and torques and inputs acting on the follower. The second scheme is an admittance based force feedback controller which
Figure 5.1: Overall control architecture for the entire system, FL-FFC ensures compliance of the generated trajectory of the follower UAV with the interaction contact forces acting on it. It simulates virtual spring mass damper systems along each coordinate axis for implementing the FFC. Performance of the both the FFCs is compared to a traditional PID based Position Feedback Controller (PFC) for the follower UAV. It may be noted that implementing this controller requires communication of leader position to the follower. Availability of such information makes this an ideal controller and the objective of the FFC is to achieve the performance of the PFC to the extent possible. The control architecture for both the proposed control schemes for the follower UAV are shown in Fig. 5.1 and Fig. 5.2.

5.0.1 Leader UAV Controller Design

The control $u_l$ (see Fig. 4.1) for the leader UAV is provided by the traditional PID controller as discussed in [50]. The PID control law for the position control is as follows:
\[ \ddot{\mathbf{r}}_1^{\text{des}} = k_p (\mathbf{r}_{T_l} - \mathbf{r}_l) + k_d (\dot{\mathbf{r}}_{T_l} - \dot{\mathbf{r}}_l) \]
\[ + k_I \int (\mathbf{r}_{T_l} - \mathbf{r}_l) dt + \ddot{\mathbf{r}}_{T_l} \]

Figure 5.2: Overall control architecture for the entire system, admittance FFC

where \( k_p, k_d \) and \( k_I \) are three-dimensional vectors which consist of the proportional, derivative and integral gains respectively. These gains are tuned manually in the simulation. \( \mathbf{r}_{T_l}, \dot{\mathbf{r}}_{T_l}, \) and \( \ddot{\mathbf{r}}_{T_l} \) represent the desired trajectory, its derivative, and its double derivative. It may be noted that, for the case when the control objective is to reach a desired goal point, \( \mathbf{r}_{T_l} = \{x_g, y_g, z_g\} \), and \( \dot{\mathbf{r}}_{T_l} = \ddot{\mathbf{r}}_{T_l} = 0 \). Furthermore, without loss of ability of the UAVs to track any arbitrary trajectory, we consider \( \psi_l^{\text{des}} = \psi_T = 0 \). \( \ddot{\mathbf{r}}_1^{\text{des}} \) constitutes the desired linear acceleration of the leader UAV to track the desired trajectory.
The desired roll and pitch angles for the leader’s attitude controller are derived from desired accelerations along the $X_W$ and $Y_W$ directions via linearization of the dynamics equations as:

\[
\phi_{l}^{des} = \frac{1}{g} (\mathbf{r}_{xl}^{des} \sin \psi_T - \mathbf{r}_{yl}^{des} \cos \psi_T) \tag{5.2}
\]

\[
\theta_{l}^{des} = \frac{1}{g} (\mathbf{r}_{xl}^{des} \cos \psi_T + \mathbf{r}_{yl}^{des} \sin \psi_T) \tag{5.3}
\]

If $\Delta \omega_{Fl}$ is the change in rotor speeds needed to provide acceleration along the $Z_W$ direction, it is calculated from the desired linear acceleration along the $Z_W$ direction, $\mathbf{r}_{z}^{des}$, as:

\[
\Delta \omega_{Fl} = \frac{m_l \mathbf{r}_{z}^{des}}{8 k_F \omega_{hl}} \tag{5.4}
\]

Where $\omega_{hl}$ is the nominal rotor speed required for the leader UAV to hover. It is given by:

\[
\omega_{hl} = \sqrt{\frac{m_l g}{4 k_F}} \tag{5.5}
\]

The desired pitch, roll and $\Delta \omega_{Fl}$ are used to control leader UAV’s position in $X_W$, $Y_W$ and $Z_W$ axes respectively. Deviations from the $\omega_{hl}$ for different rotors are used to navigate the UAV along different directions. These deviations are denoted as $\Delta \omega_{Fl}$, $\Delta \omega_{pl}$, $\Delta \omega_{tl}$ and $\Delta \omega_{vl}$. Here $\Delta \omega_{pl}$, $\Delta \omega_{tl}$ and $\Delta \omega_{vl}$ provide roll, pitch and yaw to the leader UAV, while $\Delta \omega_{Fl}$ provides motion along the $Z_W$ axis of the UAV. These deviations for attitude
control of leader UAV are obtained using the desired roll and pitch angles from equations 5.2 and 5.3 and are expressed as:

\[
\Delta \omega_{\phi l} = k_{p,\phi}(\phi_l^{des} - \phi_l) + k_{d,\phi}(p_l^{des} - p_l) 
\]

\[
\Delta \omega_{\theta l} = k_{p,\theta}(\theta_l^{des} - \theta_l) + k_{d,\theta}(q_l^{des} - q_l) 
\]

\[
\Delta \omega_{\psi l} = k_{p,\psi}(\psi_l^{des} - \psi_l) + k_{d,\psi}(r_l^{des} - r_l) 
\]

Where \( p_l^{des}, q_l^{des} \) and \( r_l^{des} \) denote the desired angular velocity of the leader UAV and \( \phi_l, \theta_l \) and \( \psi_l \) represents the attitude of the leader UAV at that instant. Further, we derive the desired rotor speeds of the leader UAV by using equations 5.6 to 5.8 as:

\[
\begin{bmatrix}
\omega_1^{des} \\
\omega_2^{des} \\
\omega_3^{des} \\
\omega_4^{des}
\end{bmatrix}_l =
\begin{bmatrix}
1 & 0 & -1 & 1 \\
1 & 1 & 0 & -1 \\
1 & 0 & 1 & 1 \\
1 & -1 & 0 & -1
\end{bmatrix}
\begin{bmatrix}
\omega_{hl} + \Delta \omega_{F l} \\
\Delta \omega_{\phi l} \\
\Delta \omega_{\theta l} \\
\Delta \omega_{\psi l}
\end{bmatrix}
\]

The individual rotor thrust forces and moments produced are calculated by taking into account the motor characteristics. They are computed according to the equations:

\[
F_{i,l} = k_F \omega_i^2 
\]

\[
M_{i,l} = k_M \omega_i^2 
\]

The constants \( k_F \) and \( k_M \) were considered as \( 2.2 \times 10^{-4} \) and \( 5.4 \times 10^{-6} \) respectively.
5.0.2 Follower UAV Controller Design

5.0.2.1 Fuzzy logic based controller design

The follower tracks the leader based on the interaction forces and torques exerted on it at the point of contact with the payload. This controller is implemented with the help of a fuzzy logic based force feedback controller (FL-FFC). One FL-FFC is implemented along each axis. These FL-FFC take different components of the contact force $F_3$ and torque $\tau_f$ at the follower UAV as the inputs and provide the control $u_f$ as the output. The main underlying principle in which the FL-FFC is developed is that it calculates the outputs that will minimize the contact force and torque at the follower UAV. This objective results in the achievement of the collaborative motion with the leader UAV. This principle has been proposed and discussed in [22], [23] for the collaborative transportation task using the industrial robots.

The fuzzy logic rules for the FL-FFC have been developed intuitively based on the principle of minimization of contact forces and torques. This can be explained with the help of an example as follows. Let $F_{3,x}$, $F_{3,y}$ and $F_{3,z}$ denote the contact forces acting at the follower UAV along the $X_W$, $Y_W$ and $Z_W$ axes respectively. Additionally let $\tau_{f,x}$, $\tau_{f,y}$ and $\tau_{f,z}$ be the contact torques acting on it along the $X_W$, $Y_W$ and $Z_W$ axes respectively.

Considering the dynamics of the system, it is evident that the contact force $F_{3,x}$ and contact torque $\tau_{f,y}$ producing the pitching moment are responsible for producing motion in $X_W$ axis. In order to achieve collaborative motion with leader UAV along $X_W$ axis, the follower UAV must reduce this contact force and torque acting on it by moving in
**Table 5.1: Rules for FL-FFC for X_W direction**

<table>
<thead>
<tr>
<th>torque_y</th>
<th>NL</th>
<th>NM</th>
<th>Z</th>
<th>PM</th>
<th>PL</th>
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<tbody>
<tr>
<td>NL</td>
<td>NL</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>Z</td>
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</tr>
<tr>
<td>PL</td>
<td>Z</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PL</td>
</tr>
</tbody>
</table>

**Table 5.2: Rules for FL-FFC for Y_W direction**

<table>
<thead>
<tr>
<th>torque_x</th>
<th>NL</th>
<th>NM</th>
<th>Z</th>
<th>PM</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>Z</td>
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<td>NM</td>
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<td>PM</td>
<td>Z</td>
</tr>
</tbody>
</table>

X_W direction. Thus the FL-FFC for the follower UAV along X direction should provide a certain desired pitch angle that will result in reduction of $F_{3,x}$ and $\tau_{f,y}$. Hence, if contact force $F_{3,x}$ and contact torque $\tau_{3,y}$ acting at the follower UAV are large, then high desired pitch angle is provided to the follower UAV to produce large motion along X_W axis. Similarly, the same concept is applied to develop the FL-FFC along Y_W direction. For Z_W axis, only contact force along it is used as input to provide the desired linear acceleration along Z_W axis. Rules for FL-FFC along all the three axes (developed based on the principle mentioned above) are presented in tables 5.1, 5.2 and 5.3. Where, NL is negative large, NM is negative medium, Z is zero, PL is positive large and PM is positive medium.
Table 5.3: Rules for FL-FFC for $Z_W$ direction

<table>
<thead>
<tr>
<th>$f_{3z}$</th>
<th>$z_{des}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

Hence, the FL-FFC for controlling motion in $X_W$ direction consists of the following inputs and output

$$input_{FFC,X} = (F_{3x}, \tau_{f,y})$$  \hspace{1cm} (5.12)

$$output_{FFC,X} = (\theta_{des}^f)$$

Similarly, for FL-FFC in $Y_w$ and $Z_W$ directions we have,

$$input_{FFC,Y} = (F_{3y}, \tau_{f,x})$$  \hspace{1cm} (5.13)

$$output_{FFC,Y} = (\phi_{des}^f)$$

$$input_{FFC,Z} = (F_{3z})$$  \hspace{1cm} (5.14)

$$output_{FFC,Z} = (\tilde{x}_{zf}^{des})$$

The FL-FFC was tuned manually to achieve the optimum results. The membership functions for FL-FFC along all three coordinate directions are shown in Fig. 5.4, Fig. 5.5 and Fig. 5.6. The control surface of FL-FFC for each axis are shown in Fig. 5.3. The outputs obtained from FL-FFC are provided to the attitude control of the follower.
Control surface for FL-FFC in $X_W$ direction

Control surface for FL-FFC in $Y_W$ direction

Control surface for FL-FFC in $Z_W$ direction

Figure 5.3: Control surfaces for FL-FFC in the three directions.

UAV to generate $\Delta \omega_{\phi f}$, $\Delta \omega_{\theta f}$ and $\Delta \omega_{\psi f}$ as can be seen from the control architecture presented in Fig. 5.1. We use a PD attitude controller similar to the leader as presented in Equations 5.6, 5.7, and 5.8. Similarly, the output from equation 5.14 (i.e., $\omega_{zf}^{des}$) is used to evaluate $\Delta w_{Ff}$ using equation similar to 5.4. These values are used to compute the desired rotor speeds, the rotor thrusts and moments of the follower UAV similar to the equations 5.9 to 5.11 applied for leader UAV control.
Input membership functions of Force along $X_W$ axis

Input membership functions of torque about $Y_W$ axis

Output membership functions of desired pitch angle for follower UAV

Figure 5.4: Membership functions for FL-FFC in $X_W$ direction.
Input membership functions of Force along $Y_W$ axis

![Input membership functions of Force along $Y_W$ axis](image1)

Input membership functions of torque about $X_W$ axis

![Input membership functions of torque about $X_W$ axis](image2)

Output membership functions of desired roll angle for follower UAV

![Output membership functions of desired roll angle for follower UAV](image3)

**Figure 5.5:** Membership functions for FL-FFC in $Y_W$ direction.
Input membership functions of Force along $Z_W$ axis

Output membership functions of desired linear acceleration along $Z_W$ axis for follower UAV

Figure 5.6: Membership functions for FL-FFC in $Z_W$ direction.
5.0.2.2 Admittance based controller design

The admittance controller for the follower UAV consists of a virtual spring-mass-damper system along each coordinate axis. Consider the schematic diagram as shown in Fig 5.7. The desired trajectory for the follower UAV is generated by simulating this virtual spring-mass-damper system. The desired trajectory generated for the follower UAV complies with the contact forces acting at the follower UAV. In this paper, we assume a constant desired yaw for the follower and we do not consider compliance with contact torques acting at the follower UAV. Main objective of the control scheme is to minimize the contact forces acting on the follower UAV, to achieve synchronous motion with the leader UAV. In order to achieve collaborative transportation, the follower UAV must attain equilibrium. Equilibrium position of the follower UAV is a position in which the spring is
unstretched and forces acting on the two ends are zero. Contact forces at the follower UAV are generated due to leader’s motion resulting in loss of equilibrium. Thus, the desired trajectory is generated in such a manner that simulates the response of the mass to the force acting at the base of spring-damper system. For simulation purposes, calculation of the contact forces acting at the follower UAV is done by the developed dynamic model discussed in above sections. The admittance based control law providing the desired trajectory is given by,

\[ m_v(\ddot{r}_{Tf} - \dot{r}_f) + c(\dot{r}_{Tf} - \dot{r}_f) + K(r_{Tf} - r_f) = F_3 \]  

(5.15)

where \( r_{Tf}, \dot{r}_{Tf} \) and \( \ddot{r}_{Tf} \) represent the desired trajectory, its derivative, and its double derivative of the follower UAV. \( K \) represents the stiffness of virtual spring, \( c \) is the damping coefficient of the virtual damper and \( m_v \) is the virtual mass of the spring damper system. The stiffness, damping coefficient and the virtual mass of the spring mass damper system is tuned along each coordinates axis. Compliance with contact forces is achieved by tuning the stiffness \( K \) of the springs. Higher stiffness represents low compliance while low stiffness represents high compliance with the contact forces [3]. Simulation was performed for a critically damped system in order to reduce any undesired oscillations. The critical damping coefficient is expressed as,

\[ c_c = 2\sqrt{m_vK} \]  

(5.16)
Results are also presented for an overdamped system in subsequent section with value of damping coefficient to be higher than the critical damping coefficient. Once the desired trajectory of the follower UAV is obtained by solving Equation 5.15, it is then tracked by using a PID controller for the follower as,

\[ \ddot{\mathbf{x}}_{\text{des}} = k_{p,f} \ast (r_{Tf} - \mathbf{r}_f) + k_{d,f} \ast (\dot{r}_{Tf} - \dot{\mathbf{r}}_f) + k_{I,f} \int (r_{Tf} - \mathbf{r}_f) dt + \ddot{r}_{Tf} \]  

(5.17)

where \( k_{p,f}, k_{d,f} \) and \( k_{I,f} \) are three-dimensional vectors which consist of the proportional, derivative and integral gains respectively of the follower UAV. These gains are tuned manually in the simulation. \( \ddot{\mathbf{x}}_{\text{des}} \) constitutes the desired linear acceleration of the follower UAV to track the desired trajectory. The outputs obtained from equation 5.17 are used to compute desired pitch, roll angles and \( \Delta \omega_{F_f} \) in Z direction for the follower UAV , similar to equations 5.2 to 5.4. These values are then provided to the attitude control of the follower UAV to generate \( \Delta \omega_{\phi_f}, \Delta \omega_{\theta_f} \) and \( \Delta \omega_{\psi_f} \) as can be seen from the control architecture presented in Fig. 5.1. We use a PD attitude controller similar to the leader as presented in Equations 5.6, 5.7, and 5.8. These values are then used to compute the desired rotor speeds, the rotor thrusts and moments of the follower UAV similar to the equations 5.9 to 5.11 applied for leader UAV control. The performance of the admittance based FFC is compared to a traditional PID based Position Feedback Controller (PFC) for the follower UAV. It may be noted that implementing this controller requires communication of leader position to the follower. Availability of such information makes this an
ideal controller and the objective of the FFC is to achieve the performance of the PFC to the extent possible.
Chapter 6

Results and Discussions

This section discusses the simulation results obtained by implementing the force feedback control (FFC) schemes for the follower UAV using admittance and Fuzzy logic (FL) based strategies. The leader uses a traditional PID control law to follow a predefined trajectory. The performance of the proposed control schemes is compared with the benchmarked position feedback controller (PFC) for the follower UAV. The PFC is considered as the benchmarked controller for the follower because PFC takes complete positional feedback of the leader UAV and provides it to the follower UAV, making it the most ideal controller for the follower UAV. The parameters in SI units used in simulation are:

**Parameters used for Fuzzy Logic FFC:**

$$m_l = 1\,kg, \quad m_f = 1\,kg, \quad m_p = 0.2\,kg, \quad L1 = L2 = 0.12\,m, \quad l = 0.54\,m, \quad k_p = \begin{bmatrix} 1.1 & 0.8 & 0.2 \end{bmatrix},$$

$$k_d = \begin{bmatrix} 3.6 & 1.8 & 0.8 \end{bmatrix}, \quad k_l = \begin{bmatrix} 0.2 & 0 & 0 \end{bmatrix}, \quad \psi_l^{\text{des}} = 0, \quad k_{p,\theta} = k_{p,\theta,f} = 300, k_{p,\phi} = k_{p,\psi} = k_{p,\phi,f} = k_{p,\psi,f} = 40, \quad k_{d,\phi} = k_{d,\phi,f} = k_{d,\psi} = k_{d,\psi,f} = 20, \quad k_{d,\theta} = 30$$
Parameters used for admittance FFC:

\( m_l = 1 kg, \ m_f = 1 kg, \ m_p = 0.2 kg, \ L_1 = L_2 = 0.12 m, \ l = 0.54 m, \ k_p = k_{p,f} = \begin{bmatrix} 2.2 & 0.2 & 1.6 \end{bmatrix}, \ k_d = k_{d,f} = \begin{bmatrix} 2.6 & 1 & 2.1 \end{bmatrix}, \ k_I = k_{I,f} = \begin{bmatrix} 0.2 & 0.01 & 0 \end{bmatrix}, \ \psi_l^{des} = 0, \)

\( k_{p,\phi} = k_{p,\psi,f} = k_{p,\psi} = k_{p,\psi,f} = 40, k_{p,\theta} = k_{p,\theta,f} = 210, k_{d,\phi} = k_{d,\phi,f} = 28, k_{d,\theta} = k_{d,\theta,f} = 20, \)

\( K = \begin{bmatrix} 0.02 & 0.02 & 0.02 \end{bmatrix}, \ m_v = \begin{bmatrix} 10 & 10 & 10 \end{bmatrix} \)

The initial positions of all the three entities, viz, the leader, the center of gravity of payload and the follower are: 0,0,0, \( l/2, 0, 0 \) and \( l, 0, 0 \) in 3D coordinates respectively, where \( l \) denotes the length of the payload which is 0.54 m in our case. The increment in time is taken as 0.01 sec. The results are provided for goal point navigation as well as trajectory tracking in the following paragraphs. The dotted lines represent the results for PFC whereas the solid lines are the results for FFC using a particular control scheme (fuzzy or admittance). Additionally, to get an extensive understanding of the performance of both the control schemes, two control scenarios or tasks are performed. They are:

1. **Scenario 1: Goal point navigation**

   In this scenario the leader UAV, is given a desired way point to reach and the results for the entire system are analyzed. The goal point assigned to the leader UAV for both the controls schemes (admittance and fuzzy) is 1m, 2m, 3m in 3D space.

2. **Scenario 2: Trajectory tracking**

   In this control task, the leader UAV follows or tracks a predefined trajectory. In this case, we implement the figure of 8 trajectory tracking for the leader UAV. This trajectory has been implemented in literature to evaluate the maneuverability capabilities of the UAV [51]. The equations defining the figure of 8 trajectory are:
\[ \text{scale} = \frac{20}{3 - \cos(2\omega_T t)} \]  

(6.1)

\[ r_{T,x} = \text{scale} \times \cos(\omega_T t) \]  

(6.2)

\[ r_{T,y} = \frac{\text{scale} \times \sin(2\omega_T t)}{2} \]  

(6.3)

Where \( w_T \) denotes the angular velocity of the trajectory. It is taken as 0.04 rad/sec in the simulations. \( t \) denotes the time in seconds. The z-coordinate of the trajectory \( r_{T,z} \) was assumed to be constant. \( r_{T,x} \) and \( r_{T,y} \) are the desired positions of the leader UAV in \( X_W \) and \( Y_W \) directions which are tracked by the PID controller discussed in dynamics chapter and are functions of time. The single and double time derivatives of the trajectory \( r_T \) are taken to compute the trajectory velocity and acceleration of the trajectory, which are then tracked by the PID controller of the leader UAV. The following sections discusses the results for both these scenarios for fuzzy logic and admittance based FFCs respectively.

### 6.1 Results for Fuzzy Logic based FFC

Fig. 6.1 shows the performance of Fuzzy Logic force feedback controller (FL-FFC) along \( X_W \) direction. The desired waypoint along \( X_W \) is 1m for leader UAV. As it can be seen the system shows convergence to the desired waypoint along X direction. The observed response is very stable and shows higher convergence rate as compared to the benchmarked Position feedback controller (PFC). Fig. 6.2 shows the performance of
FL-FFC along $Y_W$ direction in which the desired waypoint for leader UAV is 2m. It can be seen from the Fig. 6.2 that the system attains the desired waypoint faster as compared to PFC. It also shows a stable response with FL-FFC. Similarly, Fig. 6.3 shows the response of FL-FFC along $Z_W$ direction in which the desired way point is 3m for leader UAV. Both stability as well as faster convergence is observed for FL-FFC as compared to PFC. A slight overshoot is observed along $Z_W$ direction for FL-FFC. However, it can be compromised for, since faster convergence is obtained. Hence the small overshoot can be neglected. The desired control for leader UAV, is seen in Fig. 6.4. The desired control for the UAV consists of the desired roll angle, pitch angle and desired acceleration along $Z_W$ axis. All these three parameters for leader UAV can be seen in Fig. 6.4. The desired roll angle for the leader UAV is almost similar to one obtained from PFC, however, the magnitude of the desired roll angle is large for FL-FFC and a phase shift is observed as compared to PFC. The desired pitch angle for the leader UAV is large initially in magnitude as compared to the PFC, however as time progresses it becomes almost similar to desired pitch angle obtained by using PFC. The desired linear acceleration along $Z_W$ axis is large in magnitude initially for FL-FFC as compared to PFC. On a similar note, the controller response for the follower UAV can be observed from Fig. 6.7. The desired control for the follower UAV is obtained by implementation of FL-FFC which takes contact forces and torques acting at the follower UAV as inputs. Fig. 6.5 shows the contact forces acting at the follower UAV. The contact force along $X_W$ direction has oscillations as compared to the PFC. However, these oscillations dampen out as time progresses. The contact force along $Y_W$ direction
is almost similar in magnitude and differs in phase as compared to the contact force in $Y_W$ direction in PFC. The contact force along $Z_W$ direction is larger in magnitude as compared to PFC, with oscillations. Fig. 6.6 shows the contact torques at the follower UAV about, $X_W$, $Y_W$ and $Z_W$ axes respectively. The contact torque about $X_W$ axis is large in magnitude initially as compared to PFC. Similarly contact torque about $Y_W$ axis is large in magnitude as well as shows some oscillations in contrast to PFC. The torque about $Z_W$ axis shows slight oscillations initially using FL-FFC. These contact forces and torques are used to evaluate the desired control for the follower UAV as discussed in the previous chapters. Refer Fig. 6.7. The desired roll angle is small in magnitude using FL-FFC as compared to PFC. The desired pitch angle shows spikes as time progresses and is almost similar in magnitude with PFC, with an additional phase shift. The desired linear acceleration along $Z_W$ axis is small in magnitude as compared to PFC. Fig. 6.8 shows the actual angles of the leader and the follower UAVs and the whole system. The actual roll angle using FL-FFC is almost similar to the one obtained from PFC, however a small phase shift is observed. The actual pitch angle is larger in magnitude for FL-FFC as compared to PFC. It also shows some oscillations. The actual yaw angle of the system is large in magnitude with an additional phase shift observed, for FL-FFC as compared to PFC. Additionally, Fig. 6.9 shows a three-dimensional plot of the whole system showing trajectories of leader and follower UAVs for PFC and FL-FFC. Additionally table 6.1 and table 6.2 provide the position response characteristics of the follower UAV for PFC and FL-FFC.
6.2 Results for admittance based FFC

The results for admittance based FFC are plotted for critically damped virtual spring mass damper systems, along all three coordinate directions. The response of admittance controller along $X_W$ direction can be observed in Fig. 6.10. Similarly, Fig. 6.11 and Fig. 6.12 show the response of the system along $Y_W$ and $Z_W$ axes respectively. These responses show fast and stable convergence to the desired waypoint which is 1m, 2m and 3m along $X_W$, $Y_W$ and $Z_W$ axes respectively for the leader UAV. Fig. 6.13 shows the desired control of leader UAV for admittance scheme. It can be observed that the desired roll angle is almost similar in magnitude as compared to the one obtained by using PFC. However, less oscillations and a phase shift is observed for roll angle using admittance scheme. The desired pith angle using admittance scheme is large initially, however it converges to zero as time progresses. The desired linear acceleration along $Z_W$ direction is also large in magnitude as compared to desired acceleration obtained using PFC. The admittance controller for the follower UAV complies with the contact force acting at the follower UAV. Fig. 6.14 shows the contact forces acting at the follower UAV. The contact force acting along $X_W$ direction shows high magnitude initially and then converges to zero as compared to PFC. The contact force along $Y_W$ axis is similar in magnitude with PFC, however phase shift and less oscillations are observed using the admittance scheme in contrast to the PFC. Contact force along $Z_W$ direction is large in magnitude initially and then it converges to zero for admittance strategy. These contact forces are used in generating the desired control for the follower UAV. The desired control for the follower
UAV is shown in Fig. 6.15. The desired roll angle of the follower UAV is slightly less in magnitude as compared to the desired roll angle obtained using PFC. The desired roll angle obtained using admittance also shows less oscillations as compared to PFCs desired roll angle. The desired pitch angle shows large magnitude with oscillations initially, which dampen out as time progresses using admittance scheme. The desired linear acceleration along $Z_W$ axis for the follower UAV is very less and near zero as compared to PFC. Fig. 6.16 shows the actual angles of the leader, follower UAV and the entire system using admittance FFC. The actual roll angle is less in magnitude with less oscillations and slight phase shift over roll angle obtained via PFC. The actual pitch angle shows large magnitude and oscillations initially as compared to PFC. Though PFC shows a zero yaw angle, the actual yaw angle is observed using admittance scheme. This yaw angle shows oscillations and finally converges to zero as time progresses. Additionally, Fig. 6.17 shows a three-dimensional plot of the whole system showing trajectories of leader and follower UAVs for PFC and admittance FFC. Table 6.3 provides the position response characteristics of the follower UAV for admittance based FFC. As can be seen from all the position response characteristics tables, the admittance based strategy gives faster rise time. However, it shows slow performance in terms of higher settling time and more percent overshoot as compared to the fuzzy logic based control.
Table 6.1: Position response characteristics for PFC

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<th>Rise time (sec)</th>
<th>Settling time (sec)</th>
<th>Overshoot (%)</th>
<th>Peak time (sec)</th>
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<tr>
<td>X axis</td>
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<td>37.2930</td>
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<td>Z axis</td>
<td>18.3363</td>
<td>33.1299</td>
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Table 6.2: Position response characteristics for FL-FFC

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<td>Z axis</td>
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Table 6.3: Position response characteristics for admittance based FFC

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<td>1.44</td>
<td>3.5400</td>
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</table>

Figure 6.1: Position of leader (top), payload (middle) and follower (bottom) in m for PFC (blue) and FL-FFC (red) for desired goal point in $X_W$ direction as x=1m for leader UAV.
Figure 6.2: Position of leader (top), payload (middle) and follower (bottom) in m for PFC (blue) and FL-FFC (red) for desired goal point in $Y_W$ direction as $y=2m$ for leader UAV.

Figure 6.3: Position of leader (top), payload (middle) and follower (bottom) in m for PFC (blue) and FL-FFC (red) for desired goal point in $Z_W$ direction as $z=3m$ for leader UAV.
Figure 6.4: Desired control (angles in radians and acceleration in m/sec$^2$) of the leader UAV: desired roll (top), desired pitch (middle) and desired acceleration along $Z_W$ (bottom).

Figure 6.5: Contact forces (N) acting on the follower UAV.
Figure 6.6: Contact torques (Nm) acting on the follower UAV.

Figure 6.7: Desired control (angles in radians and acceleration in m/sec^2) of the follower UAV: desired roll (top), desired pitch (middle) and desired acceleration along $Z_W$ (bottom)
Figure 6.8: Actual angles (in radians) of the leader and follower UAVs: roll (top), pitch (middle) and yaw (bottom).
**Figure 6.9:** 3D plot of the trajectory followed by the leader in goal point navigation using FL-FFC.
Figure 6.10: Position of leader (top), payload (middle) and follower (bottom) in m for PFC (blue) and admittance FFC (red) for desired goal point in $X_W$ direction as $x=1m$ for leader UAV.

Figure 6.11: Position of leader (top), payload (middle) and follower (bottom) in m for PFC (blue) and admittance FFC (red) for desired goal point in $Y_W$ direction as $y=2m$ for leader UAV.
Figure 6.12: Position of leader (top), payload (middle) and follower (bottom) in m for PFC (blue) and admittance FFC (red) for desired goal point in $Z_W$ direction as $z = 3m$ for leader UAV.

Figure 6.13: Desired control (angles in radians and acceleration in $m/sec^2$) of the leader UAV: desired roll (top), desired pitch (middle) and desired acceleration along $Z_W$ (bottom).
Figure 6.14: Contact forces (N) acting on the follower UAV.

Figure 6.15: Desired control (angles in radians and acceleration in m/sec$^2$) of the follower UAV: desired roll (top), desired pitch (middle) and desired acceleration along $Z_W$ (bottom)
Figure 6.16: Actual angles (in radians) of the leader and follower UAVs: roll (top), pitch (middle) and yaw (bottom).
Figure 6.17: 3D plot of the trajectory followed by the leader in goal point navigation using admittance based FFC.
Chapter 7

Conclusions and Recommendations

Conclusions

The force feedback controller (FFC) proposed in this research is very useful for collaborative transportation task using multiple UAVs. Traditional position feedback control (PFC) systems, in which the follower UAV follows or tracks the leader UAV based on the position of the leader UAV, are generally used for such tasks. However, this scheme works well in indoor environments where highly accurate motion tracking systems are used, which provide precise and accurate position measurements of the leader UAV. However, if PFC is utilized outdoors, with GPS to estimate the position of the leader UAV, the system will lose its stability and performance. This is because GPS has inherent errors of over 1 to 2 meters, which leads to faulty measurements of the leader UAVs position. These faulty measurements are then provided to the follower UAVs controller to control the follower UAV. This results in instability of the whole system. On the other hand, a
force feedback system, in which the follower UAV tracks the leader UAV based on the contact force exerted at it (due to leaders motion) avoids the usage of error prone GPS to control the follower UAV. The FFC uses contact forces and torques at the follower UAV to control it. The contact forces and torques acting at the follower UAV would be provided by the force/torque sensors. In simulations, we obtain the contact forces and torques acting at the follower UAV by implementing a novel dynamic model. The FFC ensures real-world application of the collaborative lift system by removing the dependence on error prone GPS to control the follower UAV. In this thesis, two methods are proposed to implement the FFC. The methods proposed are Fuzzy Logic and admittance control. Fuzzy logic controller, emulates human behavior and solves complex control problems. Whereas, admittance control simulates a virtual spring mass damper system to implement FFC. Both these methods employ the principle of minimization of forces and torques to achieve collaborative transportation of a common payload. The follower UAV moves in such a manner that it minimizes the contact forces and torques acting at it. Simulation results are provided to demonstrate the effectiveness of both these methods. Two scenarios are performed for numerical simulations: i) Goal point navigation and, ii) trajectory tracking. The results are compared with the benchmark PFC. It was observed that both the fuzzy logic based and admittance based controllers were able to provide performance comparable to PFC confirming that force/torque feedback can be a viable way to achieve collaboration between UAVs carrying a common payload.

**Recommendations and Future Work**

The control schemes proposed in the thesis are implemented in simulations. The next
step consists of implementing and validating these schemes in experimentation. The real problems will be encountered during experimentation stage. Secondly, both the proposed control schemes should be analyzed for stability. It is quite intuitive that such a collaborative system would guarantee fault tolerance due to the failure of one or more UAVs. This is due to the implementation of force control strategy which is independent of the dynamics of the system and the number of UAVs employed. Simulations and experimentation should be performed to prove fault tolerance to the system. Also, further simulations are needed demonstrate the effectiveness of the proposed schemes when more than two UAVs are used. Additionally, here only two control schemes were provided. Other controllers such as sliding mode controller should also be implemented and compared with both the proposed control schemes.

It may be noted that using such schemes outdoors completely autonomously will always be risky due to potential faults and unforeseen circumstances. Human intervention in such cases may guarantee safety and reliability of such rescue systems. Hence, controls strategies that incorporate human-quadcopter interaction should be developed. This concept will highly desirable since such systems with human interaction can find a wide range of applications especially in industry. The control schemes proposed in this research along with the existing control schemes are sensitive to changes in mass of the system or changes in the center of gravity of the whole system. Adaptive force control strategies should be developed to address these drawbacks and prove effective control even during such scenarios. Furthermore, effectiveness of the control strategies in presence of disturbances needs to be studied and analyzed.
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