Two Dimensional Flight Trajectory Tracking and Analysis of Pterygota

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Dedication

I dedicate my thesis to my beloved country *Pakistan*.

STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

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Mishma Akhtar

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List of Abbreviations

UAV	Unmanned Aerial Vehicle
NAV	Nano Aerial Vehicle
MAV	Micro Aerial Vehicle
MFI	Micromechanical Flying Insect

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Abstract

Insects display excellent flying skills and have been the source of inspiration for technology protagonists. Vast literature has evolved around the insects flying abilities addressing issues like aerodynamics, wing-kinematics, flight performance (hovering, maneuverability, abrupt acceleration, rapid turn) and navigational cues. However, the realization of the insect-inspired flight mechanics to engineering designs is limited and of pre-mature nature. Recently, some efforts have been directed at the realization of Micromechanical Flying Insect (MFI).

This project is aimed at investigating the underlying science of typical insect-inspired flight with the objective of using the knowledge for improving the versatility of bio-inspired Micro Air Vehicles (MAVs). In this research, various trajectories of flying insects (honey bee and butterfly) are tracked in a controlled environment. Insects of different wingspans are framed in a container such that their two dimensional flight trajectories are captured. Aerodynamic evaluation of these insects is carried out for climb, descent, vertical climb as well as forward flight. The resultant dynamic and kinematic variables are compared during these phases of flight for both (butterfly and honeybee) insects.

The controlled environment for insects includes a glass container (with white background), a camera for recording the videos and a computer system. The apparatus for experiments includes glass jars (for keeping insects), net (for capturing insects), Vernier callipers, a dissection box and gloves (used during handling of insects). An algorithm was developed for post processing of the data values obtained from the tracked videos. Finally, the results obtained through experimentation are analyzed to draw conclusions about velocity, acceleration and resultant forces.

Chapter 1

Introduction

1.1 Background

The aviation industry has worked diligently during the last two decades on miniaturization of Unmanned Aerial Vehicles (UAVs). The technology required for UAVs consist of highly integrated electronic components with enormous computational power as well as highly miniaturized sensors and systems. The global investments in UAV technology is also growing on exponential scales. The variety and number of UAVs has grown considerably ranging from high altitude, long endurance (HALE) systems to mini and micro UAVs [1]. UAVs are divided in various types on the basis of their sizes that include Micro Aerial Vehicles (MAVs) and Nano Aerial Vehicles (NAVs) as well.

MAVs and NAVs are envisioned for a number of multi-faceted uses including Intelligence, Surveillance and Reconnaissance mission on the military front as well as versatile civilian roles such as surveying farms, biochemical sensing, precision farming, infrastructure inspection, dam surveillance and so on [2].

During development cycle of MAVs and NAVs, Commercial-Off-The-Shelf (COTS) solutions are typically adopted. However there are a plethora of challenges associated with miniaturization process ranging from sociology to physics and engineering as shown in Figure 1. Ethical challenges, privacy and risk of hacking these devices stand at the front of sociological issues. From engineering perspective, lightweight materials with durability, complex designs and precision manufacturing challenges looms engineering side of these vehicles. Interestingly, a lot of work has been done on understanding the physics of flight of MAVs and NAVs. However, much needs to be done from the perspective of flight characteristics. Nature is the best source to mimic. This can only be done by understanding the flight of flying insects, biologically named as *Pterygota*. In order to ensure a smooth engineering design, at first, the problems related to underlying physics of miniature flight must be understood and resolved.

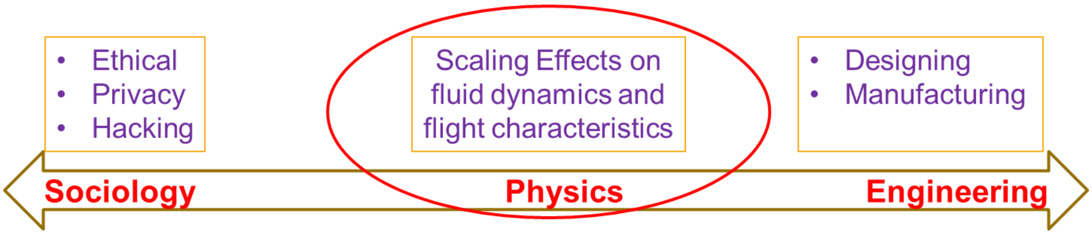


Fig 1 Challenges of miniaturization span from sociology to physics and engineering

There are three major types of UAVs; fixed wing, rotary wing and flapping wing vehicles. Flapping wing designs are inspired by biological flyers; birds and insects. The analysis and study of such flying creatures have helped to design and model MAVs and NAVs.

Flapping wing MAVs/NAVs take precedence over their counterparts, the fixed wing MAVs/NAVs, by virtue of their ability to hover in limited spaces. They use the collective advantage of thrust and lift. The smaller the size of an aerial vehicle the less reasonable will be the fixed wing configuration because such vehicles strictly rely on lift generated from the airflow above the wing when the vehicle moves through the air. This lift is generated to support the weight of the flying vehicle. On the other hand, flapping wing mechanism generates more lift as compared to fixed wing which indicates that its lift can be increased without increasing the speed of the flying vehicle. Hence, flapping wing vehicles are more wind-tolerant and efficient than fixed wing vehicles which implies that flapping wing drones can fly with more agility, and can stop mid-flight to hover in the air. Currently, the military's drones, unlike biological flyers have a limitation to stop-and-start in the air which is a serious barrier to the engineering and development of drones that offer surveillance of confined area.

A typical small UAV may weigh only a few hundred grams. In 1973 Weis-Fogh [3] devised a mathematical model describing the flight of small flying insects that fly by using clap-and-fling mechanism because conventional steady state aerodynamics do not apply on such extremely small creatures. Such insects produce lift by creating vortices near their wings.

MAVs — bird- and insect-size drones are now a well-integrated and active research area. They can perform autonomous flight in both, natural and man-made environments. MAVs are slow-speed aerial vehicles that operate in a Reynolds number regime of 10^4 –10^5 or lower, similar to most biological flyers including birds, insects, birds etc. Such small aircrafts are limited in their ability to generate adequate aerodynamic forces to stay airborne and execute complex maneuvers.

Flapping wing flying insects control and power their flight by an integrated system of flying that consists of wings to produce sufficient aerodynamic forces, muscles for wings movement and a well-developed control system for modulation of power output from their muscles.[4].

1.2 Motivation

Performance parameters of an aerial vehicle depend on numerous factors that include flight altitude, aerodynamic efficiency (lift / drag ratio) and geometric parameters, that is, wingspan, weight and so on. In this research, a thorough study is conducted on the forces acting on biological flyers which will help bio-mimic flapping flight. This research provides information useful for the development of bio-inspired flight systems in terms of flapping wing aerodynamics.

Flying insects have sensorimotor pathways for modulation of power output from muscles to the wings. This makes them capable of aerodynamic force production and agile but precise maneuvering [4].

The flight of insects has enthralled biologists and physicists for more than a century. Yet, until recently, researchers of this field were unable to thoroughly assess the complex wing movements of flapping wing insects or calculate the forces and flow of air around their wings. However, latest advancement in high-speed videography, and development of mechanical and computational modeling tools have allowed researchers to rapidly evolve in advancing the understanding of flight of insect [5].

Nowadays, a well-integrated and active research in the field of MAVs is performed bridging various aspects across computing, biology, aeronautical and mechanical engineering. Biological flapping wing configured systems that are validated and verified through an extensive period of natural selection, serve as a base paradigm whose size can be proportionated and scaled down, but pose unconventional challenges related to autonomous flight control low-speed aerodynamics. Thus bioinspired or biomimetic flight systems are anticipated to be able to serve as the basis for providing breakthrough and innovative technology and novel mechanisms to make more advancements in the future of Micro Aerial Vehicles [6].

In Pakistan, research in Micromechanical Flying Insect (MFI) and Nano Air Vehicles (NAV) is at its very rudimentary level. Further exploration is required in this domain to advance research in this area. Hence, this study is under taken to promote the exploration of this emerging field, establish dynamics of insect flight which can be mimicked by MFI's and NAVs, since numerous studies have taken inspiration from nature.

This interdisciplinary project is about development of a two dimensional tracking system for flying insects and dig out underlying science of typical flying mechanisms. In this research, trajectories of flying insects (honey bee, butterfly) are tracked in a controlled environment. The controlled environment includes a glass container (with white background) and a camera for recording the videos. Insects of different wingspans are framed in the container such that two dimensional flight trajectories are captured. Video tracking has major advantages over manual recording of insect flight behaviours such as provision of accurate position viz a viz time. It also helps to carry out uninterrupted and unbiased observations over a long span of time. This will help in the advancement of research in the field of Micromechanical Flying Insects (MFIs) and Nano Air Vehicles (NAVs).

1.3 Research Objectives

In Pakistan there is no notable research group working on the tracking of flying insects to infer information from inverse dynamics and flying trends of insects. Research on bio-inspired NAVs and MFIs is at an elementary level. NAV technology is evolving with time to reach the technological benchmarks. However, biological creatures still outperform the manmade bio-inspired technology. NAVs and MFIs have multidimensional advantages.

In this research, the flight parameters of butterflies and honeybees during phases of flight (forward flight, climb and descent) are analyzed from their respective trajectories.

The target objectives for this research are summed-up as follows:

- Development of trajectory tracking setup to record free flight trajectories of insects.
- To estimate the flight parameters (position, speed and acceleration) during different phases of flight from video tracking.
- To estimate horizontal and vertical forces during different phases of flight from inverse dynamics calculations.

1.4 Contributions

Bio- inspired UAVs have the potential to become an important asset for different tasks in future. Tracking and analysis of flight of biological creatures helps to model a bio –inspired UAV. The main contributions of the current research work include:

1. Development of low-cost experimental flight chamber.
2. Analysis on 2D flight behaviour of insects.
3. Estimation of aerodynamics forces and aerodynamic load experienced by honey bees and butterflies during different phases of fight.
4. One journal manuscript draft.

1.5 Organization of Thesis

This thesis includes five chapters. The brief outline of each chapter is discussed as follows:

Chapter 1 --- Introduction

This chapter gives a brief overview of UAV industry, the challenges associated with MAV design and development and the elementary level of research being carried out in Pakistan in the concerned field. It also describes the major research objectives.

Chapter 2 --- Literature Review

A detailed review of different studies is given in this chapter. Different techniques used for analysis of flight parameters of different insects are discussed as well.

Chapter 3 --- Problem Formulation

This chapter covers the details of how this research is carried out by taking inspiration from previous studies. A detailed description of the procedure and materials used throughout the course of experimentation is also written in this chapter.

Chapter 4 --- Results and Discussion

Results from the experiments including the relation between velocity and acceleration in horizontal and vertical direction and propulsive forces are reported in this chapter. The outcomes from the experimentation are interpreted in this chapter.

Chapter 5 --- Conclusion and Future Work

Conclusions drawn from the research conducted in this thesis are summarized in this chapter.

Chapter 2

Literature Review

A review of existing literature is performed to support the methodology undertaken in this thesis. A general survey is first performed to account for the past research efforts done in developing an experimental environment for the analysis of flight trajectories of various insects.

2.1 Insect Flight

During the past few decades, insect flight has been of considerable interest to scientists and engineers. They have strived to understand this complex locomotion and translate it to mechanical form. Insects, particularly flies can exhibit extraordinary maneuverability and agility due to sophisticated flight mechanics, hence they are an appropriate model creature for studying flight of insects [7].

The topic of capturing videos of insects and UAVs for the study of their flying patterns has been addressed previously at wider scales [8], [9] and [10]. Schell and Dickmanns [8] used machine vision techniques to study automatic landing and approach by UAVs. They used vision techniques and standard avionics sensors to rebuild the geometry of the airfield, and thus the egomotion of the air vehicle.

Srinivasan, Chahl and Zhang ([9], [10]), conversely emphasized the design of novel mechanisms that help in the analysis of insect flight. Image motion cues are used by honeybees to ensure smooth landing, hence they have been used to analyze their trajectories.

2.1.1 Tracking of different Flying Insects

The strategy of visuomotor control during flight of bees was recorded when they landed on a smooth, horizontal and plane surface. As the insect approaches a flat surface, the image motion cues are comparatively weak. The image velocity was kept constant when the insect approached the surface, thus the flight speed also approached near zero at touchdown. The variation of the instantaneous height above a flat surface, instantaneous horizontal (forward) flight speed, and instantaneous descent speed and descent angle was studied by video-filming numerous trajectories of bees landing on a flat, horizontal surface (Fig 2.1). The results revealed that (i) landing bees approach the surface at a relatively shallow descent angle; (ii) when the bees approach a surface, they try to keep angular velocity of the image of approaching surface constant, and (iii) the speed of descent of bees is proportional to their forward speed.

In this research, a model of the control scheme was developed and its predictions were verified. The feasibility of this landing strategy was demonstrated by implementation in a robotic gantry equipped with vision [9].

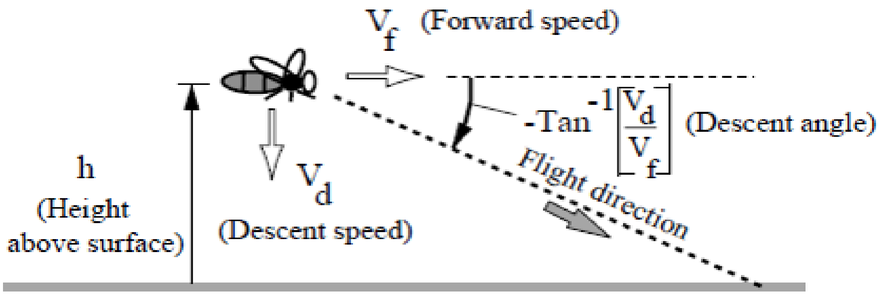


Fig 2.1 Illustration of variables including *h* (cm), height above surface; V_d (cm/s), vertical (descent) speed; V_f (cm/s), horizontal (forward) flight speed and descent angle

Srinivasan *et al.* [10], explored an application of insect visuomotor behavior to automatic control of landing. Insects, being more reliant on image motion cues are proving to be an excellent organism in which to investigate how information on optic flow is exploited to guide locomotion and navigation. They observed how bees perform grazing landings on a flat surface and deduced an algorithmic basis for the behavior. Different variables including height above surface *h* (cm), horizontal (forward) flight speed V_f (cm/s); vertical (descent) speed V_d (cm/s) and descent angle were analyzed to investigate the control of landing. A smooth landing is achieved by keeping the image velocity constant as the surface is approached, thus automatically ensuring that flight speed is close to zero at touchdown.

The research of Fry *et al.*[11] has developed new methods through two experimental settings. Firstly, it focuses on the measurement of body axis and position of honey bees approaching a food source. Secondly, a phonotactic parasitoid fly was kept under observation to record its flight trajectories. Pan-tilt cameras were used for data acquisition because they provide high virtual resolution over a large area. The innovations of this system comprise: (1) Acquisition of images in high spatial detail over large observation areas, (2) Image acquisition at a field rate of 50 Hz PAL (Phase Alternating Line), (3) Free positioning of the cameras for 3D acquisition and (4) Computation of the flight path in 3D world coordinates. They illustrated the capabilities of the system with data obtained from a calibration object as well as from the behaviour of unrestricted, free-flying flies and bees. The results of the experiment highlight the applications in psychophysics of sensory perception and behavioral neuroscience [11].

Fontaine *et al.* [12] developed a visual tracking system that determines the posture of the fly from multiple cameras. This research focused on the wing and body motion of fruit fly drosophila melanogaster. The developed tracking system helped to determine flight kinematics during different types of maneuvers. A geometric fly model was designed to capture complex body and wing rotations. They compared wing and body motion of fruit flies during voluntary and escape take-offs. The automated algorithms measure angle of attack, stroke amplitude, and few other parameters that are important for understanding of flapping-winged flight. (Fig 2.2)

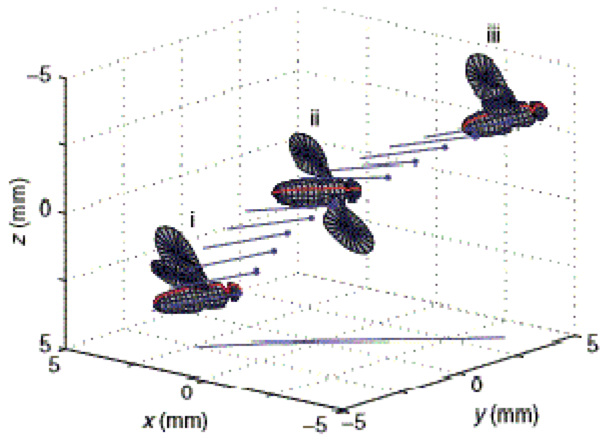


Fig 2.2 Illustration of voluntary take-off

2.1.2 Experiments on Insect Navigation

Portelli *et al.* [13], in 2010, reported experiments on outdoor honeybees. A high-roofed chamber equipped with a tunnel and moving floor was used to train the bees. Honeybees were trained inside the chamber to fly in the tunnel for understanding the underlying mechanism of speed and altitude control. These trained honeybees continued to fly above the floor at a specific height but when the floor was moved in the similar direction as of the flight, they descended to a lower height. This observed behavior revealed the fact that bees gradually restore their optical flow back to the value similar to the one they had when flew over the floor. Bees achieve their optic flow by modifying their altitude regardless of the airspeed. This study explained that measurement of optical flow helps honey bees to navigate in confined spaces like tunnels etc., thus eliminating the need of speed calculation or clearance from walls.

Srinivasan *et al.* [14] aimed to explore how bees use image motion cues to fly through narrow spaces. To investigate the hypothesis that bees use image motion cues, bees were trained to enter an apparatus with black and white moving gratings walls and a sugar solution at the end of a tunnel. When gratings were stationary, the bees flew equidistant from the two walls. If the grating was moved in a direction similar to that of the flying bees, track of bees tend to shift towards that moving wall. This shift in their path is due to the reduction of speed of their retinal motion of the eyes facing the moving wall. The speed of retinal motion on the eye relative to other was increased when the gratings on the wall moved in an opposite direction to that of the flight of the bees. Thus the trajectories of bees shifted away from the wall. Further experiments suggested that variation of the periods of the gratings on the two walls did not change the results.

This research describes that insects use motion cues to perceive their environment. Bees pass through narrow gaps by balancing the speed of image motion in the two eyes, instead of using computationally complex mechanisms to measure distance. Visually mediated behaviours of bees are described along with their applications to robots. A robot had been developed inspired by bees that use image motion to determine the distance it has travelled. The robot uses an Image-Interpolation algorithm [12]. The algorithm makes use of the fact that if a sensor captures images of the environment from two different reference positions, a known distance apart, the image corresponding to an unknown intermediate position can be approximated by a weighted linear combination of the images obtained from the two reference positions [14].

Chahl *et al.* [15], conducted a research which focused on the application of insect visuomotor behavior for automatic control of landing. The results show that a smooth landing is achieved by keeping the image velocity constant as the surface is approached, thus automatically ensuring that flight speed is close to zero at touchdown. This landing strategy was tested by implementing it on a robotic gantry so that it could be incorporated in the guidance of uninhabited airborne vehicles (UAVs). A variant of this strategy has been implemented on a small fixed-wing aircraft as well.

Honeybees use image motion cues to perform smooth landings on a flat surface but the cues derived from image expansion are relatively weak. Various trajectories of honeybees were analyzed to examine the instantaneous height above the surface (h), instantaneous horizontal (forward) flight speed (V_f), instantaneous descent speed (V_d) and descent angle. The results revealed that the descent angles had an average value of approximately 28°. The vision to the robotic gantry is provided by a video camera mounted on its head. The system uses a computer to analyze the motion in the image sequence captured by the camera, and to control the motion of the gantry. The velocity of image motion is measured by an image interpolation algorithm. The results with the robotic gantry suggest that the landing surface must carry visual texture that will enable the measurement of image motion [15].

2.1.3 Studies on Aerodynamics of Biological Flyers

Cheng *et al.* [16] in a recently published study, analyzed the detailed wing kinematics and aerodynamics of a small insect, vegetable leafminer (Liriomyza sativae), in hovering flight. High speed videos were used to measure wing motion and flows over the wings. They first measured the time course of the wing motion, using three high-speed cameras and also measured the morphological data required for aerodynamic analysis. Then, with the measured wing kinematics, the aerodynamic forces of the wings were computed by the method of CFD. Analyzing the wing motion and aerodynamic forces could provide insights into how the forces were produced.

Biological flyers are proficient in the production of aerodynamic forces and agile but accurate maneuvering. This is accomplished from their sensorimotor pathways which provide power output to the wings from their steering muscles.

Wing kinematics of flapping winged insects has conventionally been defined by three different types of flapping angles. These angles (formed with respect to stroke plane) include: elevation angle, θ ; position angle, φ; and feathering angle, α. Scaling of data and ultimately design; particularly in a flapping flight helps in the prediction of effects of scaling and unsteadiness on aerodynamic forces and features. The three major dimensionless aerodynamic parameters are Reynolds number, Strouhal number and the decreased frequency during flapping movement. Reynolds number represents the ratio of inertial to viscous force, Strouhal number characterizes the influence of flapping speed and forward speeds. Here, reduced frequency describes the rotational speed versus translational speed during the flapping of wings of insects. The aerodynamics of flapping wing associated with flight often encounter unsteady movements while keeping between *Re* ranging over $O(10^1)$–$O(10^4)$[4].

2.1.4 Development of Micromechanical Flying Insects (MFIs)

At University of California, Berkley, a biologically inspired system architecture was designed named as Micromechanical Flying Insect (MFI), a 10-25 mm (wingtip-to-wingtip) device eventually capable of sustained autonomous flight. Smaller UAVs are indispensable for various applications where human intervention is considered difficult or dangerous. However, modern technological advancements in the fields of aerodynamics of flight and microtechnology, have laid the next step of developing tools for the fabrication of insect-inspired micro-robots.

Consequently, an electromechanical device that mimics a blowfly Calliphora was created at UC Berkeley, with a mass of 100mg, wing beat frequency of 150Hz ,wing length of 11mm, , and actuator power of 10mW.

The latest technologies in the field of micro-electrical mechanical sensors (MEMS), multichip modules and novel power and propulsion systems allow to build smaller UAVs, which reduces individual costs of UAVs. Furthermore the flight agility can be increased which makes a UAV even more attractive for various tasks [17].

2.1.5 Importance of Flapping Wing UAV

With the increasing popularity of micro air vehicles (MAVs) in the past few years, flapping-wing designs have become prominent due to their ability to exploit unsteady effects in the surrounding flow at low Reynold's numbers.

Three interactive but distinct mechanisms: wake capture, delayed stall ad rotational circulation; are the reasons behind the improved aerodynamic performance of flying insects. At higher angle of attack, when wings are swept through the air that is, only translational part of stroke, delayed stall occurs. In contrast to this, wake capture and rotational circulation are responsible for generating aerodynamic forces specifically during the course of stroke reversals that is when the wings rapidly change their direction. Both of these rotational mechanisms, in addition to generating lift, help in modulating the magnitude and direction of forces specially while performing steering maneuvers. An extensive theory that incorporates all of these (rotational as well as translational) mechanisms may help to explain te wide range of wing motion being displayed by various insect species. Most insects operate within a Reynolds number regime that is similar to that of our robotic fly. In three separate sets of experiments, we moved the robotic apparatus incrementally toward each boundary and measured the forces generated by the Drosophila kinematic pattern [18]. The lift-to-drag ratio is 0.7 whereas for larger insects, Re being about 100 or higher, the ratio is 1–1.2. This proves that, although the small fly can produce enough lift to support its weight, it needs to overcome a larger drag to do so [16].

Biological fliers control and power their flight by flapping of their wings at varying frequencies and wing kinematics. They are capable of performing sophisticated flight stability, agility and maneuverability. [19]. The lift of flapping wing aerial vehicles depends on the wing area and velocity of air flow over the wing. Small wings are more affected thus, the smaller the vehicle, the lesser is its life. Presently, most designs overcome this effect by increasing the velocity of the vehicle. A flapping wing design relies on lift generated by airflow created by both vehicle speed and wing flapping. If the scale is reduced the frequency of the flapping could be increased without affecting the minimum velocity of the vehicle. Conceivably, the size of an air vehicle could be reduced to a size of few millimetres as observed in nature. This can be concluded that flapping wings are a suitable option while designing smaller vehicles particularly MAVs (Micro Air Vehicles). Another advantage of wing flapping is the low speed of the vehicle and the ability to perform short takeoffs and landings. MAV’s with flapping wings will takeoff and land vertically when provided with enough power. Unfortunately, aerodynamics of flapping wing flight, especially MAV size, is still not fully-explored. Although a lot of studies have been done on flight of insects, however there are no proper rules for the design of flapping wing MAV, like fixed wing.

As a result, it is believed that there are two approaches for this problem. One is to learn from natural flyers and try to mimic them. The other solution is to study the aerodynamics of flapping-wing and try to improve upon it. From the analysis of natural flyers, it is found that the MAV size falls within the range of small birds, bats, hummingbirds, and large insects [20].

2.1.6 Tracker used by other Researchers

"Tracker: Video Analysis and Modeling Tool" is a free tool built on Open Source Physics (OSP). It is developed and validated by researchers at Cabrillo College, California. Tracker is constantly hosted by engineers at comPADRE.

It employs tracking and video modeling techniques in order to combine videos with computer modeling. It has the capability to measure position and calculate velocity of the object to be tracked. Tracker can analyze three different video types including digital video files (.mov, .avi, .mp4, .flv, .wmv, .ogg, etc.) which require a video engine, animated GIF files (.gif) and image sequences that comprises of one or more digital images. Xuggle video engine is used to open such digital video files. Additionally, it is equipped with a Model Builder which creates kinematic and dynamic models of point mass particles and two body systems.

Brown *et al.* [21] carried out various experimentations including the calculation of thermal expansion in an aluminium-water setup using single-slit diffraction, non-thermal emission of lasers, fluorescent lamps and dyes, gases, and air resistance on free falling cupcake cups.

A live and a pre-recorded video from a video camera or the internet were obtained and then opened in Tracker. Subsequently, they formulated a scale and reference frame for position data. After which the video was examined frame-by-frame to track the objects of interest [21].

Wee *et al.* [22] a has used tracker as an instructive tool for pedagogical purposes of projectile motion in physics. It has provided assistance in relating abstract physics concepts to real life by connecting computer modelling with video analysis. Numerous student's mathematical models were tested against the video analysis of actual motion of a projectile for endorsement [15].

2.2 Missing Links in Literature

Research on bio-inspired Nano Air Vehicles (NAV) and Micromechanical Flying Insect (MFI) is at a rudimentary level. There are very few research groups working on the research and development of such Unmanned Aerial Vehicles (UAVs). Currently, there is no such research group in Pakistan working on the transformation of insect flight mechanics and control characteristics to Micro Air Vehicle (MAV) design philosophy with the objective of harnessing insect's agile and versatile flight capabilities.

This study is conducted at RCMS, NUST to address the flight physicist perspective which will lead to the successful formulation of the complete framework for the study of insect flight and transformation to biomimetic designs.

Chapter 3

Problem Formulation

3.1 Inspiration from Prior Studies

Several methods have been identified in literature for carrying out analysis of flight trajectories of biological flyers and using the extracted data for modeling and design of Unmanned Aerial Vehicles. However, during the course of the research it was discovered that a common framework cannot be used for recording and then analyzing the flight trajectories. This thesis works as a framework to show how to develop an experimental setup to conduct successful experiments for analysis of insects in different phases of flight. The strategies developed and suggested by previous researchers have been thoroughly studied carefully and taken as an inspiration to develop a basis for the work performed.

3.2 General Problem Formulation

Biological flyers demonstrate flight at various scales such as fruit fly, locust, humming bird, bat, pigeon and the largest living bird on planet, Albatross. They all show different behaviors in terms of flight, agility and flight characteristics. Defense industry is pushing academia towards the miniaturization of flying vehicles known as Micromechanical Flying Insect (MFI), Nano Aerial Vehicle (NAV), and Micro Aerial Vehicle (MAV) as shown in Fig 3.1. The methods presented by the previous researchers reveal that there is a great potential for collaborative research between biologist and engineers because MAVs and biological flyers share similar dimensions, flight characteristics and flight environment.

The techniques of recording the free flight of insects presented by other researchers were used as an inspiration to formulate a framework of research including the experimentation and analysis part according to the needs of the researcher and the resources available.

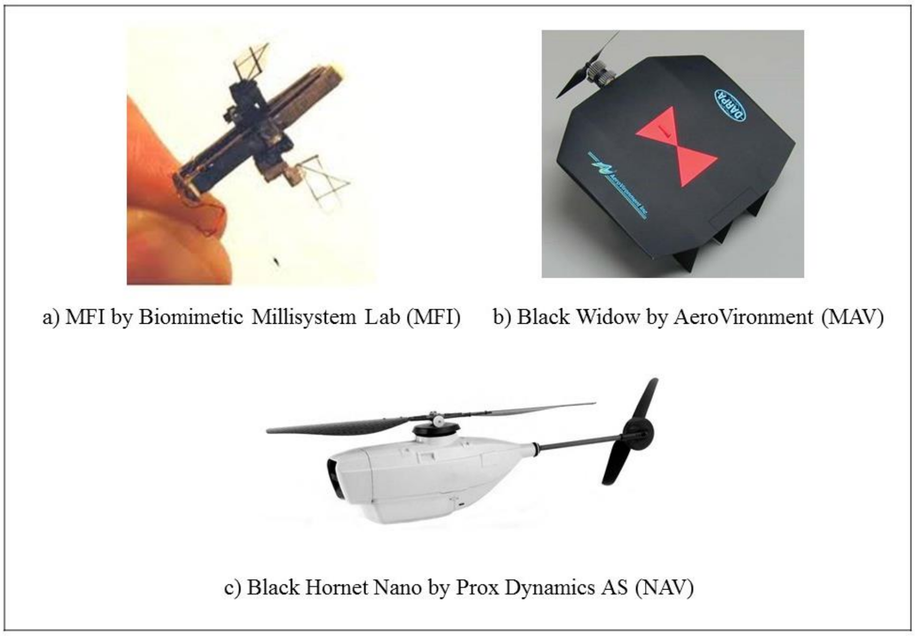


Fig 3.1 Different Types of UAVs

The methodology followed throughout the thesis project phase is shown in Figure 3.2.

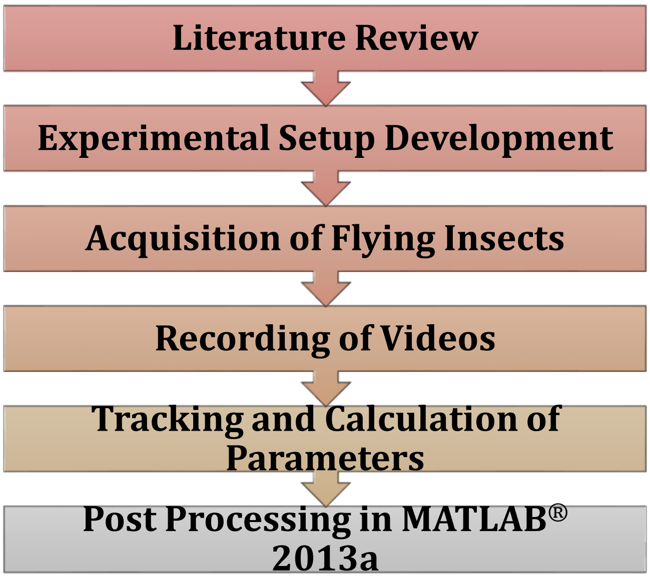


Fig 3.2 Methodology Flowchart

Initially a comprehensive literature study was done to review the research carried out previously to analyze the flight trajectories of insects. Different motion capturing techniques were studied to select one method for capturing the insect flight. The design of experimental flight chamber was formulated after going through the previous researches. In the second phase, Insect Flight Lab (IFL) was developed (Fig 3.3) for the experiments.

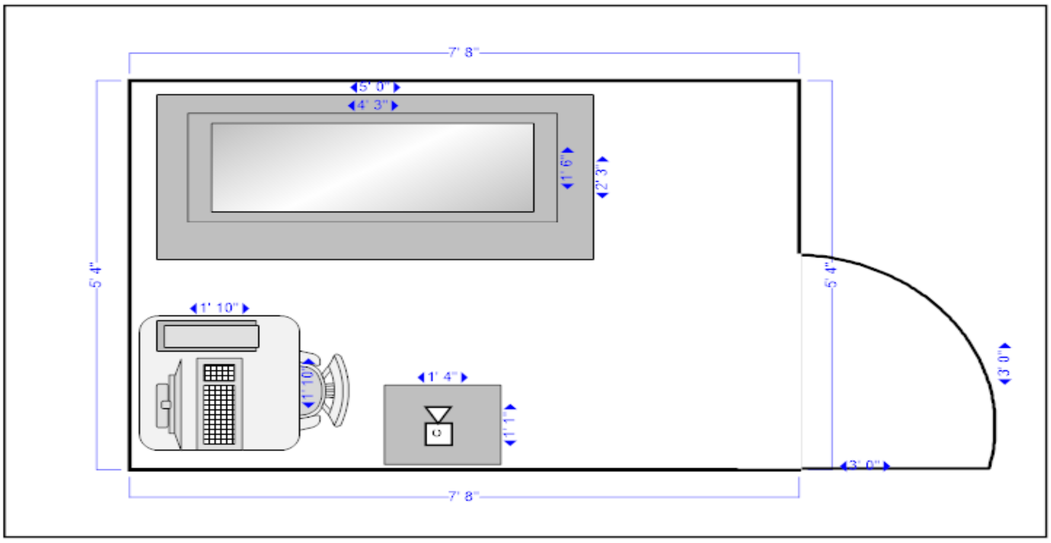


Fig 3.3 Floor plan of Insect Flying Lab

The flight chamber was constructed at IFL where the flying insects were to be kept during experimentation. The apparatus for experiments was acquired including glass jars (for keeping insects), net (for capturing insects), Vernier callipers, a dissection box and gloves (used during handling of insects).

An algorithm was developed on MATLAB® 2013a for post processing on the data values obtained from the tracked videos. In the next phase, insects were captured and acquired from National University of Sciences and Technology (NUST) and Pir Meher Ali Shah Arid Agriculture University Rawalpindi (PMAS AAUR) respectively.

Then, insect experiments were conducted by placing the insects one by one in the flight chamber. Finally, the results obtained through experimentation were analyzed to draw conclusions about position, velocity, acceleration and aerodynamic forces.

3.3 Methodology

3.3.1 Materials and Methods

This research is based on tracking of flying insects (with different wingspans) to have a sound understanding of insect behavior and flight trends. To ensure that the project objectives do not alter and ultimately lead to a failure of the entire project, the experimental setup design of the system is very crucial.

3.3.1.1 Insects

A team of researchers from Mechanics Interdisciplinary group (MIG) netted two different species of butterflies from National University of Sciences and Technology, Islamabad in May 2018. Honey bees were obtained from PMAS Arid Agriculture University, Rawalpindi in July 2018. Table 3.0 enlists the details of insects that were kept under observation. All experiments were conducted in the same day of capture. *Eurema blanda* and *Pieris canidia* are shown in Fig 3.4 and Fig 3.5 respectively, whereas *Apis mellifera ligustica* is shown in Fig 3.6.

Fig 3.4 *Eurema blanda*

Fig 3.5 *Pieris canidia*

Fig 3.6 *Apis mellifera ligustica*

The above mentioned insects can be found in almost any habitat. They are sometimes very observable but other times careful observation and hard work is needed to discover them. Our team visited a variety of habitats to collect various insects. For the collection of insects we visited few prime locations including grassy *Bougainvillea* fields and lake at NUST, Islamabad where such insects were prolific.

Butterflies and honey bees are fully active in summers and spring, so author and the team captured adult butterflies in the months of April and May, 2018. Catching insects for experimentation and observation is somewhat easy but it is more of a physical challenge particularly for butterflies as they exhibit agile and fast maneuvering. The foremost important piece of collecting equipment is the glass *jar*. The captured butterflies were collected in separate glass jars with holes in their lids. These holes provided for the fresh air for the captivated insects. This procedure required very soft handling because they are more prone to damage because of their fragility.

Another most recognized piece of equipment for capturing insects is the *insect net*. The most commonly used net is an *aerial* or *butterfly net*. An aerial net is used to net insects that are flying or hovering in the air or maybe residing in herbaceous vegetation (green and supple stems). To capture any spotted insect, the team members swept the butterfly nets through the air until the insect entered the net. The hoop of the net was swiftly flipped till it touched the droopy side of the net. This rapid movement acts as a lid of the net hence trapping the captured insect into the (droopy) lower part of the net. This method of insect catching is known as a *sweep and flip* technique. However, another method was adopted too to fulfil the same purpose. If the insect was seen or spotted on the ground or a plant, aerial nets were dropped over the resting insect. Net was also used by the team for scoping a resting insect from a reposing site on a plant. The team had to be very careful during collection of such delicate specimens because wings of butterflies broke easily when thrashed by the net. Fig 3.7 and Fig 3.8 represents the sweep and flip motion of aerial net respectively.

Fig 3.7 Sweep

Fig 3.8 Flip

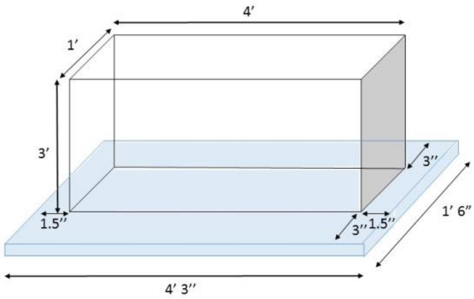
Attributes / Insect	Mass '*m*' (g)	Wingspan '*b*' (cm)	Weight '*W*' (10^{-2} N)	Species	Common Name
Honey bee	0.1133	2.8	1.1103	*Apis mellifera ligustica*	Italian bee
	0.1098	2.3	1.0760	*Apis mellifera ligustica*	Italian bee
	0.0988	1.9	0.9682	*Apis mellifera ligustica*	Italian bee
Butterfly	0.017	3.5	0.1666	*Eurema blanda*	three-spot grass yellow
	0.0166	4	0.1626	*Eurema blanda*	three-spot grass yellow
	0.0198	4.5	0.1940	*Pieris canidia*	Indian cabbage white
	0.0696	6.1	0.6820	*Pieris canidia*	Indian cabbage white
	0.0667	4.6	0.6536	*Pieris canidia*	Indian cabbage white
	0.712	5.9	6.9776	*Pieris canidia*	Indian cabbage white

Table 3.0 Insects kept Under Observation

3.3.1.2 Indoor Experimental Setup

The trajectories of various flying insects were tracked in a controlled environment in an Insect Flying Laboratory at RCMS, NUST, Islamabad. Butterflies and honeybees were captured in free flight in an enclosed flight chamber. The customized flight chamber is a cuboid of 4x1x3 cubic inch (1.21x0.3048x0.914 m^3) (Fig. 3.9a). The walls of the chamber were built from translucent glass whereas roof and floor made of chipboard. In the experiment, the flight chamber was in illuminated by two energy saving bulbs (20 Watts each). The bulbs were attached at the top corners of the chamber. White paper sheet was pasted at the wall at the back to have a clear background in the videos. Insect was easily detected when filmed in front of a clear white background. For estimating the height and horizontal distance covered by flying insect, a scale (in inches) was pasted along the length and height of the experimental chamber. One of the side walls was designed to be half the height as compared to the other wall. The upper opening was covered with net. Net was used for ventilation and more importantly, the flying insects were launched from here. Water and respective food of honey bees and butterflies was kept inside the container for their sustenance (Fig 3.9b).

(a)



(b)

Fig 3.9 Indoor Experimental Setup and Dimensions of Enclosed Chamber

3.3.1.3 2D Film

We filmed the flight of the butterflies and honey bees in an enclosed flight chamber using an orthogonally aligned camera (Logitech HD Pro-Webcam C920, resolution 1080p) mounted on the wall. During the experiments, an insect is launched into the motion capture environment. The camera tracks the flight motion, and transfers the video to a PC (Fig 3.10).

Fig 3.10 Logitech HD Pro-Webcam C920 used for Experiments

3.3.1.4 Morphological Parameters

The insect was neutralized with ethyl acetate vapour after filming. The total mass (*m*) was measured by a weighing scale to an accuracy of ±0.0001g. The wingspan (b) of the insect was then measured using Vernier callipers.

3.3.1.5 Software

A software named as Tracker; Video Analysis and Modeling Tool built on the Open Source Physics (OSP) Java farmework, is used for tracking the insects from the captured videos. Tracker offers features of manual as well as automated tracking along with the formation of kinematic and dynamic models of both, point mass particles and two body systems.

3.3.1.5.1 Validation of Software

Physics department of High Point University, North Carolina provided a video of a ball rolling with constant velocity. In the video, a steel ball rolls with a constant velocity on an aluminium track with almost negligible friction. Its speed is provided by them with a value of 0.32 m/s approximately. The track of rolling ball, measured from end to end, have a span of 2.2 m. The given video is a slow-speed video recorded with a time interval of 1/30 s between frames, that is 30 fps (frames per second). Fig 3.11 shows the initial point of ball while Fig 3.12 depicts its final position after rolling at a constant velocity of 0.32 m/s.

Fig 3.11 Initial Position of Steel Ball (start of the video)

Fig 3.12 Final Position of Steel Ball (end of the video)

The above mentioned video was used for validation of the software, Tracker: Video Analysis and Modeling Tool. After running the video through tracker and its further analysis showed the same results approximately. The ball is considered as point mass and marked throughout its trail. After marking the ball as it moves from the left end to the right end of the track, the video looked like the picture shown in Fig. 3.13.

Fig 3.13 Full Trail of Steel Ball

The best-fit line of the graph is calculated whose equation is given by $x = A * t + B$ where A is the slope and b is the vertical intercept. Fig 3.14 shows the values of A and B, where this B represents the constant velocity of the slow moving rolling steel ball. After tracking, the value of velocity was found out to be *0.3332 m/s* which is approximately equal to *0.32 m/s* (as calculated by the video providers). The slight difference in the values of velocity is due to human error as steel ball is tracked manually.

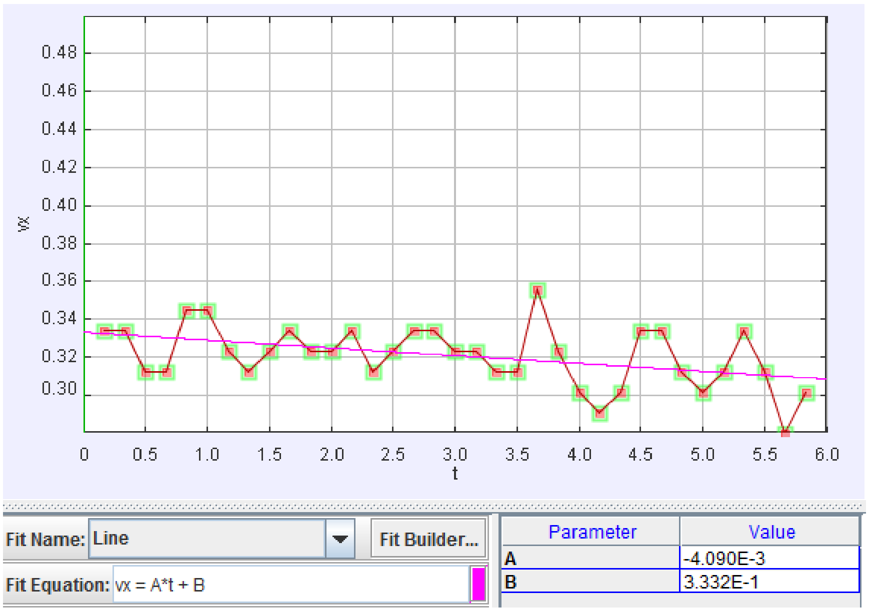


Fig 3.14 Best Fit Line in Velocity/Time Graph

Hence Tracker is validated as it gives approximately similar results when tested by the video providers and the author.

3.3.1.6 Coordinate System

The moving object, in this case, an insect is manually tracked. Tracking is performed by marking points on the object appearing in the video image with each increasing step size. Each marked point describes the position of image. Image position is measured in pixel units relative to the top left corner of the video image. For example, for a *640* x *480* pixel image, the upper left corner of image is at image position (0.0, 0.0) and the lower right corner is at (640.0, 480.0). The video being tracked is a camera view of real world. Hence, an insect (physical object) within that video image has real world coordinates. These World coordinates are gauged in scaled world units for example, meters-for distance covered relative to the specified frame of reference. Origin of reference frame may be kept and adjusted anywhere on the video image.

Tracker uses a coordinate system to transform image positions into real world coordinates. It offers a feature of grid and axis overlay that can be shown on the video image to show complete x-y plane for better understanding and efficient working. This coordinate system, after converting image positions to real world positions, describes the following three factors for each frame of the video:

- Scale (image units/world unit)
- Origin (image position relative to origin of reference frame)
- Angle (anti-clockwise angle from the x-axis of image to the x-axis of world)

3.3.1.7 Units

By default, Tracker measures LMT (length, mass and time) in units similar to those of the SI (The International System of Metric Units) metric system that is, meters, kilograms and seconds respectively. However, it provides a feature to change the units of mass and length to any desired unit. Time can be measured in seconds only. Angle can be measured in either radians or degrees.

3.3.1.8 Calibration

A calibration tape and calibration stick are provided as tools for calibrating the scale of video. Calibration between two points, here refers to the ratio of the world units of distance in meters or any preferred unit to the image distance measured in pixels. Toolbar displays a readout of world length of a calibration tape or stick. The value of the actual length is set as the world length.

The angles and distances are measured by the calibration tape. This angle is considered relative to the positive x-axis (+x-axis) and is also displayed with the length on the toolbar.

During the conduction of experiments, one of the calibration tape represented the length of base of the glass chamber (1.2m) and the other one showed the height (0.9 m). The velocities in meters per second are calculated according to the given world distances.

3.3.1.9 Point Mass

A track of a point mass represents the moving body in a video as a point-like body. This moving body in a video is referred to as a point mass. It depicts the basic model of a moving inertial object. For tracking the moving object, the respective point mass is marked (by clicking on it) at each consecutive step. Mass of the object is set to the real world mass and displayed on the tollbar as well.

In this study, the insect kept under observation was declared as point mass with its respective value of mass in grams *g*. Tracker tool offers the following mentioned ways of tracking the point mass:

A. Manual tracking:

The video clip is opened in Tracker and its video frames are set beforehand to track the desired video frames only and to avoid considering unnecessary frames. In this study, the object (flying insect) is clicked at each step to mark its exact position. Tracker offers the feature of auto-advancement to next step for quick and easy marking of object.

The video frames consisting of any phase of flight of honey bees / butterflies were observed and saved for later use. They were marked at each step of video ultimately displaying the complete trajectory of the respective flying insect. The positions and velocities were saved to be kept in record in excel files.

B. **Auto-tracking:**

Auto-tracking provides the feature of tracking the point mass automatically but the object to be tracked must have a consistent size, shape, orientation and a colour that distinguishes it from the background and environment. But butterflies and honeybees fly at a higher speed with constant change in their wing shape and orientation. Hence this feature cannot be used for their tracking.

3.3.1.10 Views

Tracker has two different methods of tracked data representation-data table view and plot view. Firstly, a table of tracked data is displayed in “data table view”. A separate window with a toolbar is dedicated to set and view the table. This toolbar has the option to choose the required track along with the selection of desired data columns. Analysis can be performed on the data selected and presented in data table by Tracker itself or it can be pasted in a spreadsheet application by copying to clipboard. Secondly, plots of a tracked data are formed in “plot data view”.

3.3.1.11 Saving Data

Tracker has the functionality to save the state of multiple videos opened in separate tabs. The information (video clip name, tracks, coordinate system, and views) of individual tabs are saved in xml-based files with an extension of “*trk*”**.** Whenever a saved *trk* (tracker) file is opened, the previously saved state is replicated in new tab. Data table view is used in order to access the world data related to the respective track.

3.3.1.12 Working of Tracker

The frames and frame rate of chosen video is used to calculate time *t* of moving object. Whereas *x* and y coordinates of the moving object is estimated by using coordinates of the marked pixel positions and the pixel scale of reference. Tracker uses numerical differentiation to determine *x*-velocity and *y*-velocity.

To measure insect's position in a video, the author needed to:

- define a coordinate system including x, y axes and origin.
- define a scale or a standard length according to the measurements of the flight chamber.

For this, two calibration tapes were used in the video for defining the values of length (length of base) and height of glass chamber. This is called calibration of the video images. This video analysis and tracking software makes it easier to measure coordinates of position (*x* and *y*) and time *t* for the flying insect under consideration. After determining the coordinate system and scale, Tracker shows a marked dot and advances the selected video to the next step size or frame. It measures the position of insect in pixel units and then this position in pixels is converted to position in meters by the use of defined calibration and coordinates system. Complete path of flying insect is mapped on the screen as well, for example in Fig 3.15, trajectory of a butterfly is mapped during climb phase.

The software, by default measures time because the frame rate of video was set beforehand to be played at 30 frames per second throughout each experiment. Thus, whenever the video advanced to next frame, the time advanced by 1/30 s. From the information of position of insect and time measured by Tracker, velocity can be calculated numerically by computing the derivative of position with respect to time. Various other variables can be derived from the basic variables which can be graphed as well.

Fig 3.15 Flight Path of a Butterfly

3.4 Procedure

Freely flying *P. canidia*, *E. blanda* and *A. mellifera ligustica* were captured and kept in glass jars. Each insect was launched separately in the experimental chamber from one end. They were allowed to fly freely in the chamber. Their flight trajectories were captured using a camera. The videos were made such that they included different phases of flight (climb, descent, horizontal flight, vertical climb) of all insects. The frame rate of videos was set at 30 *fps* (frames per second). The resulting videos of the above mentioned insects were analyzed to extract two dimensional position information. The trajectories were used to estimate velocity in vertical and horizontal direction then the acceleration was calculated. After neutralizing the insects with ethyl acetate, mass *m*, of insects was measured by a weighing scale in *grams*. Vernier callipers was used to measure the wingspan *b*, of all captured insects.

The forces acting on the airplane during flight are shown in Fig.3.16 where '*T*' is Thrust, '*D*' is Drag, '*L*' is lift and '*W*' is the weight of the airplane. In this case, the following equations are obtained.

$$F_x = T - D = m\, a_x \quad (1)$$

$$F_y = L - W = m\, a_y \quad (2)$$

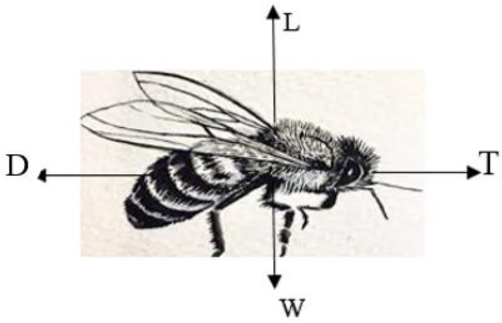


Fig 3.16 Steady level flight of Honey Bee

where, m is the mass of airplane and a_x and a_y, are the components of the acceleration along and perpendicular to the flight path respectively.

Similarly, for insects, knowing the horizontal acceleration a_x, and mass, m, the propulsive force (in horizontal direction), F_x was calculated using $F_x = ma_x$ where $F_x = T\text{-}D$. Similarly acceleration in vertical direction a_y and mass, m were used to calculate force F_y along *y-axis* (vertical here). The calculated F_y and weight, W were used to compute lift, L, acting on the respective insects during different phases of flight. Lift was determined by $L=F_y+W$. From the data, F_x/W, F_y/W and F/W were computed. Their values were used to estimate the minimum and maximum forces acting on insects during flight. The force F is divided by the weight W of the insect to non-dimensionalize the data according to the weight. Data extracted from all videos was saved in MS Excel files for further analysis.

The position (x and y) of insects under observations are interpreted as the distance and height (altitude) attained by the respective insect during its flight. The graphs generated from the obtained data revealed several interesting insights regarding the speed of flying insects. In most of the cases, the velocity in horizontal direction (V_x) is inversely proportional to the velocity in vertical direction (V_y). This leads to the fact that kinetic energy is held constant in that particular phase of flight. Elaborate details are furnished in next chapter.

Chapter 4

Results and Analysis

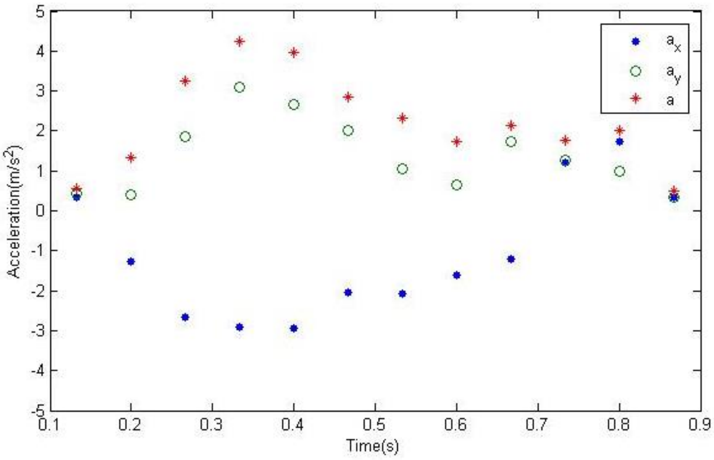
4.1 Background

Different insects were captured to investigate and analyze flight characteristics. Results of different trajectories obtained after experiments are discussed separately. The combined results from different phases (climb, descent, forward flight and vertical climb) revealed striking similarities in the behavior of honey bees and butterflies. Trajectories, minima and maxima of velocity in each trajectory, minima and maxima of acceleration and resultant forces are discussed in the light of the obtained results.

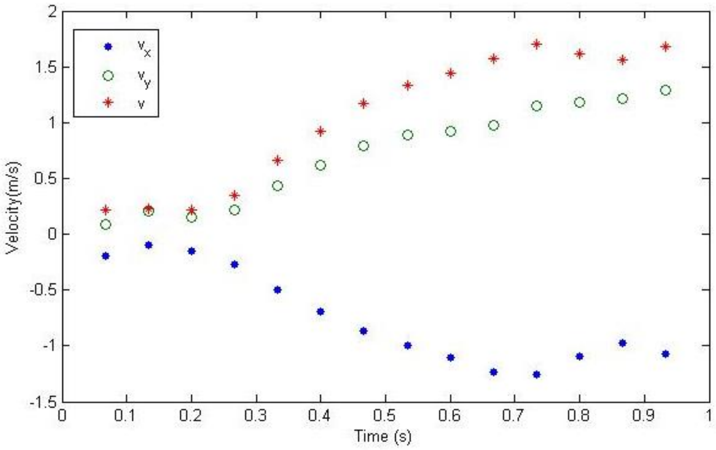
4.2 Climb Maneuver

4.2.1 Flight Analysis of Honeybees

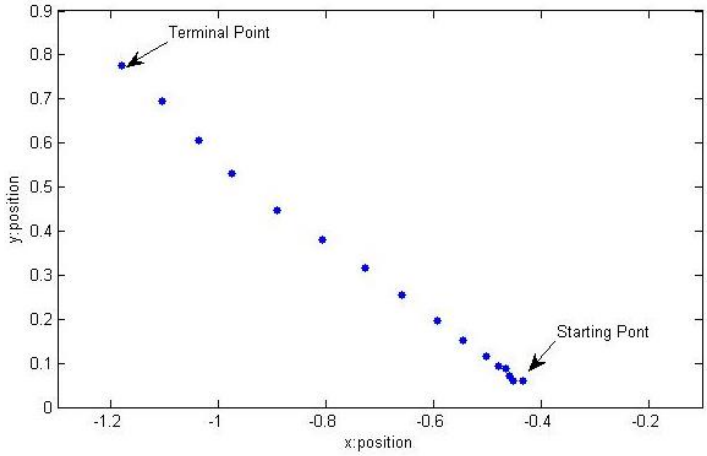
A sample trajectory of honeybees is displayed in Fig. 4.1a. According to the graphs, both acceleration in x-direction (a_x) and acceleration in y-direction (a_y) are somewhat inversely proportional. The resultant acceleration (a) is the square root of resultant of square of a_x and a_y. It has the same trend as a_y but with slightly higher values. When two curves coincide, the insect has same horizontal and vertical acceleration. If area under the curve is calculated, then it equals the change in velocity of flying insects. Fig 4.1b shows the velocity-time graph of honey bees kept under observation. Downward velocity (V_y) and forward velocity (V_x) are inversely proportional to each other. This suggests that honey bees fly with a constant energy during climb phase. Flight path of honey bee is shown in Fig.4.1c while climbing from lower to higher position.



(a)



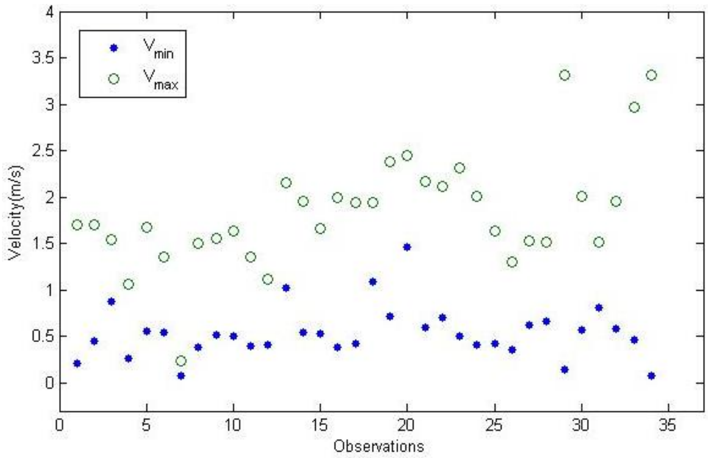
(b)



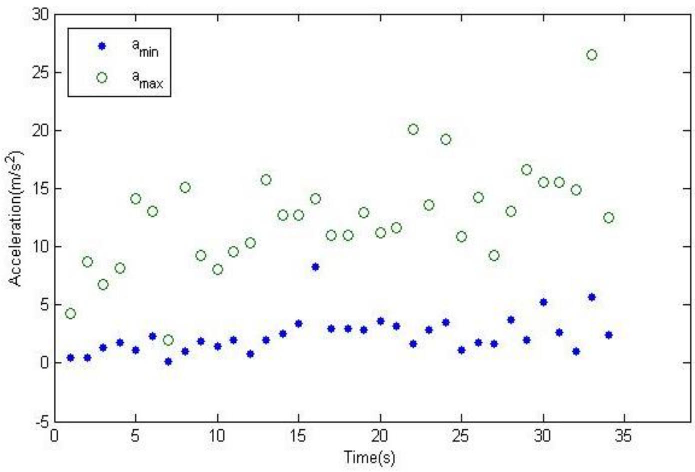
(c)

Fig 4.1 Graph of acceleration, velocity and position of honey bee

Overall 34 observations (trajectories) are recorded during the climb phase of honeybees. The maxima and minima of the flight trajectories are plotted in Figure 4.2. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.3 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.4.

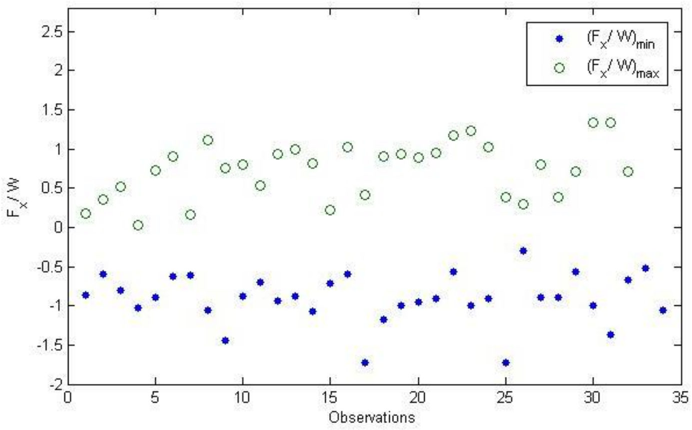


(a)

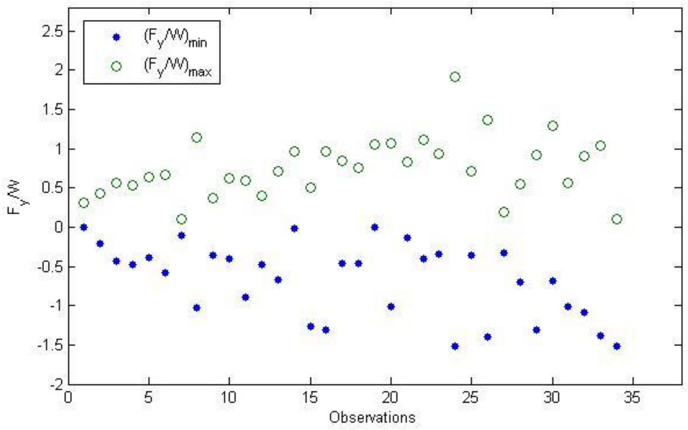


(b)

Fig 4.2 V_{min}, V_{max}, a_{min} and a_{max} during climb



(a)



(b)

Fig 4.3 Graph of minimum and maximum propulsive forces

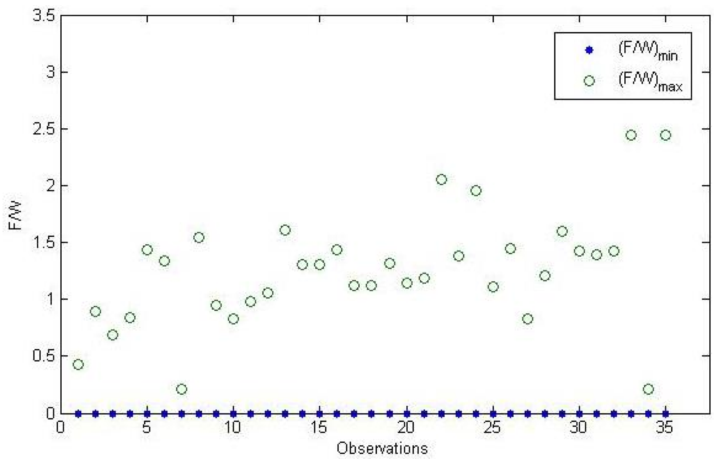
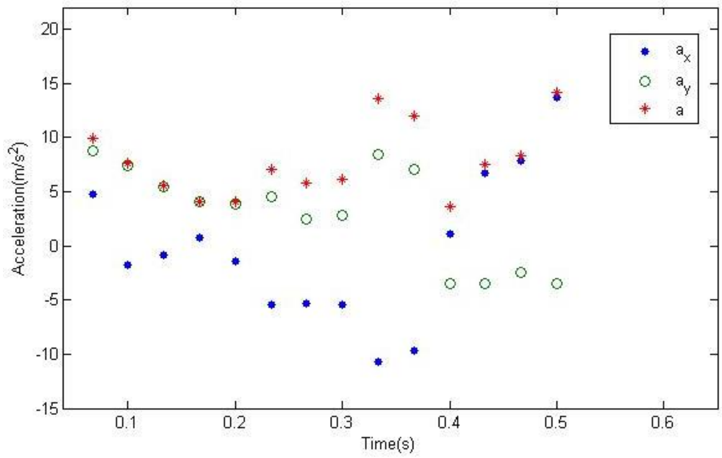


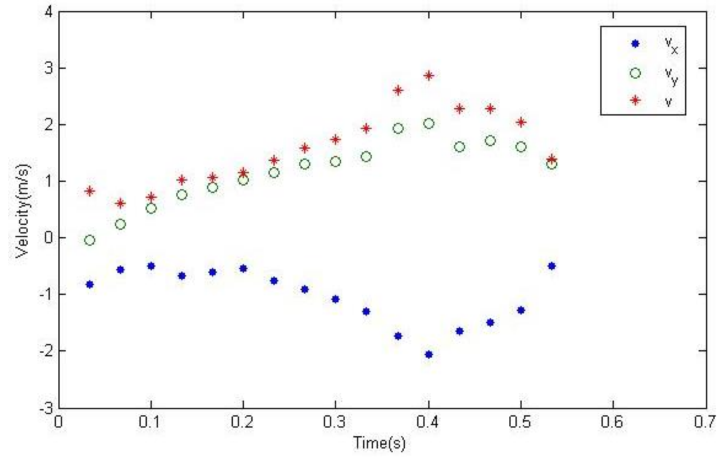
Fig 4.4 Plot of resultant force

4.2.2 Flight Analysis of Butterflies

According to a sample flight trajectory, (Fig.4.5a), acceleration in x-direction (a_x), acceleration in y-direction (a_y) and their resultant a, are shown. The resultant acceleration (a) is the square root of resultant of square of a_x and a_y. It has the same trend as a_y but a little higher values. Fig 4.5b shows the velocity-time graph of butterflies kept under observation. Downward velocity (V_y) and forward velocity (V_x) are inversely proportional to each other. The graph shows a phase difference hence butterflies fly with a constant energy during climb phase. Flight path of butterfly is shown in Fig.4.5c while climbing from a point at lower height to a point at higher height.



(a)



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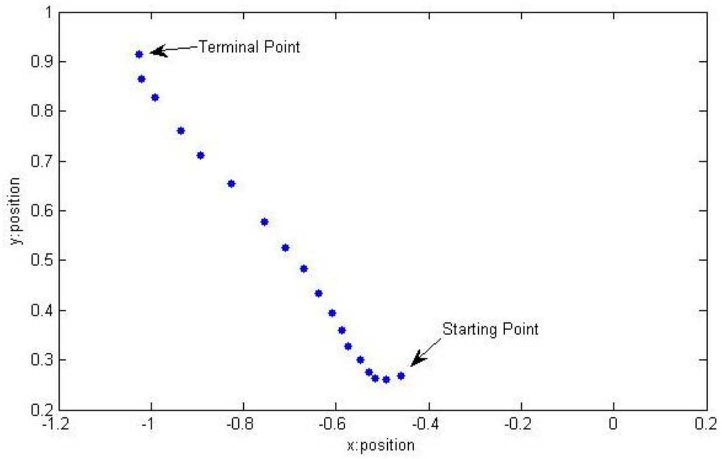
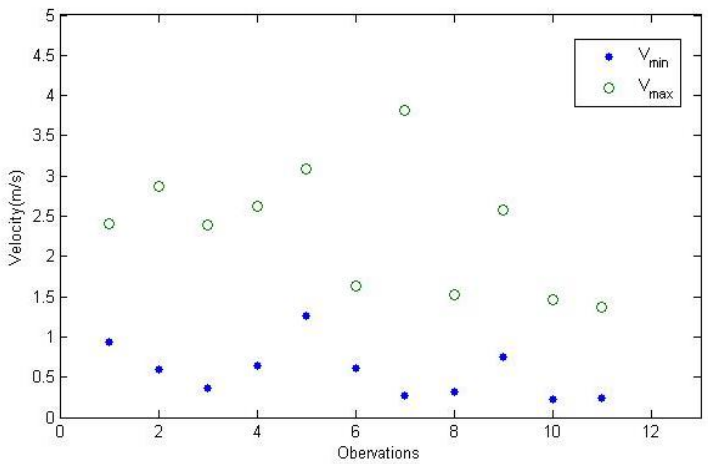


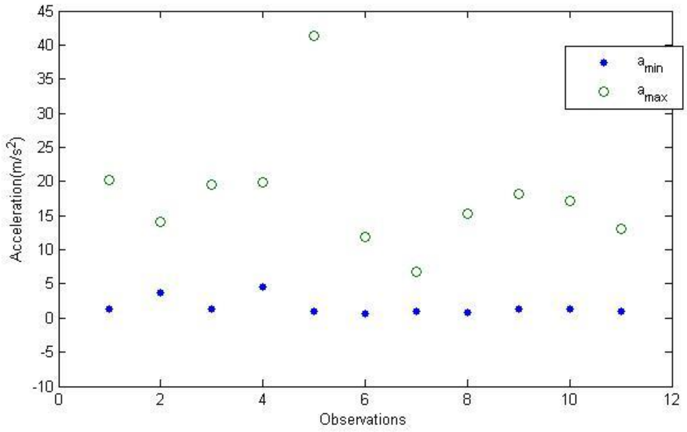
(c)

Fig 4.5 Graph of acceleration, velocity and position of Butterfly

Overall 11 observations (trajectories) are recorded during the climb phase of butterflies. The maxima and minima of the flight trajectories are plotted in Figure 4.6. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.7 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.8.

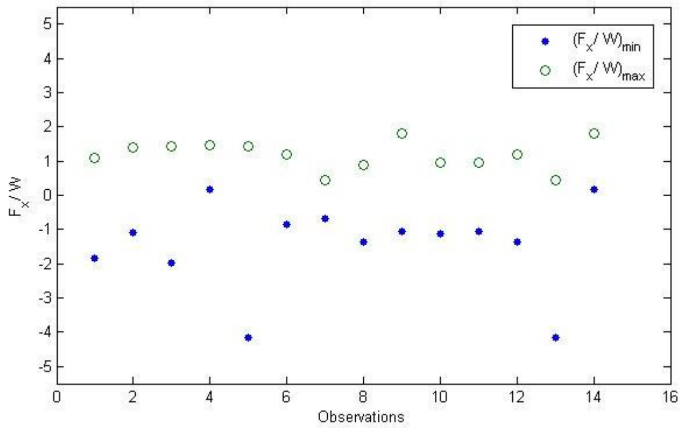


(a)

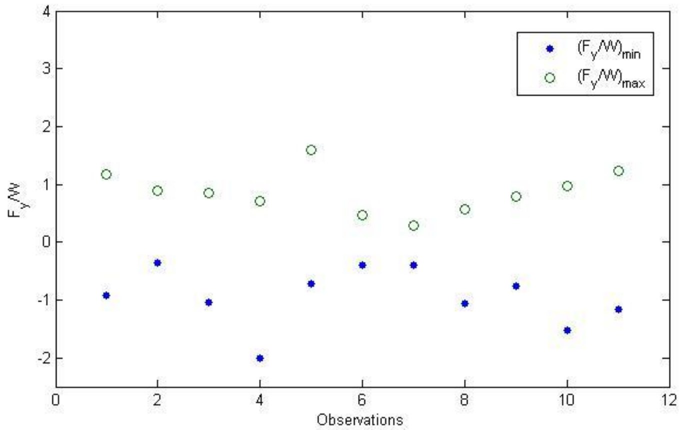


(b)

Fig 4.6 V_{min}, V_{max}, a_{min} and a_{max} during climb



(a)



(b)

Fig 4.7 Graph of minimum and maximum propulsive forces

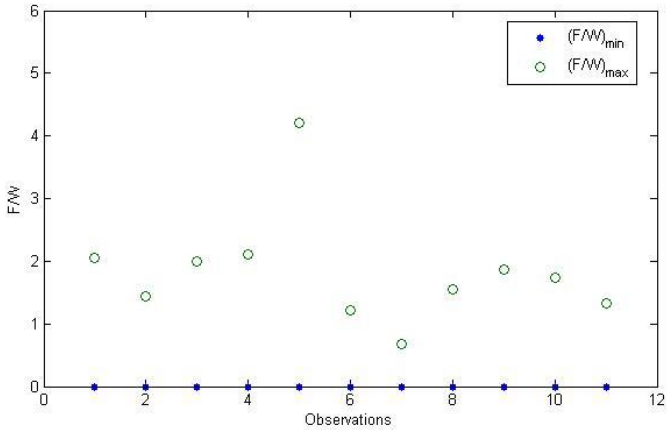
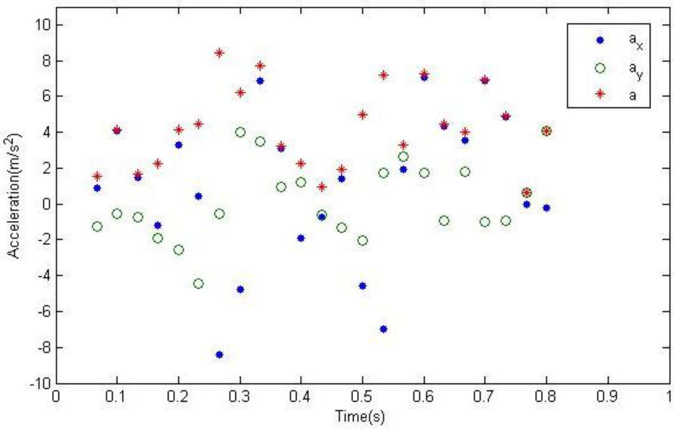


Fig 4.8 Plot of resultant force

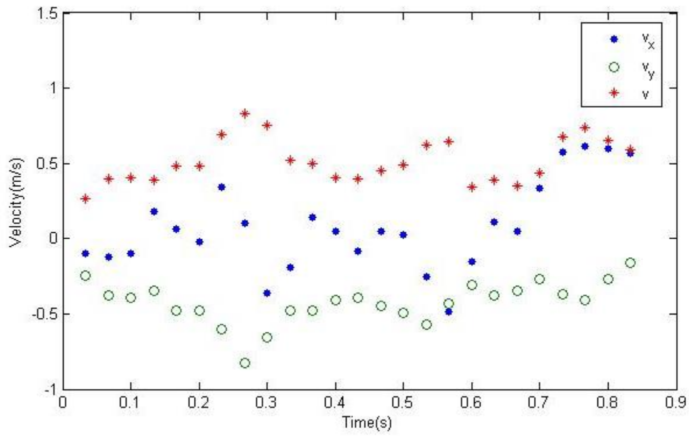
4.3 Descent Maneuver

4.3.1 Flight Analysis of Honeybees

Fig 4.9b shows the velocity-time graph of a representative trajectory of a honey bee kept under observation. Downward velocity (V_y) and resultant velocity (V) are inversely proportional to each other. Flight path of honey bee is shown in Fig.4.9c while descending from a higher point to a point at lesser height.



(a)



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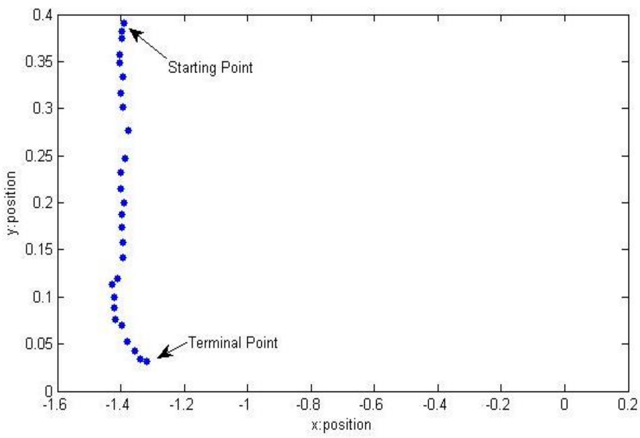
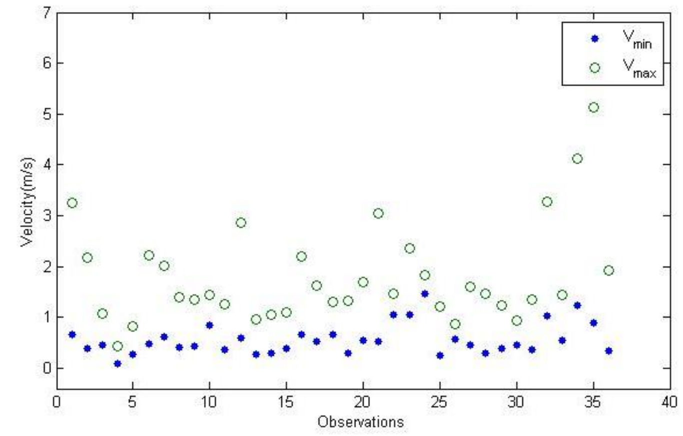


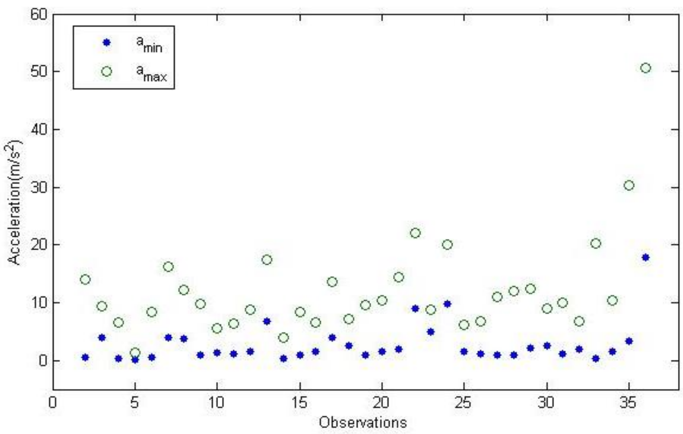
(c)

Fig 4.9 Graph of acceleration, velocity and position of honey bee

Overall 36 observations (trajectories) are recorded during the descent phase of honeybees. The maxima and minima of the flight trajectories are plotted in Figure 4.10. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.11 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.12.

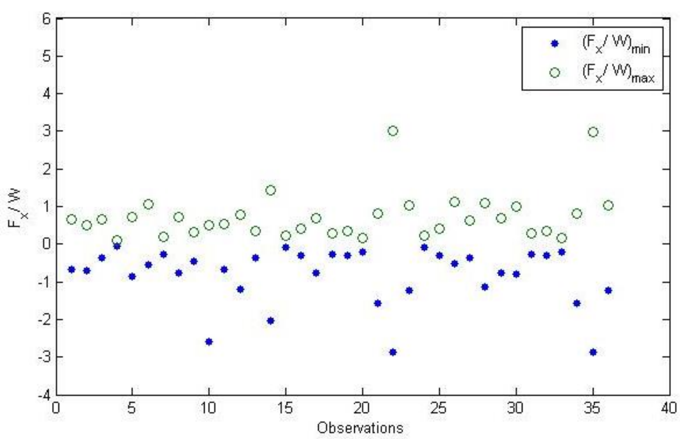


(a)

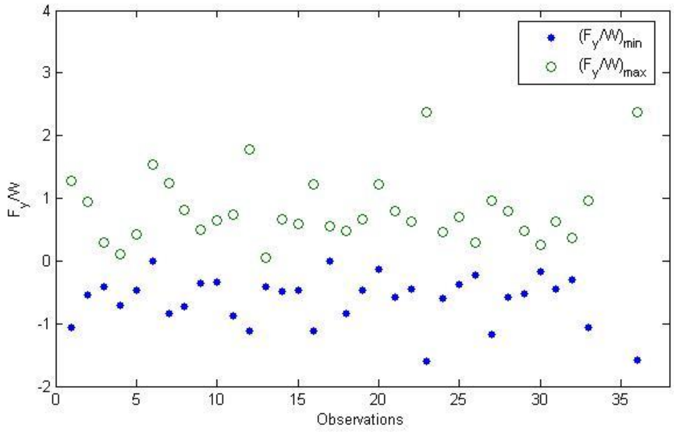


(b)

Fig 4.10 V_{min}, V_{max}, a_{min} and a_{max} during descent

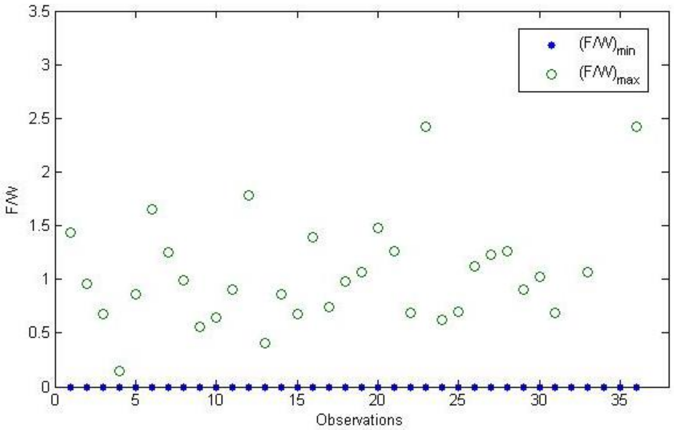


(a)



(b)

Fig 4.11 Graph of minimum and maximum propulsive force

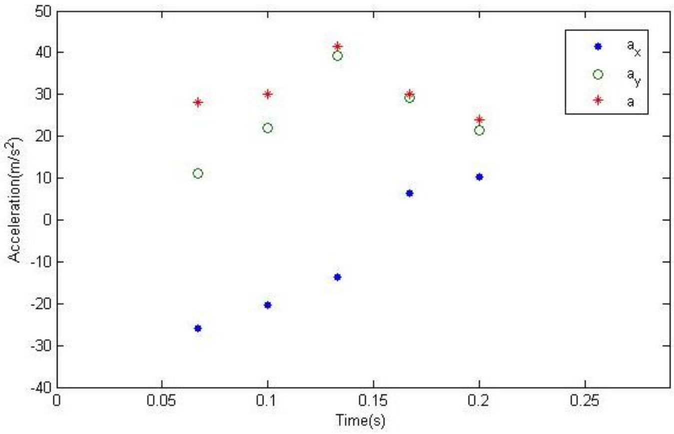


(c)

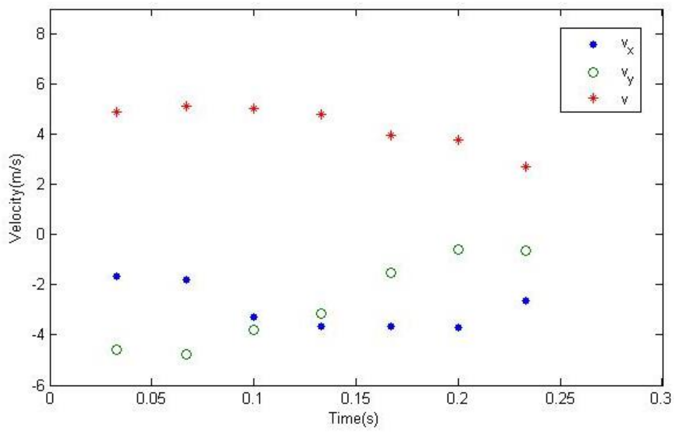
Fig 4.12 Graph of resultant force

4.3.2 Flight Analysis of Butterfly

According to the graph, (Fig.4.13a), acceleration in x-direction (a_x), acceleration in y-direction (a_y) and their resultant a, are shown. Fig 4.13b shows the velocity-time graph of butterflies kept under observation. Downward velocity (V_y) and forward velocity (V_x) are inversely proportional to each other. The graph shows a phase difference hence butterflies fly with a constant energy during descent phase. The resultant velocity (V) is directly proportional to the forward velocity (V_x). Flight path of butterfly is shown in Fig.4.13c while descending from one point to another.



(a)



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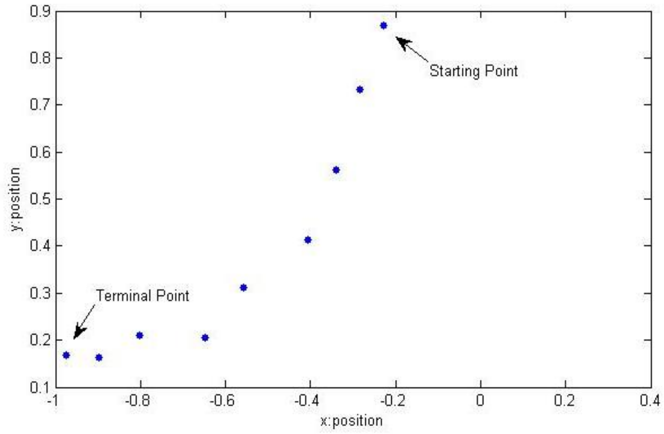
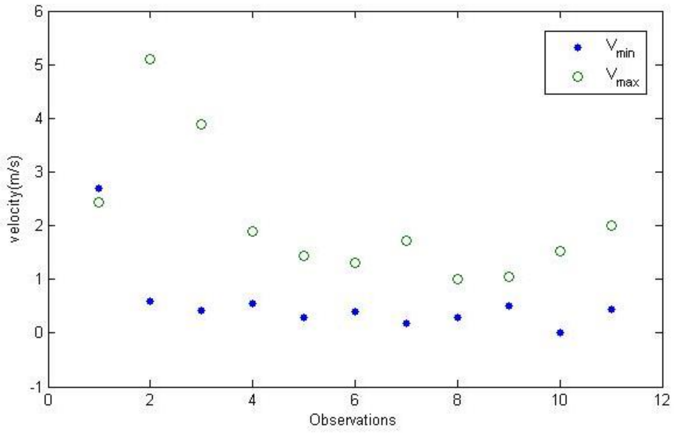


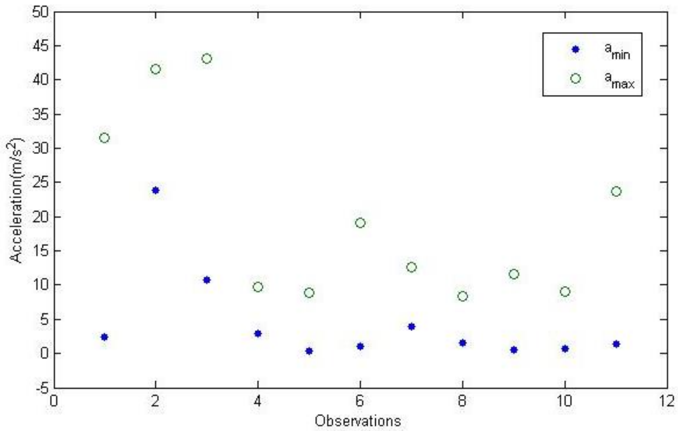
©

Fig 4.13 Graph of acceleration, velocity and position of butterfly

Overall 11 observations (trajectories) are recorded during the descent phase of butterflies. The maxima and minima of the flight trajectories are plotted in Figure 4.14. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.15 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.16.

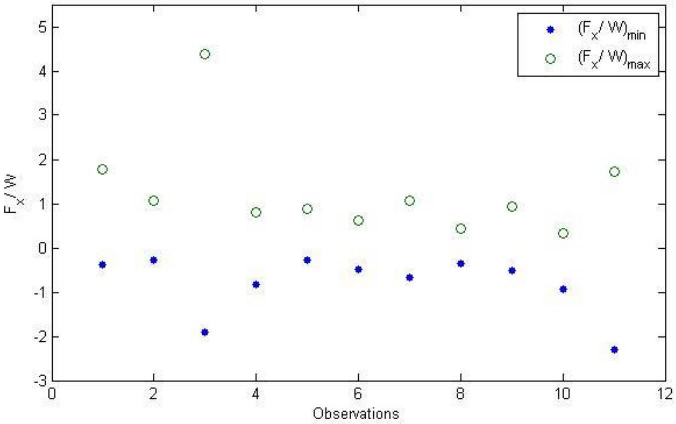


(a)

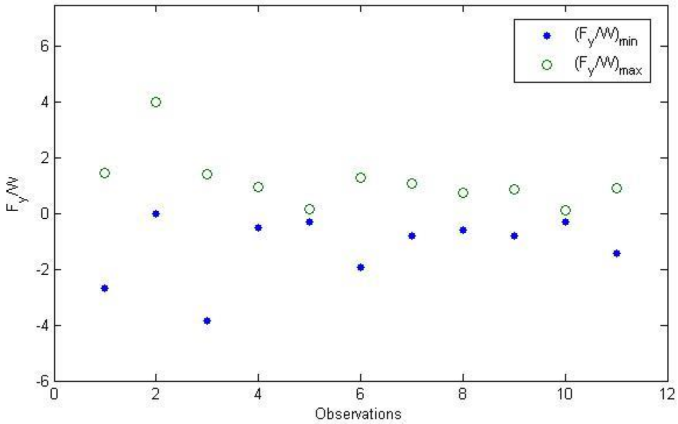


(b)

Fig 4.14 V_{min}, V_{max}, a_{min} and a_{max} during Descent



(a)



(b)

Fig 4.15 Graph of minimum and maximum propulsive force

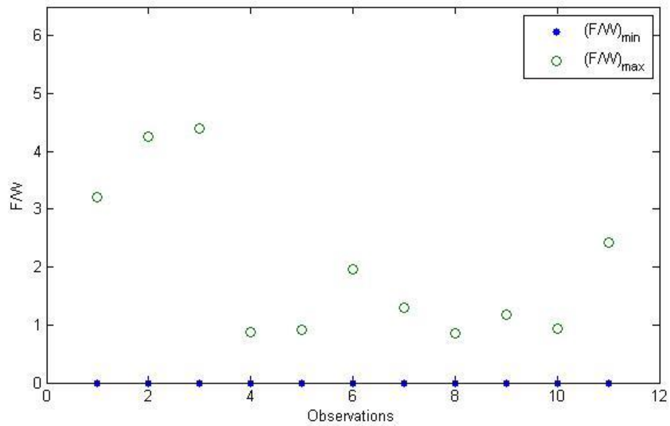


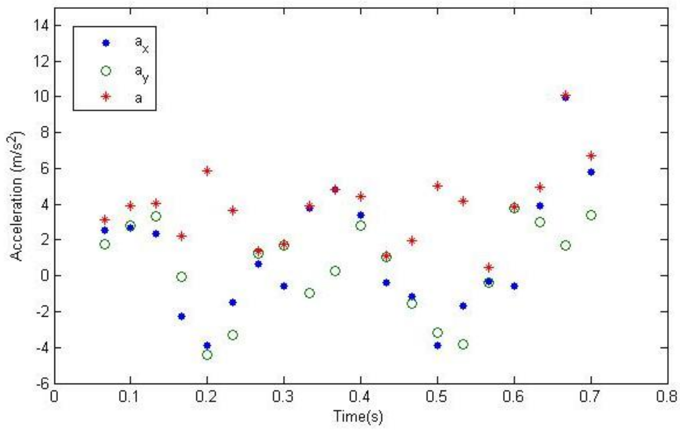
Fig 4.16 Graph of resultant force

4.4 Forward Flight

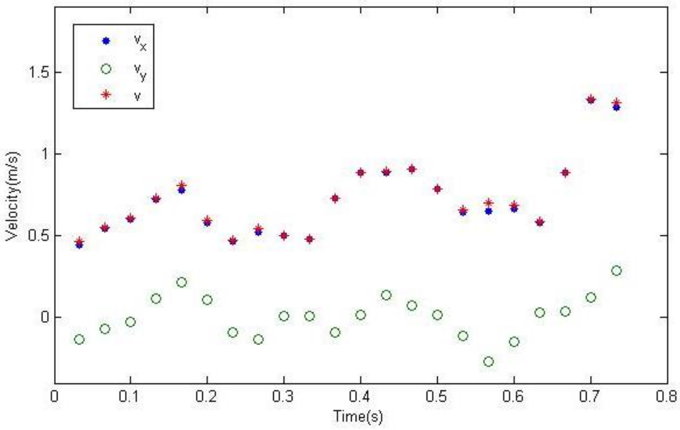
4.4.1 Flight Analysis of Honeybees

According to the graph, (Fig.4.17a), acceleration in x-direction (a_x), acceleration in y-direction (a_y) and their resultant a, are shown for a representative trajectory of honeybee. Forward acceleration (a_x) and vertical acceleration (a_y) are almost directly proportional to each other, whereas the resultant acceleration (a) is inversely proportional to them.

Horizontal flight of honey bees Fig 4.17b shows the velocity-time graph of kept under observation. Downward velocity (V_y) and forward velocity (V_x) are directly proportional to each other. Forward velocity is approximately equal to the resultant velocity V. Flight path of honey bee showing a horizontal flight is shown in Fig.4.17c.



(a)



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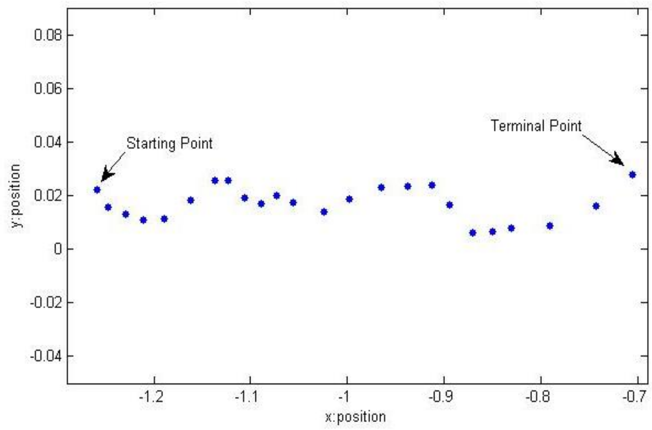
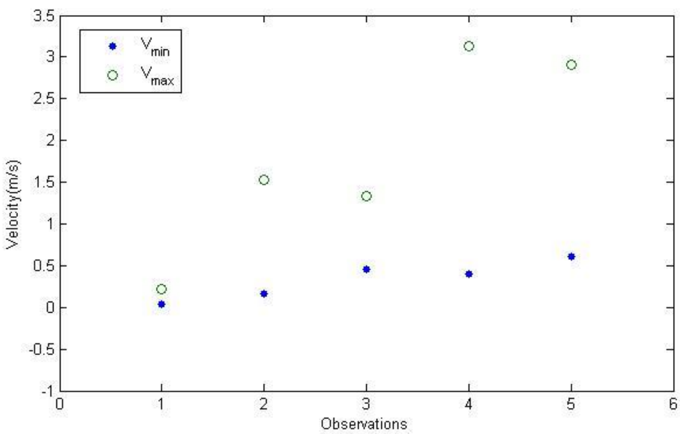


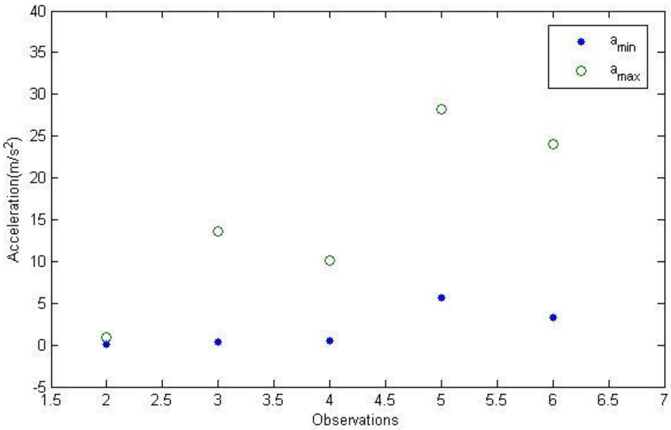
(c)

Fig 4.17 Graph of acceleration, velocity and position of Honey Bee

Overall 5 observations (trajectories) are recorded during the horizontal flight of honeybees. The maxima and minima of the flight trajectories are plotted in Figure 4.18. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.19 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.20.

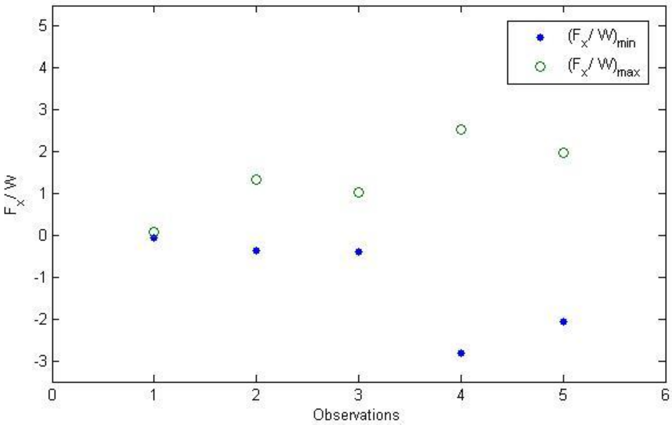


(a)

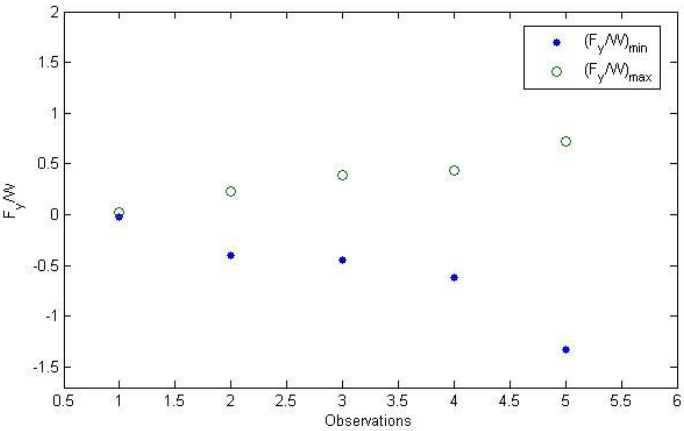


(b)

Fig 4.18 Vmin, Vmax, amin and amax during horizontal flight



(a)



(b)

Fig 4.19 Graph of minimum and maximum propulsive force

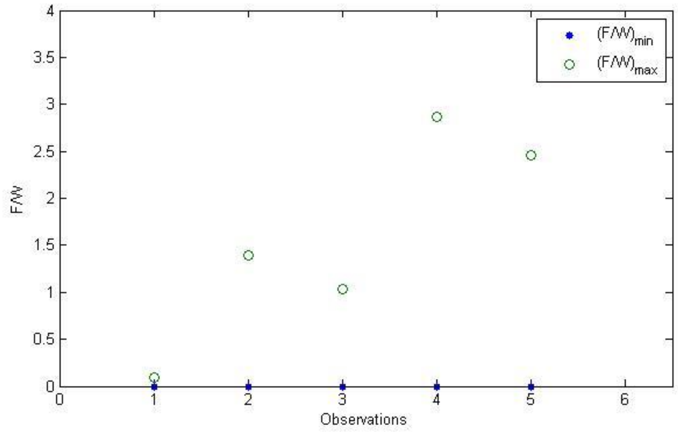
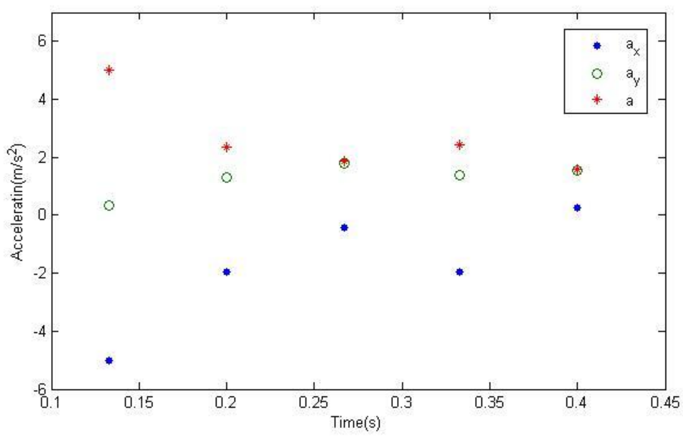


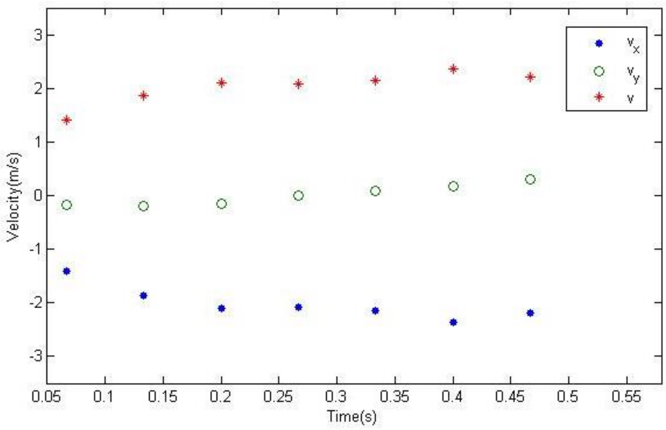
Fig 4.20 Graph of resultant force

4.4.2 Flight Analysis of Butterflies

According to the graph, (Fig.4.21a), both acceleration in x-direction (a_x) and acceleration in y-direction (a_y) directly proportional to each other whereas acceleration in x-direction (a_x) is inversely proportional to resultant acceleration. Fig 4.21b shows the velocity-time graph of butterfly kept under observation. The velocity ranges from 1.4m/s to 2.3m/s. Butterflies undergo non-uniform acceleration during this flight phase. Flight path of butterfly in horizontal flight is shown in Fig.4.21c



(a)



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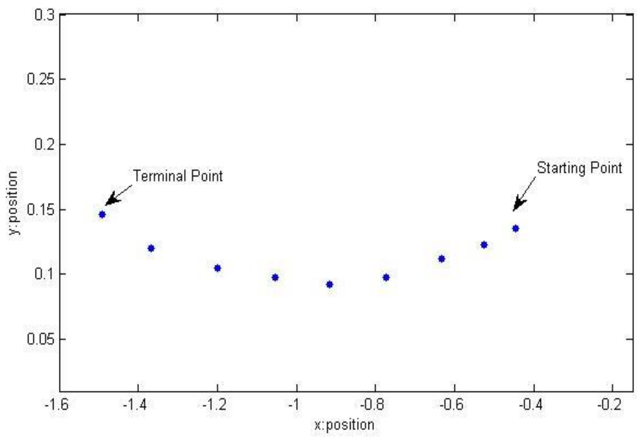
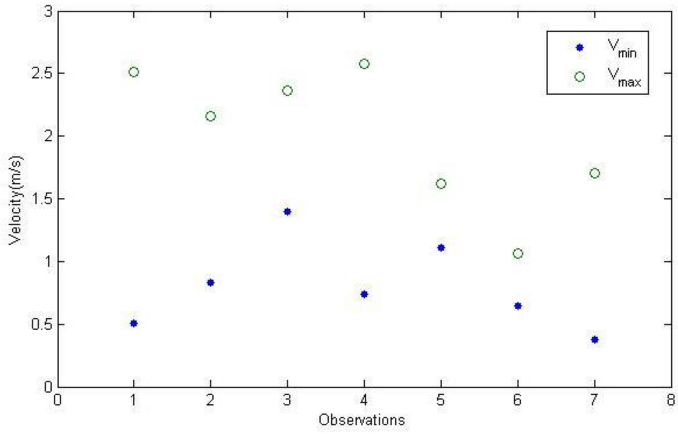


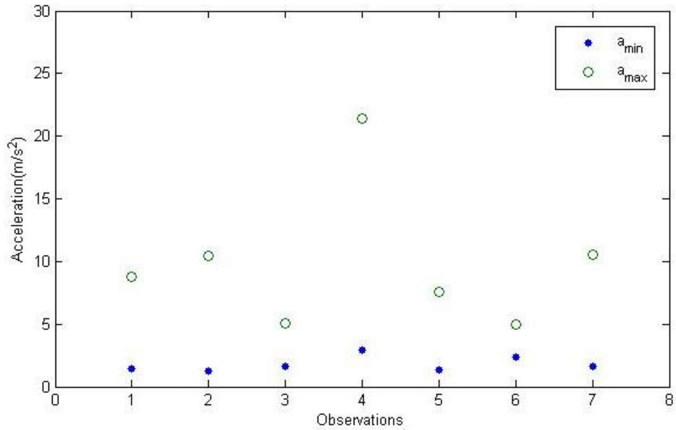
(c)

Fig 4.21 Graph of acceleration, velocity and position of Butterfly

Overall 7 observations (trajectories) are recorded during the forward flight of butterflies. The maxima and minima of the flight trajectories are plotted in Figure 4.22. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.23 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.24.

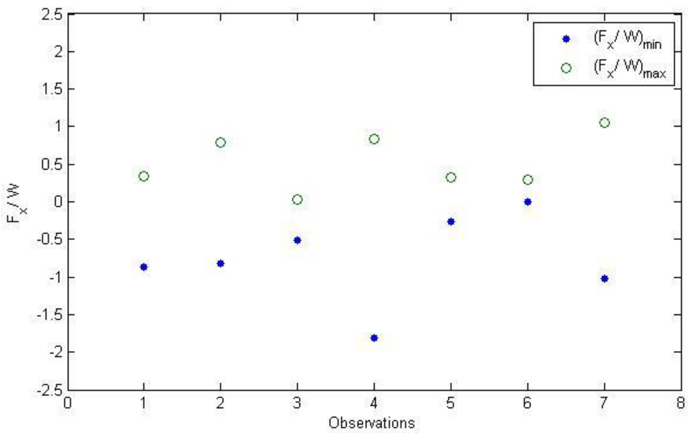


(a)

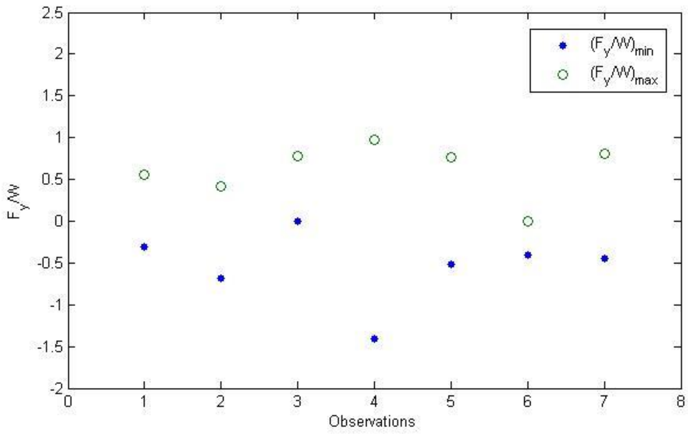


(b)

Fig 4.22 Vmin, Vmax, amin and amax during horizontal flight



(a)



(b)

Fig 4.23 Graph of minimum and maximum propulsive force

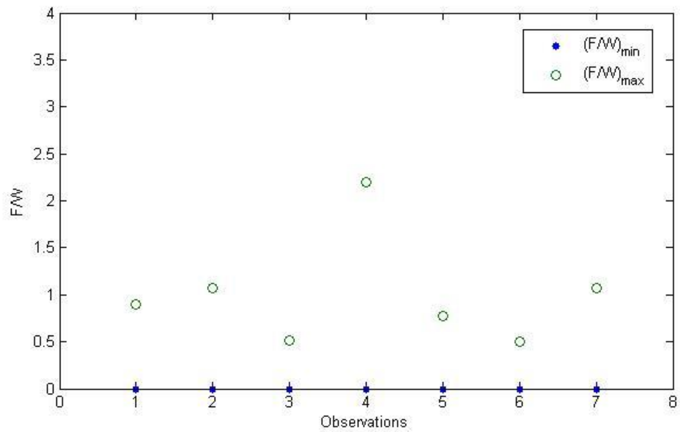
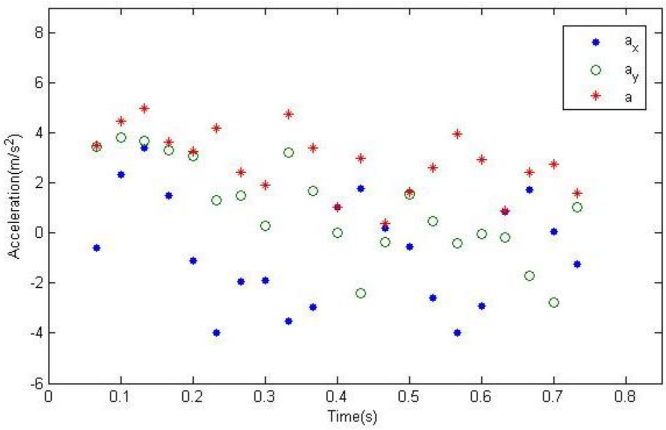


Fig 4.24 Graph of Resultant Force

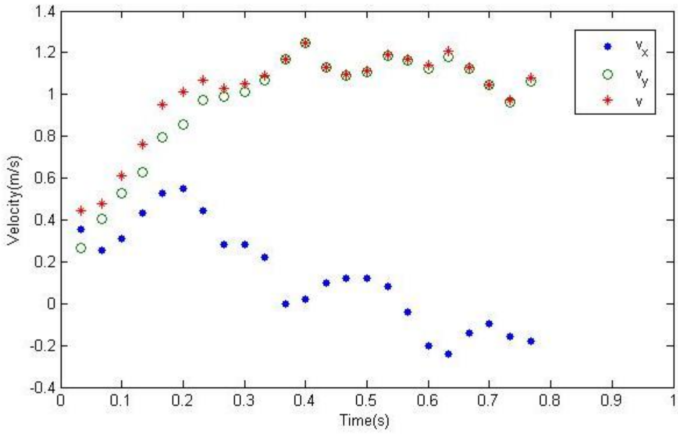
4.5 Vertical Climb

4.5.1 Flight Analysis of Honeybees

Fig 4.25b shows the velocity-time graph of honey bees kept under observation. Flight path of honey bee is shown in Fig.4.25c in a vertical climb phase.



(a)



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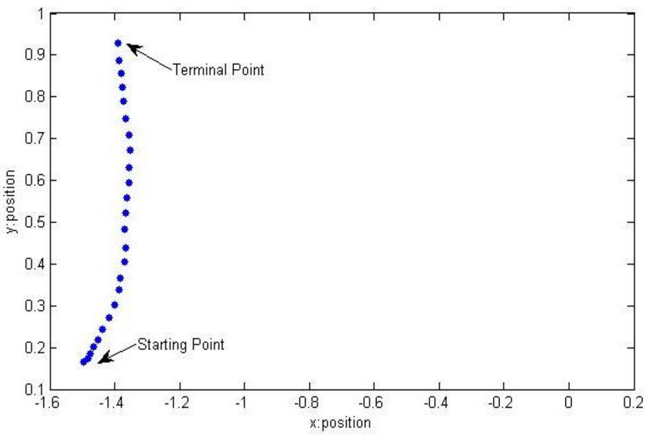
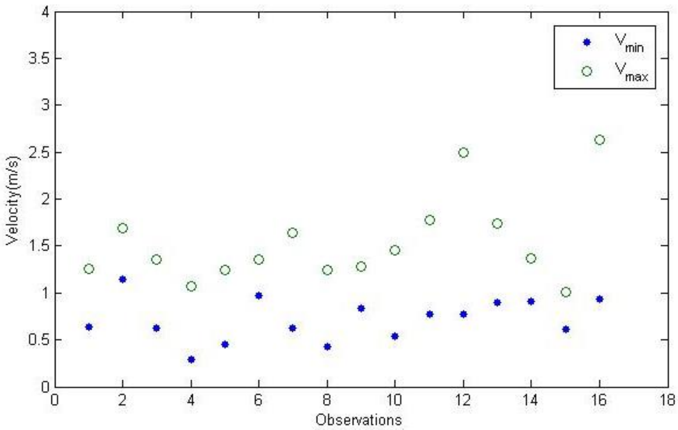


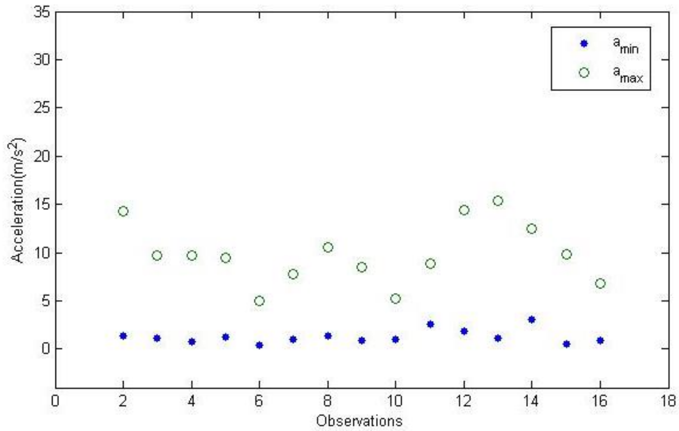
(c)

Fig 4.25 Graph of acceleration, velocity and position of Honey Bee

Overall 16 observations (trajectories) are recorded during the vertical climb phase of honeybees. The maxima and minima of the flight trajectories are plotted in Figure 4.26. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.27 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.28.

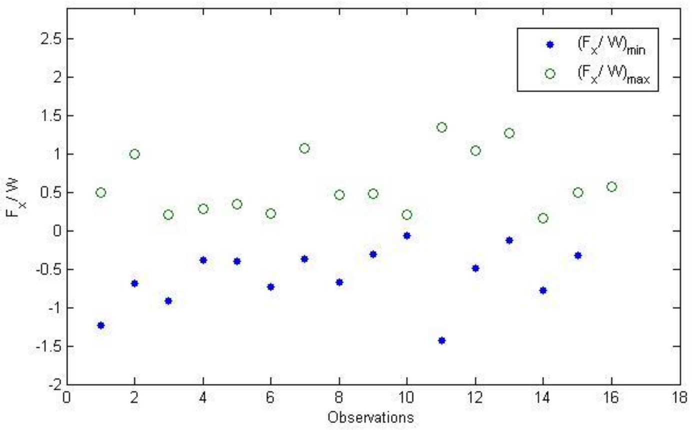


(a)

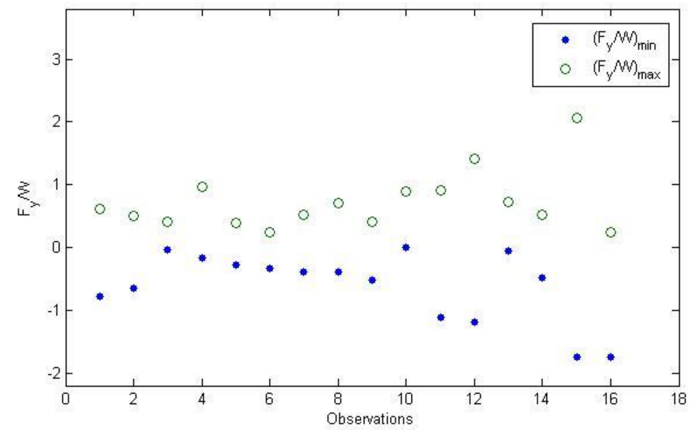


(b)

Fig 4.26 V_{min}, V_{max}, a_{min} and a_{max} during Vertical Climb



(a)



(b)

Fig 4.27 Graph of minimum and maximum propulsive force

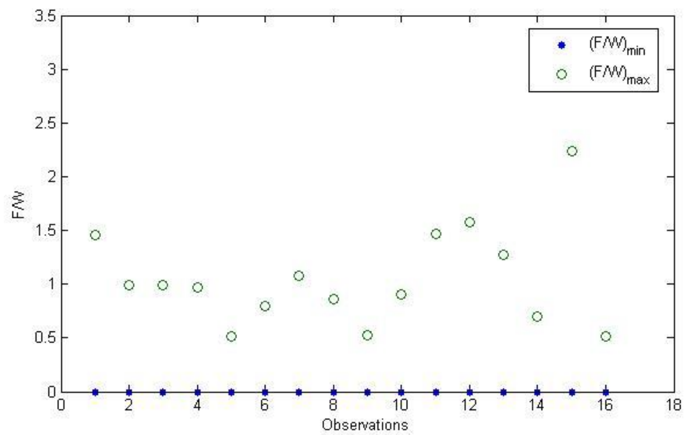
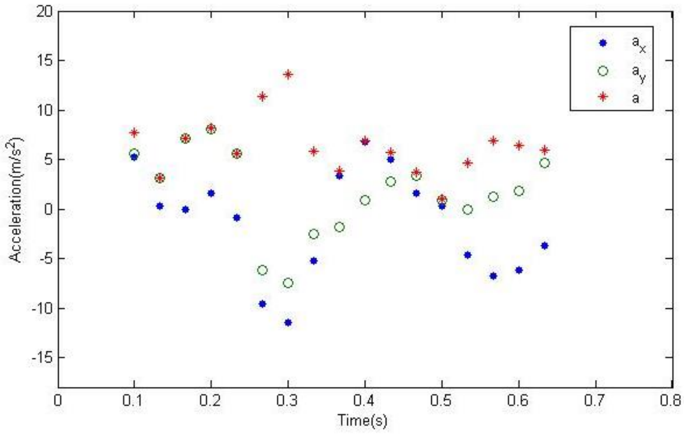


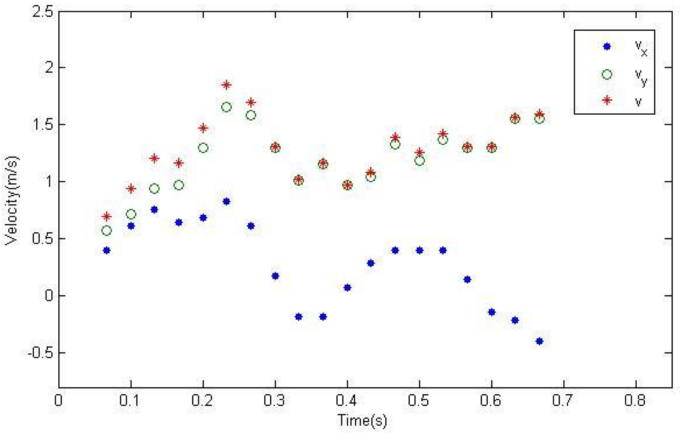
Fig 4.28 Graph of resultant force

4.5.2 Flight Analysis of Butterfly

According to the graph, (Fig.4.29a), both acceleration in x-direction (a_x) and resultant acceleration (a) are somewhat inversely proportional. Fig 4.29b shows the velocity-time graph of butterfly kept under observation. Flight path of butterfly is shown in Fig.4.29c while climbing from a point at lower height to a point at higher height.



(a)



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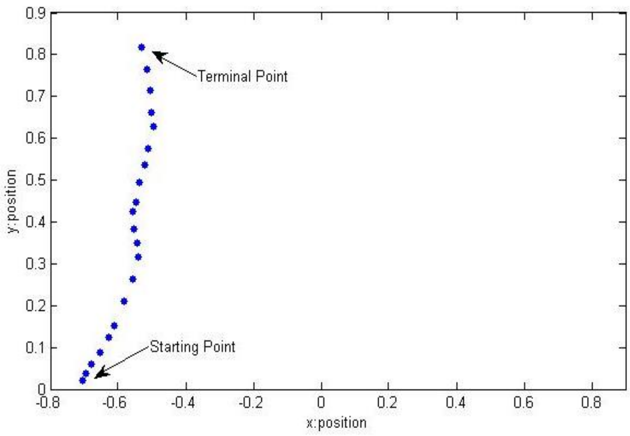
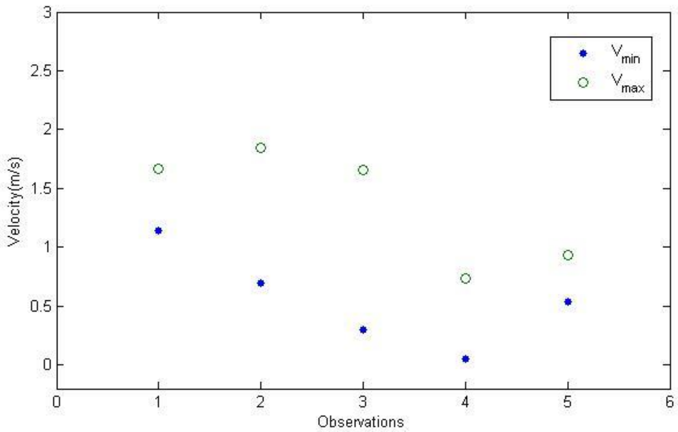


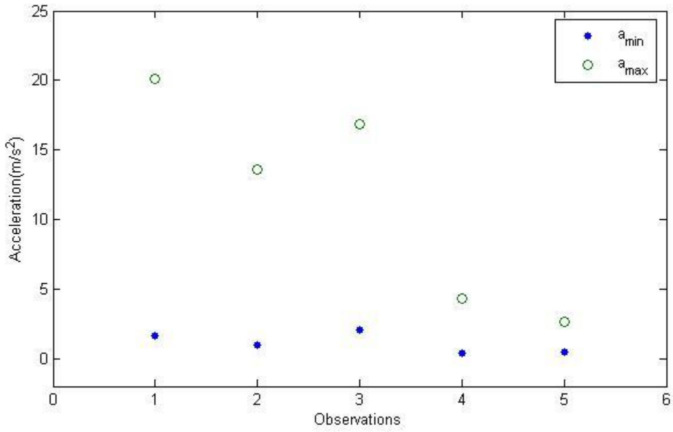
(c)

Fig 4.29 Graph of acceleration, velocity and position of Butterfly

Overall 5 observations (trajectories) are recorded during the vertical climb phase of butterflies. The maxima and minima of the flight trajectories are plotted in Figure 4.30. Similarly, the maxima and minima of horizontal and vertical forces are plotted in Figure 4.31 of several trajectories. The resultant of vertical and horizontal forces is shown in Figure 4.32.

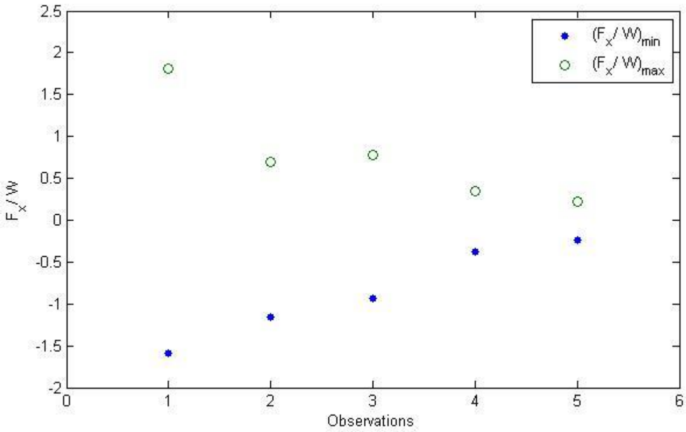


(a)

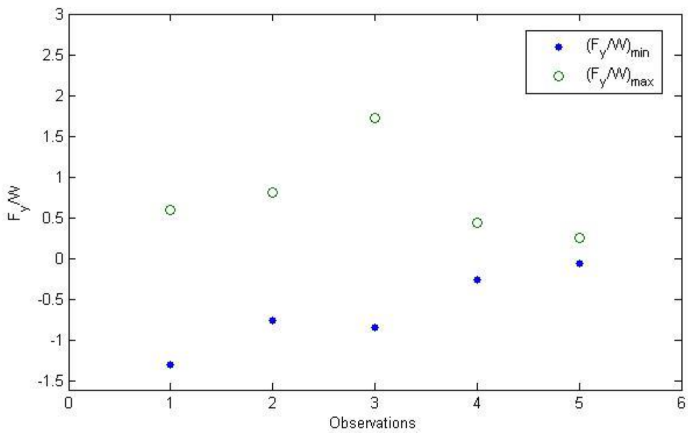


(b)

Fig 4.30 V_{min}, V_{max}, a_{min} and a_{max} during vertical climb



(a)



(b)

Fig 4.31 Graph of minimum and maximum propulsive force

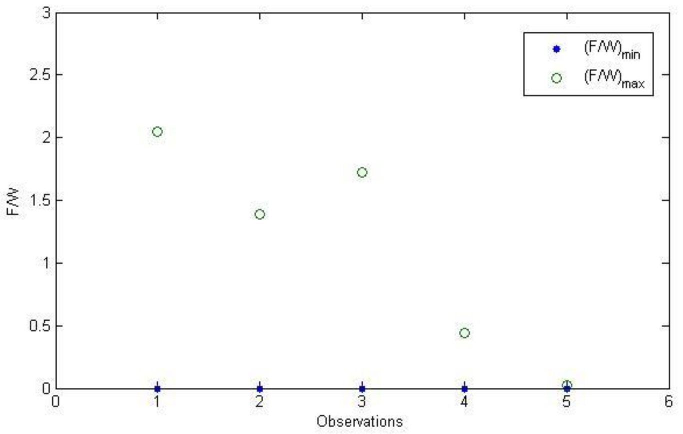


Fig 4.32 Graph of resultant force

4.6 Comparative Analysis between honeybees and butterflies

Table 4.1 shows the minimum, maximum and average of velocities for honey bees and butterflies during different phases of flight including climb, descent, horizontal flight and vertical climb. The values of maximum velocity of honey bees (obtained from tracking) during flight is approximately 1.8m/s in each phase. This leads to the fact that velocity of honey bees is independent of phase of flight. They restrict their speed due to navigational aids.

Table 4.1 Average minima and maxima of velocity for all trajectories of honeybees and butterflies

	Honeybee			**Butterfly**		
Phases of Flight	**V_{min} (m/s)**	**V_{max} (m/s)**	**V_{avg} (m/s)**	**V_{min} (m/s)**	**V_{max} (m/s)**	**V_{avg} (m/s)**
Climb	0.554	1.797	1.175	0.56	2.34	1.450
Descent	0.561	1.802	1.181	0.648	2.13	1.389
Horizontal Flight	0.336	1.824	1.08	0.802	1.99	1.396
Vertical Climb	0.715	1.539	1.127	0.546	1.37	0.958

The maximum velocity of butterflies is approximately 2.34 m/s during climb, descent and horizontal flight. It is not a performance limitation but the environment that limits the velocity.

The trend of velocity is similar for both, butterfly and honey bee. The value of maximum velocity of both insects during vertical climb is slightly lower from rest of the values. But butterflies show a larger gap between these values. They attained a maximum speed of 1.37 m/s during vertical climb. This performance limitation is probably due to the larger size of butterfly as compared to honeybees with lower F_y/W values as shown in Table 4.4. Honeybees are smaller in size so the decrease in velocity during vertical climb is lesser as compared to the decrease in velocity of butterflies.

Table 4.2 Average minima and maxima of acceleration for all trajectories of honeybees and butterflies

	Honeybees			**Butterflies**		
Phases of Flight	**a_{min} (m/s^2)**	**a_{max} (m/s^2)**	**a_{avg} (m/s^2)**	**a_{min} (m/s^2)**	**a_{max} (m/s^2)**	**a_{avg} (m/s^2)**
Climb	0.13	26.43	13.28	0.69	41.42	21.05
Descent	0.06	50.73	25.39	0.43	43.13	21.78
Horizontal Flight	0.09	28.16	14.12	1.29	21.45	11.37
Vertical Climb	0.39	21.94	11.16	0.38	20.1	10.24

Table 4.2 shows the minimum and maximum values of acceleration of honey bees and butterflies during different phases of flight including climb, descent, horizontal flight and vertical climb. Honey bees flew with a maximum acceleration of 50.73 m/s during the phase of descent which is much higher as compared to the values of maximum acceleration in other phases of flight. The table also shows the minimum and maximum values of acceleration of butterflies during different phases of flight including climb, descent, horizontal flight and vertical climb. The minimum values of acceleration hovers around

0 m/s^2. The maximum values of acceleration during vertical climb is lesser in both cases whereas during other phases, higher values are attained. The results show a consistent pattern of acceleration of honeybees and butterflies.

Table 4.3 $(F_x/W)_{min}$, $(F_x/W)_{max}$ and $(F_x/W)_{avg}$ for all trajectories of honeybees and butterflies

	Honeybees			**Butterflies**		
Phases of Flight	**$(F_x/W)_{min}$**	**$(F_x/W)_{max}$**	**$(F_x/W)_{avg}$**	**$(F_x/W)_{min}$**	**$(F_x/W)_{max}$**	**$(F_x/W)_{avg}$**
Climb	-1.723	1.235	-0.244	-4.15	1.814	-1.168
Descent	-2.87	2.998	0.064	-2.309	4.386	1.038
Horizontal Flight	-2.805	2.54	-0.132	-1.8102	1.056	-0.3771
Vertical Climb	-1.528	1.341	-0.093	-1.582	1.813	0.115

The force *F* is divided by the weight *W* of the insect to non-dimensionalize the data according to the weight. The minima, maxima and average of propulsive force of honey bees and butterflies is depicted in table 4.3. The maximum value of propulsive force $(F_x/W)_{max}$ of honeybees is 2.998 m/s whereas for butterflies, the value comes out to be 4.386 m/s. Both, honey bees and butterflies, have a similar trend of having higher values of propulsive force during descent maneuver. During other phases, they both have comparatively lesser values. The results also specify that both insects have higher values of $(F_x/W)_{min}$ during vertical climb phase. Moreover the average of minima and maxima of propulsive forces indicate lesser values during climb maneuver performed by honey bees as well as butterflies.

Table 4.4 $(F_y/W)_{min}$, $(F_y/W)_{max}$ and $(F_y/W)_{avg}$ for all trajectories of honeybees and butterflies

	Honeybees			Butterflies		
Phases of Flight	$(F_y/W)_{min}$	$(F_y/W)_{max}$	$(F_y/W)_{avg}$	$(F_y/W)_{min}$	$(F_y/W)_{max}$	$(F_y/W)_{avg}$
Climb	-1.517	1.91	0.196	-2.016	1.603	-0.206
Descent	-1.599	2.38	0.390	-3.858	4.012	0.077
Horizontal Flight	-1.326	0.726	-0.3	-1.414	0.976	-0.219
Vertical Climb	-1.742	2.062	0.16	-1.298	1.723	0.212

The information reported in Table 4.4 show a lesser value of $(F_y/W)_{max}$ to be 0.726 and 0.976 during horizontal flight of honey bees and butterflies respectively. The higher values of 2.38 and 4.012 during descent are also shown. Hence a consistent pattern for minimum values of $(F_y/W)_{max}$ during horizontal flight and maximum values of $(F_y/W)_{max}$ during descent maneuver is revealed from the results.

Table 4.5 $(F/W)_{min}$, $(F/W)_{max}$ and $(F/W)_{avg}$ for all trajectories of honeybees and butterflies

	Honeybees			Butterflies		
Phases of Flight	$(F/W)_{min}$	$(F/W)_{max}$	$(F/W)_{avg}$	$(F/W)_{min}$	$(F/W)_{max}$	$(F/W)_{avg}$
Climb	0	2.447	1.223	0	4.213	2.106
Descent	0	2.427	1.213	0	4.387	2.193
Horizontal Flight	0	2.873	1.436	0	2.197	1.098
Vertical Climb	0	2.239	1.119	0	2.044	1.022

Results from experiments listed in Table 4.5 indicate that the values of $(F/W)_{max}$ of honeybees is consistent nearly about 2 whereas there is an increase in its value for butterflies in climb and descent maneuver. Moreover, the comparison of values of $(F/W)_{avg}$ of both insects specify that butterflies, as compared to honey bees, exert less power in forward flight (horizontal flight) and vertical climb.

Chapter 5

Conclusion & Future Work

5.1 Conclusion of Research Study

The conclusions drawn from this thesis comprise of several aspects which are distributed in groups based on the conclusions whether they are related to experimental setup, video recording, insect species, information obtained about different parameters.

5.1.1 Conclusion Related to Experimental Setup

- Firstly design requirements of experimental setup were determined according to the need of the study being conducted. A glass chamber was constructed by the author and members of MIG by acquiring the material for its construction. An Insect Flight Lab was established at Research centre for Modeling and Simulation (RCMS), Islamabad where this glass chamber was kept for experiments.
- Successful flight experiments of insects were conducted using the developed setup.

5.1.2 Conclusion Related to Video Recording

- A camera was placed in front of the glass container for recording the flight of different insects placed inside it. The captured videos were slowed down at a frame rate of *30fps*.
- It was noted that at 30 frames per second the video motion appeared to be smoother. Hence, it was much easier to track insects in videos.

5.1.3 Conclusion Related to Insect Species

- In the beginning of this research, an elaborative study was performed on various insect species including fruit flies, honey bees, butterflies, dragonflies and house flies. But after studying and exploring about them, the author had to select only two of the insects, that is, honey bees and butterflies. Each insect was captured from different localities to test their flight. Fruit flies and houseflies are very small in size making it difficult to capture a clearer video and then tracking them. Dragonflies, on the other hand, have a larger wing and body size. It was observed that they did not fly in a confined area.
- After successful attempt of experiments, honey bees and butterflies were selected for the comprehensive study.

5.1.4 Conclusion Related to Flight Analysis

- In climb phase, forward acceleration (a_x) and vertical acceleration (a_y) of honey bees are inversely proportional to each other. Downward velocity (V_y) and forward velocity (V_x) are also inversely proportional to each other. This suggests that honey bees fly with a constant energy during climb.
- The graph of velocity shows a phase difference hence butterflies fly with a constant energy during climb phase.
- Downward velocity (V_y) and resultant velocity (V) are inversely proportional to each other during descent maneuver of butterfly.
- In horizontal flight of honey bee and butterfly, both, downward velocity (V_y) and forward velocity (V_x) are directly proportional to each other along with forward acceleration (a_x) and vertical acceleration (a_y).
- Velocity of honey bees is independent of phase of flight. They restrict their speed due to navigational aids.

- The trend of velocity is similar for both, butterfly and honey bee. The value of maximum velocity of both insects during vertical climb is slightly different from velocity in some other phase. But butterflies show a larger gap between the values. This is a performance limitation due to the larger size of butterfly as compared to honeybees. Honeybees are smaller in size so the decrease in velocity during vertical climb is lesser as compared to the decrease in velocity of butterflies.
- The maximum values of acceleration of honey bees and butterflies both, during vertical climb is lesser whereas during descent, higher values are attained. The results show a consistent pattern of acceleration of honeybees and butterflies.
- The force *F* is divided by the weight *W* of the insect to non-dimensionalize the data according to the weight.
- Both, honey bees and butterflies, have the same trend of having higher values of propulsive force during descent maneuver. It is also specified by the results, that both insects have higher values of $(F_x /W)_{min}$ during vertical climb phase. Moreover the average of minima and maxima of this propulsive forces indicate lesser values during climb maneuver performed by honey bees as well as butterflies.
- Comparison of both insects provide a consistent pattern for minimum values of $(F_y/W)_{max}$ during horizontal flight and maximum values of $(F_y/W)_{max}$ during descent maneuver.
- The comparison of values of $(F/W)_{avg}$ of both insects specify that butterflies, as compared to honey bees, exert less power in forward flight (horizontal flight) and vertical climb.

5.2 Addition of Body Knowledge / Filled Literature Gap

It is a pioneering research based on making videos of flying insects for insect flight observation and two dimensional analysis. Being novel research in Pakistan, it is a distinguished addition to the literature. The results obtained from this research will push further the forefront technology of the small bio-inspired mechanical flying insect development in our country. Author also determined different parameters including velocity, acceleration and propulsive forces from insect flight which has never been accomplished in respective area of study.

5.3 Implications for Future Work

While designing, developing and evaluating the insect flight trajectory tracking system for analysis of flight of Pterygota, the author has found few future implications of this study. They are enlisted below:

- This study could be upgraded to three dimensional tracking and analysis of Pterygota. It will provide more information about various flight parameters. The information obtained from 3D analysis would serve as the basis for proposing a model of a real world UAV. A better understanding would be developed about the flight of insects.
- More insect species can be incorporated for the similar project for generalization of data. The more the insects are used, the more information about flight of biological fliers is retrieved.

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