（千葉大学学位申請論文）

Autonomous Formation Flight Control of Multiple UAVs with Motion Capture System

モーションキャプチャーシステムを用いた複数UAVによる自律編隊飛行制御

2013年1月

指導教官：野波 健蔵 教授

千葉大学大学院工学研究科
人工システム科学専攻 機械コース

モハマド　ファディール　ビン　アバス

ABSTRACT

The evolution from a single entity to multiple entity flight has introduced numerous possibilities of performing multi task by using multiple agent system. In a multiple entity flight or formation, the search in a feasible way of acquiring individual position and attitude estimation system as a decentralized system has include the use of GPS, INS, Onboard Stereo Camera, Laser Range Finder and also Motion Capture System. The feasibility of each method of position and attitude estimation system as a decentralized system is presented as a part of this thesis. The use of onboard stereo camera is very promising for decentralized system but at the current state of onboard technology, the speed of the onboard stereo camera system is very slow. GPS in the other hand is widely used but the accuracy of such system for short range formation flight is questionable. For formation flight testing and evaluation, the used of motion capture system is very reliable.

Formation flight for multiple agents Quad-rotor Aerial Vehicles (QAVs) has lead from conventional way of leader-follower formation flight to nature based formation flight. The first part of the formation in this thesis is based on a conventional way of leader-follower formation. The formation developed is a Simultaneous Angle and Distance Regulation (SADR). This type of formation is used for a curving or circular motion where by the distance of the leader-follower through the center and the angle between the leader and follower is regulated. Although the development has yielded good result, some negative attributes can be seen. The first is that the whole system relies directly on the leader. If the leader were nonfunctional, the whole system will be nonfunctional. There is no policy of algorithm were by the leader's task can be pass to other quad-rotor UAV.

In finding the solution to the negative attributes, nature's behavior is looked into. Swarm based formation control which depicts the flight of bees and flies have been developed by other researches. The swarm based formation control utilized the effect of potential flow. Potential flow suggests that the obstacle is opposing and the goal is attraction. This yields unshaped structure of the formation. Besides that, such a formation control is lack in intelligence and leader task passing. For this, 'flock formation' is introduced. Flock formation can be seen in migrating birds where the birds fly in a V-shape structure were any new bird will enter the formation at the edge. Besides that, each bird in the formation can be the leader. Such a formation has yielded 12-20% reduction in total energy usage of the migrating bird. The development of the flock formation can be divided into three categories. These categories include shape control/keeping, shape entrance control and also leader change control. The first category is developed and accessed. The shape control/keeping in this thesis uses a virtual mass-spring-damper interconnection as a means of shape keeping. This method will enable any of the QAV to be the leader mode but still maintain the shape. Migrating bird such as Ospreys and

Honey Buzzards has the ability to correct wind drift due to changing in direction. To include this attribute, a centripetal force effect is also considered in maintaining the shape. The shape control/keeping of flock formation has been developed and yielded promising result.

論文概要

単一機による飛行から複数機による飛行へと進化することはマルチエージェントシステムを用いたマルチタスクの遂行の可能性を大きく広げるものである．複数機による飛行やフォーメーションフライトにおいて，分散システムとしてそれぞれの機体の位置や姿勢を推定するのに適した方法はGPS，慣性航法システム，オンボードステレオカメラ，レーザーレンジファインダー，そしてモーションキャプチャシステムの使用があげられる．分散システムとして位置や姿勢を推定する上でどの方法が有効であるかについて本論文の中で述べている．オンボードステレオカメラを用いることが分散システムとしては最も有効に思えるが，オンボードに関する現状の技術では処理速度がとても遅く，実用的でない．一方でGPSは広く使われているが，機体が近接した状況でのフォーメーションフライトにおいてはそのようなシステムの精度は信用ならない．フォーメーションフライトのテスト，および評価のためにはモーションキャプチャシステムを用いることが最善と言えよう．

複数の4発ロータ型ヘリコプタ(QAVs : Quad-rotor Aerial Vehicles)を用いたフォーメーションフライトは従来のリーダーとフォロワーを設けた方法から自然ベースの方法へと移行している．本論文のフォーメーションに関する内容の序盤では従来のリーダーとフォロワーを設ける方法について述べる．発展的なフォーメーション形成方法としてSimultaneous Angle and Distance Regulation(SADR)が挙げられる．この種の方法はリーダーとフォロワーの間の距離や角度を調節し，弓状または円形飛行に飛行する際に用いられる．この方法は確かに大きな成果をあげているが，短所もいくつか見受けられる．例えばシステム全体がリリーダーに直接的に依存していることである．もし，リーダーの動作に不具合があった場合，システム全体が機能しなくなってしまうのである．その際に他のQAVにリーダーの機能を移譲するようなアルゴリズムは開発されていない．

このような短所を克服する方法として自然的な振る舞いを用いる方法が注目されている．ハチやハエの飛行を模倣した無秩序な集団ベースのフォーメーションコントロールが様々な研究者によって開発されてきた．この方法はポテンシャル流れの効果を利用している．ポテンシャル流れによって目の前の障害物や目的地が近づいていることを知ることができる．この方法では整形されていない不完全な構造のフォーメーションとなる．加えてそのフォーメーションは知的なものではなく，リーダーの機能も喪失してしまっている．そこで，群体フォーメーションが考案された．このような群体フォーメーションは渡り鳥がV字型の構造体を形成し，新たに群れに加わる鳥はフォーメーションの端について行くような習性に見られる．さらに，群れに参加するそれぞれの鳥がリーダーになることができる．そのような飛行方法は渡り鳥の飛行に必要なエネルギーの

TABLE OF CONTENTS

CHAPTER 4 FORMATION CONTROL 77

LIST OF TABLES

Chapter 1

Introduction

1.1 Brief History on Flying Machine

The first flying machine which has been flown by man was on 21st November 1783 [1]. The machine was a hot-air balloon and was made by Montgolfier brothers, Joseph and Etienne. Figure 1.1 shows the hot-air balloon in research in that century.

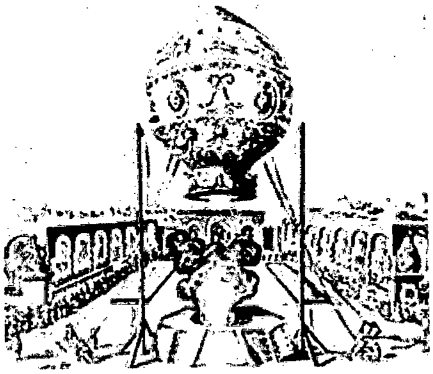
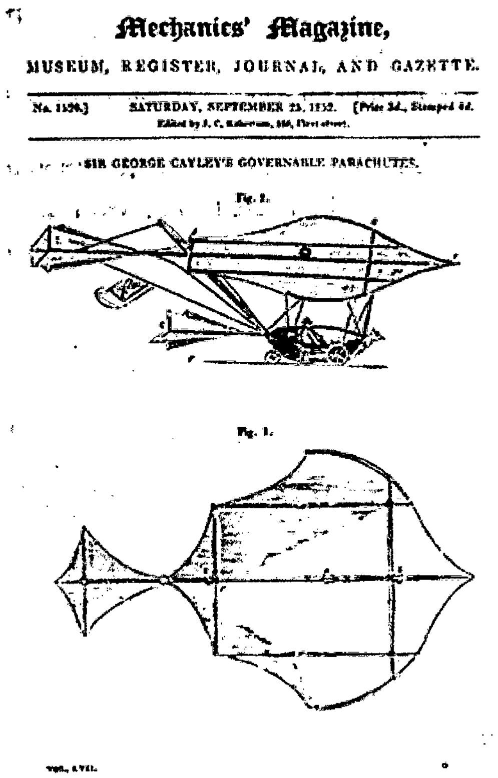


Figure 1.1: Montgolfier hot-air balloon

The first fix wing machine concept was founded by Sir George Cayley, 6th Baronet. The concept introduces a separate system for lift, propulsion and control. He also contributes to the identification of flight forces that is weight, lift, drag and thrust. In 1853, he build and flown the first human glider which is shown in Figure 1.2.



Mechanics' Magazine,

MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 1520.] SATURDAY, SEPTEMBER 25, 1852. [Price 3d., Stamped 4d.

SIR GEORGE CAYLEY'S GOVERNABLE PARACHUTES.

Figure 1.2: Sir George Cayley's Governable Parachutes

After Sir George Cayles's successful flight, there are numerous attempts to power the fix wing machine but was not successful. The first successful man operated flight with a powered fix wing machine was in 1903 by Orville and Wilber Wright [1]. The fix wing machine was named Flyer I and can be seen in Figure 1.3. Since then the development of flying machine has propelled forward.

1.2 Brief History on Unmanned Aerial Vehicles (UAV)

Similar to the history of flying machine, UAV was used as a mediatory for concept and theory experimentation. Early UAVs is in a balloon form build by Montgolfier brothers. As describe in the preceding subchapter, the hot-air balloon based flight was tested with unmanned balloons. After successful trial and errors, the hot-air balloon was used for manned flight.

John Stringfellow and William Henson in 1848 have successfully built a steam powered propeller driven model fix wing aircraft. The fix wing aircraft named Aerial Steam Carriage flew a distance of about 50m. Aerial Steam Carriage was guided with wires to prevent wall crashing.

Other historical development using UAV was the Aerodrome Number 5 which was developed by Samuel Langley in 1896. It had flown a distance of 1.2m with steam power. The Aerodrome Number 5 can be seen in Figure 1.3.

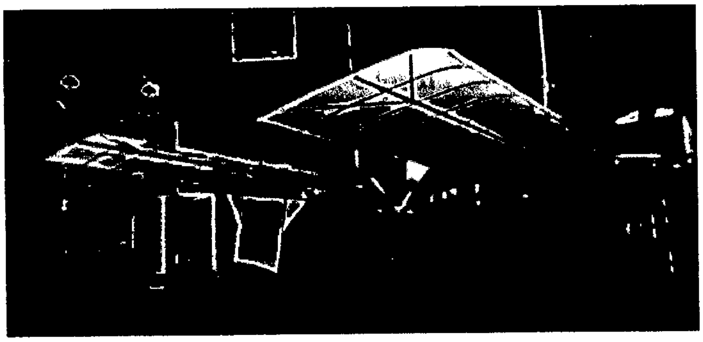


Figure 1.3: Samuel Langley's Aerodrome Number 5

The first major American UAVs were the 'Flying Bomb' was first flown in 1918. The design was consulted by Orville Wright of Wright Brothers. The Flying Bomb was designed to be flown at a maximum distance of 80m and was gasoline fuel driven.

The most successful first remote controlled flying machine were developed by the United State during World War II in 1942. Named 'Interstate BQ-4/TDR(TDN)', the remote controlled flying bombs successfully guided using TV camera mounted in the nose for steering.

From the transaction of flying bombs, modern UAV has been developed for multi session use and can be used repeatedly. Mainly the used of modern UAV is used for reconnaissance coverage and also as a transporter for bombs such as the Global Hawk and Predator from United States as can be seen in Figure 1.4 and Figure 1.5.

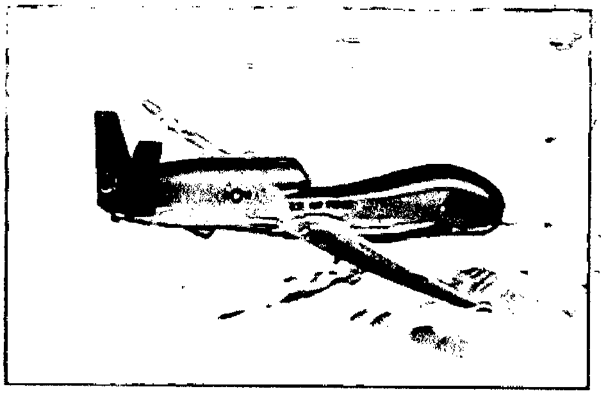


Figure 1.4: Global Hawk

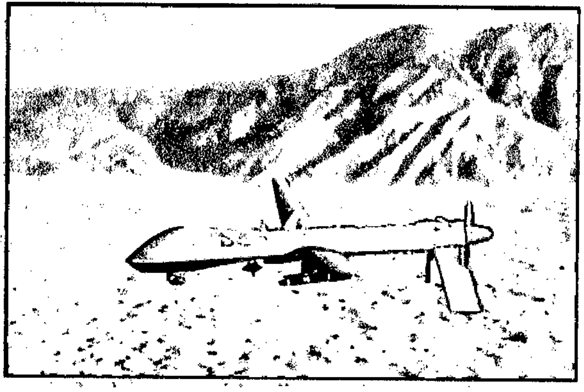


Figure 1.5: Predator Drone

Although the use of UAV is used for military purposes, the use of UAV for civilian application is also possible. The application in civilian usage can be a planetary exploration, terrain inspection, disaster monitoring, utilities inspection, search and rescue, traffic surveillance and many others.

1.3 Category of UAV

UAV can be categorized based on its aerodynamic configuration, weight, size and intended application. Based on aerodynamic configuration, the UAV can be broadly categorized as:

1. Fix-wing UAV. This category includes airplanes which are particularly used for high cruise speed and long endurance.

2. Rotary-wing UAV. This category includes helicopters, duck-type rotorcraft, tilting rotorcraft and multi-rotor rotorcraft. This UAV has advantages in takeoff and landing as it can vertically take-off and landing (VTOL). Besides that rotary-wing UAV has hovering capability and high maneuverability.
3. Blimps UAV. Unlike fix-rotor UAV, the blimps is a balloon type UAV with has the capability for long endurance but could not high speed cruise.
4. Flapping wing UAV. This type of UAV utilized wing that flaps instead of being propelled via motor or engines. This type of UAV is inspired from birds and bees.

UAV can also be categorized by the following [2].

1. Micro/Mini UAVs. This type of UAV has the lightest maximum takeoff weight among the category. The takeoff weight is less than 30kg and can reach a maximum altitude of less than 300m.With a lower endurance of less than 2 hours, this type of UAV can only be used for scouting, surveillance inside building, film and broadcast industries, agriculture, pollution measurements and communications relay. Microbat, Fancopter, Aladin and RMAX are example of Micro/Mini UAV as can be seen in Figure 1.6.
2. Tactical UAVs. This type of UAV is rank 2nd in the maximum takeoff weight category at between 150kg to 1,500kg. Unlike Micro/Mini UAVs, the Tactical UAVs can reach a maximum flight altitude of 8km. With an endurance of up to 48 hours, the tactical UAVs application extends from Micro/Mini UAVs application to mine detection, search and rescue and RSTA (Reconnaissance, Surveillance and Target Acquisition). RoboCopter 300, Neptune, Smart-UAV and Darkstar are examples of Tactical UAVs and can be seen in Figure 1.7.
3. Strategic UAVs. This type of UAV has the heaviest maximum takeoff weight among the category at between 2,500kg to 12,500kg and can fly at an altitude of 15km to 20km. It is more suited for airport security. Global Hawk as shown in Figure 1.4 is an example.
4. Special Task UAVs. This type of UAV is used for special task. The maximum takeoff weight, endurance and maximum height is with in all three categories above. This type of UAV is especially build for anti-radar, anti-ship and aerial and naval deception. Figure 1.8 shows one of the examples.

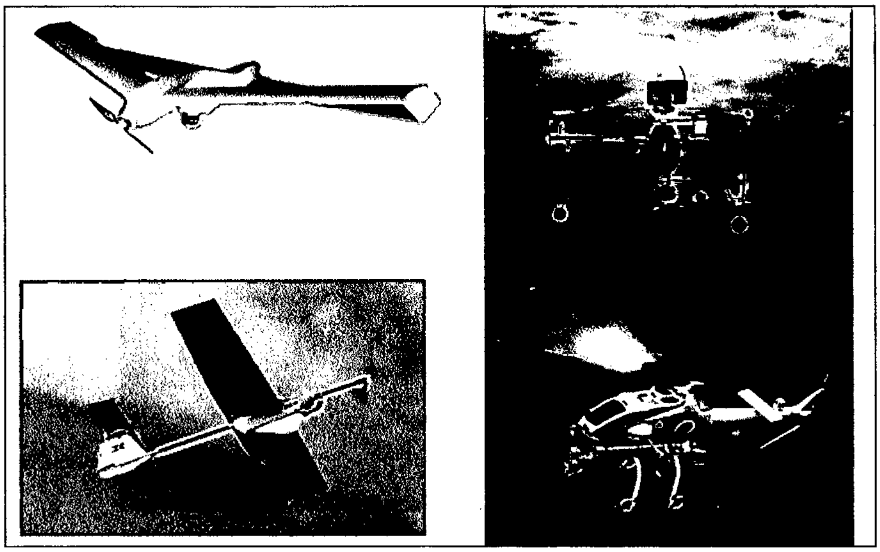


Figure 1.6: (top-left) Microbat, (top-right) Fancopter, (bottom-left) Aladin and (bottom-right) RMAX.

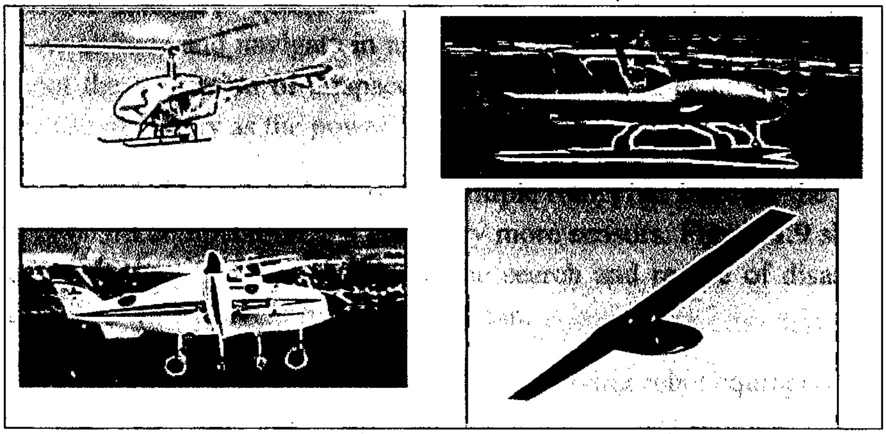


Figure 1.7: (top-left) RoboCopter 300, (top-right) Neptune, (bottom-left) Smart-UAV and (bottom-right) Darkstar.

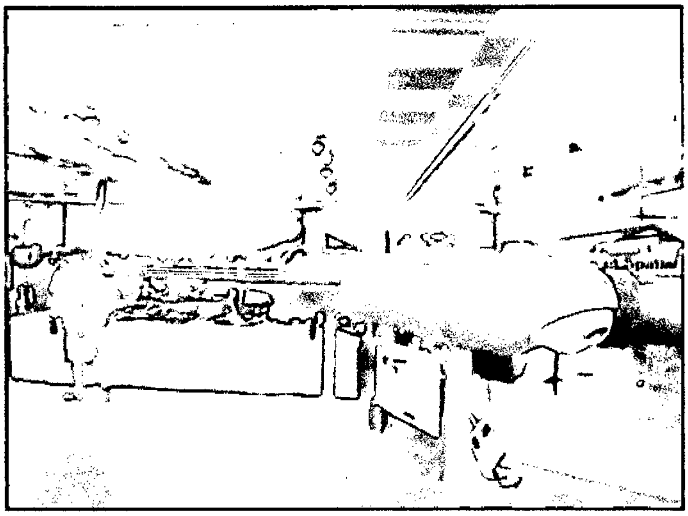


Figure 1.8: Marula Drone

1.4 UAV: Laboratory Research

In Professor Kenzo Nonami's MAV/UGV laboratory, we are interested in Multi-rotor Aerial Vehicles (MAV), which utilizes rechargeable based battery as the mean of power source. This type of UAV is categorized as Micro/Mini UAV in [2]. MAV was chosen since it has the ability to vertically takeoff and landing (VTOL). Thus there is no need for runways. Besides that, MAV can hover, fly at low altitude and navigate in narrow place. This is very suitable for indoor and outdoor uses without the restriction of airspace and can easily gather information in rooms or corridors. Since the use of battery as the power source, the noise level is low and it is safe.

The development of MAV from single rotor to multiple rotors has increase the payload. Thus, the MAV can use onboard computation and can carry more sensors. Figure 1.9 shows the flow. In the future, the developed MAV is planned for the search and rescue of disaster site where hazardous material exists which is very harmful to human.

Currently, the research done includes the indoor flight of flying robot equipped with IR sensor [3, 4, 5], short range MAVs formation control using fully embedded onboard stereo vision [6], localization of MAV in GPS-Denied Environment Using Embedded Stereo Camera [7], six-rotor aerial vehicle [8], formation flight [9, 10, 11] and others.

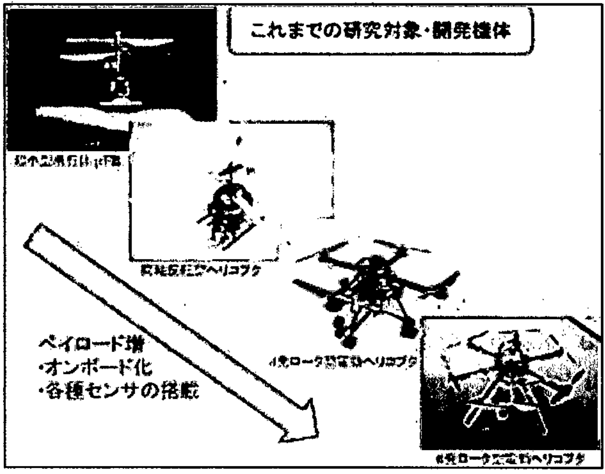


Figure 1.9: MAV flow

1.5 Control and Navigation

Aerospace system which includes UAVs, aircraft and spacecraft are control with less input than the configuration variables. This means that the system is underactuated. Flight controllers are design to produce desired forces from the aircraft for stabilization and also movement in terms of acceleration for the purpose of navigation and trajectory following. In a task were by a search and rescue is involved, multiple task needs to be done such as autonomous takeoff, trajectory planning, trajectory tracking, object detection and avoidance, hovering, formation if needed, detection and data relaying.

In order to successfully execute the above task, the UAV needs to be able to have sensors for localization and environment detection. Besides that, the UAV also needs a microprocessor/ microcontroller / microcomputer for on-board computation of low-order control such as stabilization and trajectory following and high-order control for formation, data relaying and task management. In order for these to happens, the low-order controller needs to map the measurement into forces and torques in order the UAV to perform. There are numerous control and navigation approaches that have been done such as model-based and learning-based control method.

The model-based control and navigation uses dynamic model of the UAV. This method is widely used in aerial based machines. Linear and non-linear model is used to duplicate the behavior of the UAV. This has been done but not limited to by M. V. Nieuwstadt et al and J. Hauser et at in [12] and [13] respectively. Approximate input-output linearization using differential flatness property has successfully been applied to VTOL UAVs control design.

System identification can be used to model the UAV dynamic system. The modeling includes unmodeled dynamics and the parametric effect of the system [14]. A non-parametric identification system has also been used. This method utilizes Gaussian processes [15]. The approach enables a nonlinear model to be developed using flight data. In [15], Brumby MKIII UAV is used to demonstrate the process. Robust control techniques works in [16, 17] has handled unmodelled dynamics and parametric effect. Besides robust control which is unsuitable for modeling uncertainty are large, neural network based adaptive control is used [18, 19, 20].

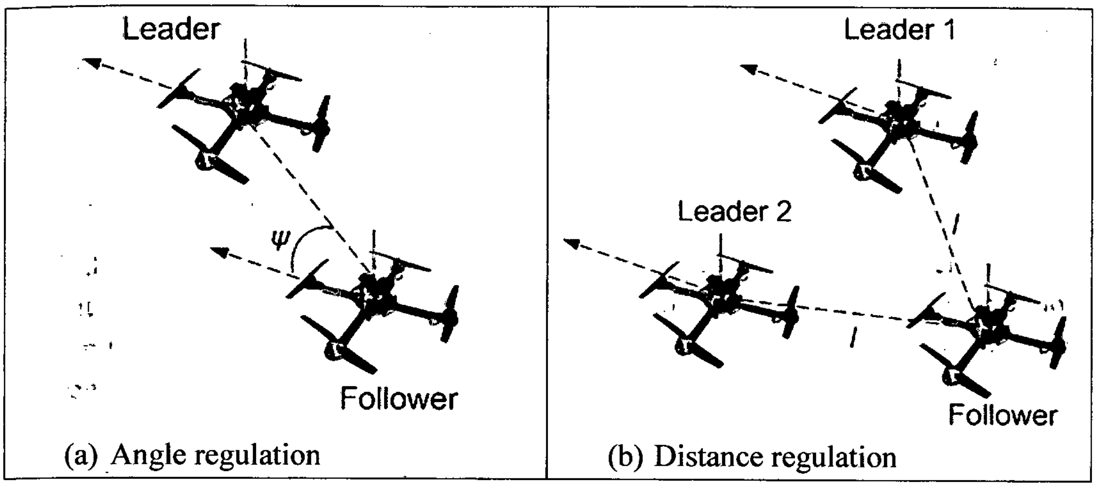
Besides model-based, learning-based control methods can also be used. This includes fuzzy logic and neural network. Unlike model-based which need the model of the dynamic system, learning-based does not used dynamic model but self-learning. Several iterations are needed to train the controller. Successful learning-based methods have been implemented in [21].

1.6 Formation

Formation can be divided and not limited to three categories. This categories are leader-follower strategy, virtual structure approach and behavior-base method [22]. Each of the formation categories has its advantages and disadvantages when applied to multiple QAV formation.

1.6.1. Leader-Follower Strategy

Formation strategy based on leader-follower formation is a popular strategy. In a leader-follower formation, one or more QAV is assigned as the leader. Other research that has been done also uses a virtual leader. The leader will follow a predefined path which than the follower will follow the leader. The follower can follow by regulating either the angle or the distance between the follower and the leader. Figure 1.10 shows an example of regulating the angle and regulating the distance.



(a) Angle regulation (b) Distance regulation

Figure 1.10: Leader-Follower Formation Regulation

Daisuke NAKAZAWA et al in their paper [23] deals with distance regulation of a single leader to multiple followers. A point of interest (virtually) near the rear of the leader is calculated based on the distance from the center of the helicopter and the helicopter's yaw angle. The virtual point is then used to control the distance of the two followers to the leader. This principle can be classified as distance regulation as presented in Figure 1.10. The leader and followers uses a GPS based localization sensor. The paper did not access any angular regulation in case of curving/circular trajectory but only accessed on straight trajectory. Since a motion can be subdivided into straight and curving motion, the motion in curving/circular state needs to be assessed.

Gian Luca Mariottini et al in their paper [24] use panoramic cameras attached on individual autonomous vehicles for localization. One of the autonomous vehicles (UGV type) is assigned as a leader. Communication system is equipped on all the UGV and the paper presumes that there is no communication delay. The leader UGV moves with a predefined S-shape trajectory. The localization of each follower to the leader is estimated via Unscented Kalman Filter (UKF). Linear velocity and angular velocity in which each follower needs to follow is transmitted from the leader to the followers and vice versa. The distance between the leader and follower is regulated but the angle is not. Since a UGV is used, the effect of a circular/curve motion is almost the same as a straight motion.

Travis Dierks et al in [25] use leader-follower formation based on Neural Network (NN). Without the knowledge of a complete model of a UAV, the use of the NN is to online learn the total dynamics of the UAV which includes unmodeled dynamics [25]. The leader tasked is to follow a desired path with a desired yaw angle. The follower will than follow the leader at a specified distance with a specified yaw angle at a specified angle from the leader. The communication aspect between the leader and multiple followers is also discussed.

1.6.2. Virtual Structure Approach

Virtual structure approach suggests that an entire multiple unmanned vehicle as one entity. Each unit in an entity is placed in a specific shape. While keeping the geometric relationship, this shape can be expanded in different direction [26]. The aim of this approach is for high precision formation control.

Kenichi Fujibayashi et al in [27] suggest that each element in a formation is first freely moving without constrain. Then the element is rearranged in a special pattern similar to the one found in crystal. The special pattern is done by fist outlining the desired group in a specific shape. The element will rearrange itself in this shape. For this to happen, the paper suggests using a virtual spring as a virtual interconnection between each element.

Norman H. M. Li in paper [28] utilized a virtual structure based formation. Unlike paper [28], there is no virtual spring interconnection. Instead a virtual point is used. Besides that, paper [28] uses an autopilot model which provides tracking errors for velocity, heading and altitude commands, and also provides trajectory command modifications. In this paper, the use of a synchronization technology developed by UTIAS [29, 30] can enhance the virtual structure.

Virtual structure formation approach can be subdivided into two that is rigid virtual structure and flexible virtual structure [31]. In paper [31], a flexible virtual structure approach is used to solve the limitation of rigid virtual structure in turning formation of nonholonomic unmanned vehicles. The desired virtual reference is used in flexible virtual structure formation based on constant relative curvilinear coordinates by referencing to the formation point.

1.6.3. Behavior-Based Method

Unlike leader-follower and virtual structure method, in order to reach a final goal, behavior-based method integrates several goal oriented behaviors. Each entity is given several behaviors such as obstacle avoidance, formation keeping and goal seeking. Most of behavior-based are bio-inspired such as from swarms of bees, school of fish or flock of birds. By mimicking nature, some degree of autonomy can be achieved.

Rafael Fierro et al in [32] use a group of nonholonomic mobile robot equipped with range sensors. Combining all three controls, coordination and trajectory generation, a single behavior is composed and builds in a modular fashion. The total control action or emergent behavior is a weighted average control action for each basic behavior [32].

Swarm based formation has been developed in [33, 34]. Swarm based formation is mimicking the behavior of a swarm of bees. This type of formation uses single or multiple leaders where leader/s can be of physical or virtual type. Swarm based formation type controls a group of unmanned vehicles where the shape and structure of the group is shapeless. Some work remove the need for a leader and control the entire group as it is a single entity [32].

Antonio Franchi et al in their paper [35] expand the application of swarm robotics. Paper [35] suggest a human intractable swarm based formation flight. This is considered a semi-autonomous system.

1.7 Localization and Estimation System

Localization and estimation system is the basic building block of unmanned systems. There is numerous methods to uncouple the localization and estimation system from being centralized. Some methods are discussed here.

Huaiyu wu et al in [36] uses a micro vision system for localization and estimation system. This paper also explains about their solutions towards five issues on building a MAV. The first was about wing reference indices such as the mean aerodynamic chord (MAC), the center of gravity (CG), and the aerodynamic performance of wing sections used for MAV prototype at low chord Reynalds number. The second is the development of micro vision system including a micro radio frequency transmitter and vision receiving antenna with a high-gain low-noise amplifier (LNA). The third is the development of a small-sized propulsion and power testing setup to examine the static performance of the motor-propeller-battery combination so that the optimum propulsion and power configuration for MAV can be chosen. The forth is building two electrically powered MAV with wingspans of 380 and 360mm, respectively. The fifth and final is the flight test to complete the mission while acquiring the color images of the target by a home-made micro vision system. Two MAVs have been made successfully which is the TH360 and TH380.

A combination of vision system and FPGA is used in [37]. This paper explains a MAV system which is implemented on a Field Programmable Gate Array (FPGA). The system performs the processing tasks necessary to identify and track a marked target landing site in real-