Simulation of optic flow based flight control for a flapping wing micro aerial vehicle

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Simulation of optic flow based flight control for a flapping wing micro aerial vehicle

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For the degree of Master of Science in Embedded Systems at Delft University of Technology

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The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) for acceptance a thesis entitled

**SIMULATION OF OPTIC FLOW BASED FLIGHT CONTROL FOR A FLAPPING WING MICRO AERIAL VEHICLE**

by

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Abstract

Bio-inspired flying micro drones, formally known as Flapping Wing Micro Aerial Vehicles (FWMAV) are a booming class of robots in today’s world. Navigation and flight control of these drones is an interesting area of research that has become popular among roboticists and engineers due to its challenges. A bio-inspired optic flow based flight control system for Flapping Wing Micro Aerial Vehicle (FWMAV) using six optic sensor configuration was proposed earlier. However, there is not enough evidence to validate the control methodology discussed. This thesis presents a validation in the form of a flight simulator to test the optic flow based control strategy. The simulator consists of functional modules such as a kinematic module to generate the motion of the FWMAV based on inertia, external forces and torques, an optic sensor system module to generate the optic flow as perceived by the six optic sensor configuration, a flying environment to test the flight of the FWMAV and an optic flow based controller module to stabilise the aircraft in three dimensional space. Simulation results show that the optic flow based controller can successfully stabilise the FWMAV under normal flying conditions.
# Table of Contents

<table>
<thead>
<tr>
<th>Acknowledgements</th>
<th>viii</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Introduction</strong></td>
<td></td>
</tr>
<tr>
<td>1-1 Context of Present Study</td>
<td>1</td>
</tr>
<tr>
<td>1-2 FWMAV Projects</td>
<td>2</td>
</tr>
<tr>
<td>1-3 Objective of present study</td>
<td>3</td>
</tr>
<tr>
<td>1-3-1 Strategy</td>
<td>3</td>
</tr>
<tr>
<td>1-4 Approach of present study</td>
<td>3</td>
</tr>
<tr>
<td>1-5 Synopsis</td>
<td>5</td>
</tr>
<tr>
<td><strong>2 Bio-inspired insect navigation</strong></td>
<td>6</td>
</tr>
<tr>
<td>2-1 Insect Senses</td>
<td>6</td>
</tr>
<tr>
<td>2-1-1 Compound Eyes</td>
<td>6</td>
</tr>
<tr>
<td>2-1-2 Ocelli</td>
<td>7</td>
</tr>
<tr>
<td>2-1-3 Halteres</td>
<td>8</td>
</tr>
<tr>
<td>2-2 Stabilization and navigation</td>
<td>8</td>
</tr>
<tr>
<td><strong>3 Optic Flow</strong></td>
<td>11</td>
</tr>
<tr>
<td>3-1 Introduction</td>
<td>11</td>
</tr>
<tr>
<td>3-2 Optic Flow and Micro Aerial Vehicle (MAV)</td>
<td>12</td>
</tr>
<tr>
<td>3-3 Optic Flow in Atalanta</td>
<td>13</td>
</tr>
<tr>
<td>3-3-1 Determining Optic Flow</td>
<td>14</td>
</tr>
<tr>
<td>3-3-2 Six optic sensor configuration</td>
<td>14</td>
</tr>
<tr>
<td>3-3-3 Optic flow equations</td>
<td>16</td>
</tr>
<tr>
<td>3-4 Optic flow Experiments</td>
<td>20</td>
</tr>
<tr>
<td>3-4-1 Experimental Setup</td>
<td>20</td>
</tr>
<tr>
<td>3-4-2 Result</td>
<td>22</td>
</tr>
<tr>
<td>3-4-3 Conclusion</td>
<td>24</td>
</tr>
</tbody>
</table>
# Table of Contents

## 4 Simulator

4-1 Introduction ......................................................... 25  
4-2 Three Dimensional Model  
  4-2-1 Flying Environment  ........................................... 26  
  4-2-2 Flying Sensor platform  ...................................... 26  
  4-2-3 Motion  .......................................................... 27  
  4-2-4 Distance measurement  ....................................... 28  
4-3 Optic Flow .......................................................... 32  
4-4 Parameter Estimation .............................................. 35

## 5 Control Strategy

5-1 Introduction .......................................................... 41  
5-2 Three dimensional kinematic model  ................................ 42  
5-3 Flight Control .......................................................... 44  
  5-3-1 Wing control ...................................................... 44  
  5-3-2 Height control .................................................... 46  
  5-3-3 Obstacle avoidance .............................................. 47  
  5-3-4 Control signals .................................................. 48  
5-4 Results ................................................................. 48  
  5-4-1 Case I : Height control for a pure translational motion  ... 49  
  5-4-2 Case II : Wing control - Roll and Pitch stabilization ....... 51  
  5-4-3 Case III : Hovering .............................................. 53

## 6 Conclusions and Recommendations

6-1 Inference .............................................................. 57  
6-2 Future Recommendations ........................................... 58

## Glossary

List of Acronyms .......................................................... 61  
List of Symbols ............................................................ 61

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Master of Science Thesis

Abhimanyu Selvan
List of Figures

1-1 Insect-inspired MAV design of the Atalanta project ........................................... 2
1-2 Schematic of the optic flow based stability and obstacle control system of the four wing flying sensor platform. The cameras are shown as the grey boxes with the direction of view. Source: [4] ................................................................. 4

2-1 Schematic illustration of the compound eye of an insect. A: surface of compound eye, showing the facet lenses. B: longitudinal cross section of an ommatidium. C: structure of one of the photoreceptor cells within an ommatidium, showing the microvilli, containing the photopigment, that contribute to the structure of the rhabdom. D: detail of microvillar structure, illustrating the location and inferred alignment of the photopigment (rhodopsin) molecules. Source: [9] ......................... 7
2-2 Anatomy (a,c,e) and optic flow response fields (b,d,f) of interneurons in blowflies. Source: [10] ................................................................. 8
2-3 Top view view of the blowfly head. lce and rce mark the left and right compound eye, respectively. The three ocelli of the blowfly are labelled mo, llo, and rlo, which stands for medial, lateral left, and lateral right ocellus. Source: [11] ........ 9
2-4 Crane fly, with a pair of halteres visible behind the wings as appendages, about as long as the animal’s antennae, with knobs on the end. Source: [12] ................................. 9
2-5 Figures (b) - (d) show the mean and standard deviation (gray areas) of more than 100 flight trajectories of bees flying through a tunnel with black and white gratings (figure (a)). Small arrows indicate the flight direction of bees. Big arrows show the direction of pattern movement. Bees tend to fly in the middle of the tunnel when the grating on the walls are not moving (b), closer to gratings moving in the same direction (b), and further away from gratings moving in the opposite direction. Figures (a) - (d). Source: [9] ................................. 10

3-1 Optic Flow. Source: [13] ................................................................. 11
3-2 The arrangement of the two optic flow detectors in the F2 MAV. Source: [17] .... 12
3-3 Integration of the Tam4 optical flow sensor in the Robobee ................................. 13
3-4 10g FWMAV developed by Berkeley ................................................................. 13
3-5 Six degree of freedom of the MAV. Adapted from Zingg et al.[23] .......................... 14
3-6 Optic flow during the translational motion of the optic sensor. Adapted from Zingg et al.[23] ........................................... 15
3-7 Six optical sensor configuration of the Atalanta. Sensor X+ looks in the direction of the positive x-axis, Sensor X- in the direction of the negative x-axis, etc. Source: [4] ........................................... 15
3-8 Perception of optic flow from a sensor on a 2D plane ........................................... 16
3-9 Optic flow due to translation of the X+ sensor along negative y-axis ......................... 17
3-10 Optic flow due to rotation of the X+ sensor about z-axis ......................................... 17
3-11 Optic flow due to translation of the X+ sensor along z-axis ...................................... 18
3-12 Optic flow due to rotation of the X+ sensor about y-axis ......................................... 18
3-13 Schematic of the experimental setup ............................................................. 20
3-14 ADNS 9800 optical flow sensor setup with the lens system .................................. 22
3-15 Working of the optic flow setup. Images from left to right depicts the translational motion of the patterned wall. ........................................... 22
3-16 Magnitude of optic flow vs distance for varying velocities .................................. 23
3-17 Magnitude of optic flow vs velocity for varying distances .................................... 24

4-1 Modules in the simulator .......................................................... 26
4-2 Flying environment of the Atalanta .................................................. 27
4-3 Model of the Atalanta in three dimensions with the rotating frame attached. The grey discs represent the mouse optical sensors placed at 1 cm from the center. ........................................... 27
4-4 Linear motion of the Atalanta ..................................................... 28
4-5 Circular motion of the Atalanta .................................................. 28
4-6 Initial flying state of the Atalanta ................................................ 29
4-7 Translation and rotation of the Atalanta from state (N) to state (N+1) ..................... 31
4-8 Distance measurement for a linear motion ...................................................... 32
4-9 Distance measured from X+ and X- sensor ................................................... 33
4-10 Distance measured from Y+ and Y- sensor ................................................... 33
4-11 Distance measured from Z+ and Z- sensor ................................................... 33
4-12 Optic flow module ................................................................. 34
4-13 Velocity and Angular Velocity of the Atalanta in 3D for a circular motion .............. 35
4-14 Distance measured from X+ and X- sensor ................................................... 36
4-15 Distance measured from Y+ and Y- sensor ................................................... 36
4-16 Distance measured from Z+ and Z- sensor ................................................... 36
4-17 Optical flow from X+ and X- sensor ...................................................... 37
4-18 Optical flow from Y+ and Y- sensor ...................................................... 37
4-19 Optical flow from Z+ and Z- sensor ...................................................... 37
4-20 Estimation of velocity in the x direction ....................................................... 39
4-21 Estimation of angular velocity in x direction ................................................... 39

5-1 3D kinematic model and controller module in the simulator ...................................... 41
5-2 Fixed four wing configuration of the Atalanta ................................................... 43
List of Tables

3-1  Preset actuator values with corresponding velocities ........................................... 21
3-2  Varying distances to the wall ................................................................................. 23
4-1  Parameter estimation: Known and unknown entities .................................................. 38
5-1  Parameter settings for Case I, II and III .................................................................. 49
5-2  Initial disturbances .................................................................................................. 53
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“All our knowledge has its origins in our perceptions.”

— Leonardo da Vinci
Chapter 1

Introduction

Micro Aerial Vehicle (MAV) is an area of research that’s being explored by Scientists, Engineers and Governments across the globe to develop state of the art unmanned aerial vehicles that are able to turn around corners, fly into buildings and navigate through cluttered confined spaces. MAVs find a wide range of applications in the field of military, aerospace, commerce and entertainment. Downscaling these drones has always been a challenging area of exploration and nature acts as a source of inspiration. Insects are nature’s most accomplished flyers. Their method of flight is power efficient and allows for exceptional feats of agility. In this section the context and the goal of this thesis project is described and an overview of the chapters discussed is given.

1-1 Context of Present Study

An exponential growth in technology and science can be witnessed today. The field of MAVs is one such area which has witnessed an enormous advancements over the past couple of years. As the MAV researchers turn to nature for inspiration, the complexity in terms of structures and aerodynamics increases. Even a simple hovering motion of a flying insect requires a gargantuan number of theories to model.

Bio-inspired flapping winged insect like robots is the next big thing and only a handful of universities and research groups have been successful in developing them. The Atalanta project, named after the Vanessa Atalanta butterfly is DEVLAB’s Flapping Wing Micro Aerial Vehicle (FWMAV) project which aims at developing an insect-like 4 wing flying robot, whose wing span is 100 mm and has a body mass of 4 g. The main mode of operation of the Atalanta is Hovering and we are also aiming to achieve a slow indoor flight.

The project was defined based on two important aspects

- Low total mass - The total mass of the Atlanta is low which requires light components and only allows for a very small payload.
Low power consumption - Smart power management and energy efficiency is required as the onboard storage capacity is small.

Working on the Atalanta Project Bolsman[1] designed the body of the MAV with four wings and they were actuated by a compliant ring structure, based on the insect thorax as shown in Figure 1-1. A flapping frequency of 28.5 Hz was generated but the design was not able to hover due to the weight of the actuator and the absence of a control system.

1-2 FWMAV Projects

Some of the FWMAV projects across the globe are described briefly here.

- The Toronto Mentor project[2] was a response by SRI International of Menlo Park, California to an initiative by Defence Advanced Research Projects Agency (DARPA) to develop tiny remotely piloted aircraft. The Mentor is based on two pairs of clap-fling wings which provide dynamic balance and also increases the clap-fling thrust augmentation. The SF-3 demonstration model of the Mentor had a maximum span of 14 in (356 mm) and weighed 440 g. It used a central Electroactive polymer artificial muscles (EPAM) actuator drive system and achieved a flapping frequency of 30 Hz. A NiCd battery pack (8 cells, 600mAh each) was used as power source. A PID control mechanism using 3-axis gyros for feedback was developed and the angular rate commands were sent via radio control by a pilot. Mentor yielded good aerodynamic efficiency results in hovering considering early stage of development of flapping wing flight.

- The RoboBee[3] by Harvard is a micro sized flying robot that weighs 60 mg and has a wingspan of 1.2 in (30 mm). The wings are controlled by a piezoelectric actuator with thin ceramic strips and they produce a flapping frequency of 110 Hz. RoboBee uses optic sensors and a UV targeting sensor which acts as the brain of the robot, controlling and monitoring it’s flight.
1-3 Objective of present study

Designing a flight control system for a bio-inspired FWMAV requires good understanding of how insects and birds navigate through space. The functioning of sensory organs such as Ocelli, Halteres and Compound eyes that aid the flying creatures to perform a collision free flight is studied. How nature provides simple solutions to control complex manoeuvres of these animals is truly inspiring for the remainder of the research. The Atalanta is inherently an unstable flying vehicle which requires a stabilization control system. In order to achieve hovering and slow indoor flight, Goosen[4] proposed a bio-inspired sensor system based on optical flow for flight stabilization and control. The system uses six optical mouse sensors facing in $X\pm$, $Y\pm$ and $Z\pm$ directions and the optical flow output from the sensors drive the control actuators in the wings and the main flapping actuator. However, there is not enough evidence yet to substantiate the research proposal and that leads to a main research question: "Can the six sensor optic flow configuration stabilize and control the flight of the Atalanta?"

1-3-1 Strategy

- To design and develop a flight simulator which acts as a platform to mimic the real time flight of the Atalanta. The simulator is also used to test the six sensor optic flow system configuration of the Atalanta.

- Mathematically determine the optic flow output as perceived by the six optic flow sensor configuration on the Atalanta during its flight.

- Develop the optic flow based controller and test it in flight simulator.

1-4 Approach of present study

In order to achieve the objectives, as described in Section 1-3, the following steps are performed.

- Insect Hovering and its navigation through space is described by Optic flow. A visual phenomenon that provides a perception of distance and movement of objects in the environment. An investigation of optic flow used in various MAV projects is conducted and analyzed. A Mathematical relationship between optic flow and the distance to objects for the six camera sensor configuration is derived and tested. Experiments were performed to check the validity of the optic flow sensors.
The simulator that is developed consists of the following modules,

- Motion/Three dimensional kinematic module
- Optic flow module
- Controller module

Optic Flow is a combination of velocity of the Atalanta and its relative distance to an object in an environment. The optic flow module determines the optic flow as perceived by the six sensors of the Atalanta at every instant of its flight. It consists of a submodule which calculates the distance to the walls in the environment that is required to generate the optic flow.

A step wise approach is followed to test and build the motion module. First, a system with well defined motions is used to generate translational and the rotational parameters of the Atalanta. Later, a three dimensional kinematic module of the flight of a FWMAV is developed. Forces such as drag, lift, gravity and Torques are taken into account in the module. Path followed by the Atalanta is defined by its position, velocities, angles and angular velocities.

An optic flow based controller is developed based on the configuration as shown in Figure 1-2 by Goosen[4]. The simulated optic flow sensor outputs of the flying sensor platform are combined arithmetically to generate control signals to the wing actuators which performs the roll, pitch stabilization and the control signals to the flapping actuator which performs height control. Hovering of the Atalanta in the simulated environment is achieved.

The development of the three-dimensional flying environment, the three dimensional kinematic module, optic flow module and the controller is done using MATLAB.

![Figure 1-2: Schematic of the optic flow based stability and obstacle control system of the four wing flying sensor platform. The cameras are shown as the grey boxes with the direction of view. Source: [4]](image)

Master of Science Thesis
Abhimanyu Selvan
1-5 Synopsis

This MSc. thesis is divided into six chapters with the following subjects:

**Chapter 2** This chapter investigates the flight of insects in nature. The house fly is investigated to find out the function of the sensory organs and their effect on its flight control. A brief study on how ‘Optic flow’ influences the navigation in honeybees is also investigated.

**Chapter 3** This chapter describes the phenomenon called ‘Optic flow’ and how it is mathematically obtained. A brief study on optic flow and its application on the current FWMAV projects across the globe is included. Description of the six sensor configuration of the Atalanta and the construction of its optic flow equations is illustrated. A review of the optic flow experiment conducted is also included.

**Chapter 4** This chapter illustrates the development of the flight simulator and it describes the function of each module used in the simulator. Optic flow results for a pre-defined motion are illustrated. A brief study on the estimation of the motion parameters from the optic flow is also included.

**Chapter 5** This chapter describes how the three dimensional kinematic module is coupled to the control module. The control strategy used to stabilize the Atalanta in three dimensional space is investigated. Roll and pitch stabilization along with altitude stabilization is achieved and the results are analysed.

**Chapter 6** This chapter presents the overall conclusions of this thesis. It also includes some recommendations for future work.
Chapter 2

Bio-inspired insect navigation

Insects such as bees and ants do not travel over thousands of kilometres and are not seasonal navigators. However, on a day-to-day basis they cover about hundreds or thousands of meters, which is about a million times their body length. Wehner [5] points out that these insects rely on visuals from both the sky and the terrestrial environment for stabilization and navigation. The question of how they acquire this spatial information in order to navigate with such precision, considering their extremely small brain size raised a curiosity to explore the flight of these unbelievable creatures.

2-1 Insect Senses

The common housefly demonstrates extreme manoeuvrability in its flight, despite very limited computation power of the brain, only a few hundred neurons out of 3,38,000 neurons actively take part in the control mechanism. They rely more on sensory inputs from 80,000 sites on the body and uses a sensor-rich feedback control paradigm, Zbikowski [6]. To get a better understanding of how these sensory organs in the arthropods function, an overview is given.

2-1-1 Compound Eyes

The insect eye is different from the vertebrate eye. They are called compounds eyes and are made up of repeating units, the ommatidia, each of which functions as a separate visual receptor. Each ommatidium receives the light from the environment which then passes it through the crystalline cone-shaped region which is connected to cells called the rhabdome, surrounded by the retina cells. The cone, the rhabdome and the retina cells are surrounded by the pigment cells that optically isolate the ommatidium from its neighbours, Muller[7]. The panoramic vision obtained is a culmination of images perceived by each ommatidium. Insects such as Honeybees have immobile eyes with fixed-focus optics that are placed close to one another yielding to an inferior spatial acuity [8]. Figure 2-1 describes the structure of the ommatidium of an arthropod, Srinivasan[9].

Master of Science Thesis

Abhimanyu Selvan
Apart from the imagery, insect’s compound eyes provide a spatial sense of direction and motion in form of a field called the optic flow field, Zbikowski [6]. It depicts the insect’s motion relative to its surroundings. Each facet in the compound eye as seen in Figure 2-2 consists of photoreceptors called elementary motion detectors (EMD) with a field of view and direction of motion, Krapp et al.[10]. By mapping the receptive field of these interneuron and presenting the visual stimuli, Krapp et al.[10] found that the interneurons’ motion response were similar to optic flow fields.

2-1-2 Ocelli

Ocelli in Latin means ‘little eye’ and they are predominantly found in flying insects like house flies, dragon flies, cockroaches etc. Ocelli determine the orientation of the insect by providing information about light levels in the environment. There are three ocelli in an insect namely, medial, lateral left, lateral right as show in Figure 2-3. If the fly is rolled to the left by a gust of wind, the visual field of the left ocellus is exposed to a darker ground while the right ocellus is exposed to more of the sky receiving much more light. The brain senses the change in illumination between the left and the right ocellus as a roll to the left. If the medial ocellus with its frontal visual field is included, the system can also detect a pitch movement, [11].
2-2 Stabilization and navigation

Figure 2-2: Anatomy (a,c,e) and optic flow response fields (b,d,f) of interneurons in blowflies. Source: [10]

2-1-3 Halteres

Halteres are drumstick shaped features from the insect’s thorax that sense the rotation of the insects, see Figure 2-4. The halteres vibrate as the wings flap and function like vibrating gyroscopes and as it rotates its body, the coriolis effect introduces forces out of the plane of vibration measuring angular momentum.

2-2 Stabilization and navigation

Insects use the signals from the sensory organs to stabilize and navigate in space. For instance, the crane flies use halteres to maintain the equilibrium during its flight. The combined signals from compound eyes and ocelli act as control stabilization reflexes in honeybees. Honeybees
2-2 Stabilization and navigation

Figure 2-3: Top view view of the blowfly head. *lce* and *rce* mark the left and right compound eye, respectively. The three ocelli of the blowfly are labelled *mo*, *llo*, and *rlo*, which stands for medial, lateral left, and lateral right ocellus. Source: [11]

Figure 2-4: Crane fly, with a pair of halteres visible behind the wings as appendages, about as long as the animal’s antennae, with knobs on the end. Source: [12]

rely on several attributes to determine the proximity to objects in the environment. When a bee flies in a straight line, the images of the objects move past their eyes at speeds that indicate how far they are. Objects that are far from the insects appear to move slowly when compared to the objects that are nearby. This phenomenon is called “Optic Flow” and most of the insects navigate without any collision by constantly monitoring it. Srinivasan [9] conducted several experiments to study the behaviour of flight of the honey bees in a tunnel with black and white gratings 2-5a. From the recordings of hundreds of flight trajectories Srinivasan [9] found that the bees tend to fly in the middle of the tunnel when the walls were stationary,
see Figure 2-5b, but fly closer to the walls where the grating moved in the same direction, see Figure 2-5c and further away from the gratings moving in the opposite direction, see Figure 2-5d. He concluded that bees do not measure absolute distance for obstacle avoidance and navigation but by balancing the optic flow perceived by the left and the right eye. Srinivasan [9] also found that the bees use optic flow to regulate the flight speed. When the gratings on both the walls were moving in the same direction as the bee, it flew faster and slower when the gratings on both walls were moving in the opposite direction from which he concluded that the strong image flow warns them that they are close to an object and this causes them to slow down. These set of experiments shows that optic flow in insects not only aids in obstacle avoidance and navigation but also regulate the speed of their flight.

![Figure 2-5: Figures (b) - (d) show the mean and standard deviation (gray areas) of more than 100 flight trajectories of bees flying through a tunnel with black and white gratings (figure (a)). Small arrows indicate the flight direction of bees. Big arrows show the direction of pattern movement. Bees tend to fly in the middle of the tunnel when the grating on the walls are not moving (b), closer to gratings moving in the same direction (b), and further away from gratings moving in the opposite direction. Figures (a) - (d). Source: [9]](image-url)
3-1 Introduction

It is evident from Chapter 2 that insects mainly navigate using optic flow, a visual phenomenon that everyone experiences on a daily basis. When you are sitting in a train and looking out through the window, one might notice that the objects closer to the eye appear to move faster than the objects that are far away. This apparent motion of the objects as one moves through the world is *optic flow*.

![Optic Flow](image)

*Figure 3-1: Optic Flow. Source: [13]*

This image motion can be described by an optic flow vector field as shown in Figure 3-1 where each velocity vector points in the direction of motion of the corresponding image point with a vector length proportional to the magnitude of the velocity [14]. These visual cues tend to move in a direction opposite to that of the motion of the observer.
3-2 Optic Flow and MAV

The use of optic flow for MAV navigation is a widespread approach. Biological inspired flight navigation strategies rely on optic flow as seen in Chapter 2. Srinivasan [9] found out that honeybees flying through a tunnel try to balance out the optic flow on both sides in order to maintain equidistance from the walls, while Tammero et al.[15] demonstrated that fruit flies avoid obstacles by turning away from high optic flow regions. Serres et al.[16] adapted these insect behaviours and developed an autopilot for a fixed wing MAV for lateral obstacle avoidance. The system had two optic flow sensors at $\pm 90^\circ$ that recorded the optic flow. By balancing the optic flow on either sides they made the robot navigate equidistance from the walls. Zufferey et al.[17] implemented an optic sensor based system as for obstacle avoidance on a miniature airplane.

![Figure 3-2: The arrangement of the two optic flow detectors in the F2 MAV. Source: [17]](image.png)

The MAV is equipped with two wide field of view optic flow detectors (OFD) looking at an angle of $45^\circ$ off the forward direction as shown in Figure 3-2. Increasing divergence in the optic flow detected by the left and right OFDs indicated the presence of an obstacle which is avoided with proportional rudder deflection.

Ruffier et al.[18] developed an altitude control system by placing two optical flow sensors in the downward direction. Zufferey et al.[19] and Green et al.[20] implemented a landing system by maintaining a constant optic flow and reducing the speed, thereby allowing the MAV to land. Duhamel et al.[21] controlled the vertical flight of a 101-mg Robobee using on-board optical flow sensor Tam4 which was developed in collaboration with Centeye. The optic flow signal was used to estimate the vertical position of the robot and is used as a feedback for real time altitude control. Robobee as shown in Figure 3-3 was able to maintain an altitude of 5 cm over a period of 20 seconds.
Garcia et al.[22] developed a 10 g ornithopter as shown in Figure 3-4 with an on-board cell phone camera. Down sampled on-board camera images were stored during flight and transmitted to a computer to compute the optic flow. They demonstrated the significance of pitch oscillations due to the flapping of wings on the optic flow direction estimates.

3-3 Optic Flow in Atalanta

As we have seen in the Section 3-2, several universities and research institutes across the globe are using optic flow as the primary source of input for the flight control of MAVs. Optic flow is used in fixed-wing MAVs and FWMAVs for obstacle avoidance and altitude control. High resolution on-board cameras with image processing algorithms were used in some of the projects as discussed earlier. The Atalanta will also use optic flow as its primary input to achieve hovering and a slow indoor flight. The following are the salient features of the Atalanta,
• Six degrees of freedom, (see figure 3-5).
• Low resolution mouse optic sensor
• Six sensor configuration, (see section 3-3-2).
• Bio-inspired optic flow control algorithm, (see section 5-3).
• Roll/Pitch stabilization, height control and obstacle avoidance

These features make the Atalanta unique and stand apart from its contemporaries.

Figure 3-5: Six degree of freedom of the MAV. Adapted from Zingg et al.[23]

3-3-1 Determining Optic Flow

Consider a linear motion of the optic sensor as shown in Figure 3-6. Optic flow is a function of the velocity $v$, the distance to the obstacle $r$ and the angle between the direction of travel and the obstacle $\alpha$. Optic flow can be mathematical defined by the Equation 3-1.

$$OF = \frac{v}{r}\sin\alpha.$$  \hspace{1cm} (3-1)

The magnitude of optic flow is larger as the optic sensor moves closer to an obstacle and it is maximum when $\alpha$ is 90°, that is perpendicular to the direction of motion. Therefore when the distance to the obstacle and the velocity of the sensor are available, the optic flow can be calculated, see Equation 3-1), as long as the motion is purely translational.

3-3-2 Six optic sensor configuration

The Atalanta navigates in six degrees of freedom which is translation in $x$, $y$, $z$ direction and rotation roll($\phi$), pitch($\theta$) and yaw($\psi$) as shown in Figure 3-5. Rotations can cause additional optic flow apart from the optic flow caused due to translation. The sensor system configuration is based on six optic sensors, each looking along an axis and identified by its
viewing axis as shown in Figure 3-7. Each optic sensor is mounted at 90° to one another. This configuration gives an all-around view and the possibility to distinguish the patterns for translations, rotations and the information needed for flight stabilization, [4].

Optic Flow on a 2D plane

Each camera of the six optical sensor configuration provides an output for the two optical flow components over its surface. Consider an optic sensor, which is facing a wall in the positive x direction, see Figure 3-8a. An optic flow in the y direction and the z direction is perceived by the sensor as seen in Figure 3-8b. Similarly optic flow in two directions from each of the other five optic sensors is obtained, so twelve optic flow sensor signals are available from the six optical sensor configuration at every instant of time.
3-3 Optic Flow in Atalanta

Figure 3-8: Perception of optic flow from a sensor on a 2D plane

3-3-3 Optic flow equations

Deriving the optic flow equations is vital in order to understand how the optic flow depends on factors such as velocities, angular velocities and distances to the obstacles. The equations are derived for the apparent optic flow from a specific viewpoint in three dimensional space.

Constructing the Optic flow equation

Let us consider the single optic sensor (X+) placed at the origin o looking in the positive x direction and determine how the optic flow equation is obtained. The optic flow obtained is due to the translational and rotational components along the y and z direction as explained in the previous section. In the Figure 3-9, the sensor translates at a velocity \( v_y \) along the negative y-axis, the relative motion is depicted by the dots with green being the start point and red being the end point. The optic flow due to translation along negative y-axis \( (T_y) \) is given by,

\[
OF^X_+ = \frac{-v_y}{r_1} \sin \alpha.
\]  

(3-2)

The negative sign in equation 3-2 indicates that the optic flow moves in the direction opposite to that of the sensor. \( r_1 \) is the distance from the optic sensor X+ to the obstacle. \( \sin \alpha = 1 \),
as $\alpha = 90^\circ$, so the sin component is avoided.

![Optic flow due to translation along y-axis](image)

**Figure 3-9:** Optic flow due to translation of the X+ sensor along negative y-axis

The sensor X+ rotates at an angular rate of $\omega_z$ about z-axis which results in an optic flow in the y-direction as seen in Figure 3-10. The optic flow due to rotation in y direction ($R_y$) is given by,

$$OF_{R_y}^{X+} = -\frac{\omega_z}{\beta}.$$  \hspace{1cm} (3-3)

The negative sign in equation 3-3 denotes that the direction of optic flow is towards the negative y-axis for a positive rotation of the X+ sensor about z-axis. $\beta$ is a scale down factor of the angular velocity $\omega$. It is chosen in order to balance the effect of translation and rotation on the optic flow, else the effect of rotation will be predominant. It depends on the optics of the sensor such as field of view, focus, etc.

![Optic flow due to rotation about z-axis](image)

**Figure 3-10:** Optic flow due to rotation of the X+ sensor about z-axis
In the Figure 3-11, the sensor translates at a velocity \( v_z \) along the z-axis. The optic flow due to translation along z-axis (\( T_z \)) is given by,

\[
OF_{T_z}^{X+} = -\frac{v_z}{r_1}\sin\alpha.\tag{3-4}
\]

The negative sign in equation 3-4 indicates that the optic flow moves in the direction opposite to that of the sensor. The sensor X+ rotates at an angular rate of \( \omega_y \) about y-axis which results in an optic flow in the z-direction as seen in Figure 3-11.

The optic flow due to rotation in z direction \( (R_z) \) is given by,
The positive sign in equation 3-5 denotes that the direction of optic flow is towards the positive z-axis for a positive rotation of the X+ sensor about y-axis. By combining Equations 3-2, 3-3, 3-4, 3-5 we get the final equation of optic flow for a sensor looking in the positive x direction.

\[ OF^X_+ = \frac{-v_y}{r_1} \sin \alpha - \frac{\omega_z}{\beta} + \frac{-v_z}{r_1} \sin \alpha + \frac{\omega_y}{\beta}. \]  

(3-6)

**Optic flow equations for the six sensor configuration**

Optic flow for the X+ optic sensor is represented by the equation 3-6. Applying the same methodology and logic, we derived a set of optic flow equations for the six sensor configuration of the Atalanta,

\[ OF^{X-} = \frac{-v_y}{r_2} \sin \alpha + \frac{\omega_z}{\beta} + \frac{-v_z}{r_2} \sin \alpha - \frac{\omega_y}{\beta}. \]  

(3-7)

\[ OF^{Y+} = \frac{-v_x}{r_3} \sin \alpha + \frac{\omega_z}{\beta} + \frac{-v_z}{r_3} \sin \alpha - \frac{\omega_x}{\beta}. \]  

(3-8)

\[ OF^{Y-} = \frac{-v_x}{r_4} \sin \alpha - \frac{\omega_z}{\beta} + \frac{-v_z}{r_4} \sin \alpha + \frac{\omega_x}{\beta}. \]  

(3-9)

\[ OF^{Z+} = \frac{-v_x}{r_5} \sin \alpha - \frac{\omega_y}{\beta} + \frac{-v_y}{r_5} \sin \alpha + \frac{\omega_x}{\beta}. \]  

(3-10)

\[ OF^{Z-} = \frac{-v_x}{r_6} \sin \alpha + \frac{\omega_y}{\beta} + \frac{-v_y}{r_6} \sin \alpha - \frac{\omega_x}{\beta}. \]  

(3-11)

where,

- \( v_x, v_y, v_z \) are the velocities in x, y and z direction.
- \( \omega_x, \omega_y, \omega_z \) are the angular velocities in x, y and z direction.
- \( r_1, r_2, r_3, r_4, r_5, r_6 \) are the relative distances to the obstacle from the X+, X-, Y+, Y-, Z+ and Z- optic sensors respectively.

The set of equations constitute the sensor block of the simulator which will discussed in chapter 4. Optic flow sensor signals of the Atalanta depends on the translation and the rotation motion. However, it is difficult to differentiate the optic flow caused due to translation and the optic flow caused due to rotation from the total optic flow.
3-4 Optic flow Experiments

The optic flow sensors in the computer mouse are cost effective, requires low power, and yield high precision which we believe is apt for the optic flow based flight control of the Atalanta. In order to test the effectiveness of the mouse optic sensors, an experiment was conducted by a group of bachelor students, to extract optic flow from a mouse optic sensor (ADNS 9800), Bas et al [24]. The main objective of their work is,

- To verify whether an optical mouse sensor can be used to determine the translation motion of an object.
- To operate the mouse optic flow sensor IC at greater distances compared to the default configuration which provides an operating distance of 2 mm.
- To verify the trigonometric optic flow equation,

\[ OF = \frac{v}{r}, \]  

(3-13)

where, \( v \) is the velocity of the observer and \( r \) is the distance to the obstacle from the observer. However, due to experimental complexity and limited time only optic flow due to pure translation was tested. Although rotation was not tested, the two are directly related so the translation measurement is sufficient to evaluate the sensors applicability.

Figure 3-13: Schematic of the experimental setup

3-4-1 Experimental Setup

Figure 3-13 shows the top view of the experimental setup and it is powered by an Arduino UNO R3 Microcontroller. For the ease of measurement and to avoid experimental setup
constraints, the optic system is kept stationary and the patterned wall is made to translate. Measurement commands are sent from the PC to the arduino which then triggers the linear actuator to translate the patterned wall. As the wall enters the field of view of the optic sensor system, the optic sensor captures the image of the moving wall and the raw image data is processed to determine the optic flow.

**ADNS 9800**

ADNS 9800 by Avago is the mouse optical flow sensor that is used in this experiment, see Figure 3-14. This sensor was chosen due to the following reasons,

- Good documentation
- Availability
- Easy integration with microcontroller

It has a high speed motion detection up to 150 ips (inch per second) and measures an acceleration up to 30 g.

**Lens**

The standard optical mouse sensors can be used at a distance of only 2 mm beyond which the sensor doesn’t detect any optic flow. This however becomes a serious issue for long range applications. In order to overcome this problem, lens as shown in Figure 3-14 with a focal length of 14 mm and aperture number of $f/1.43$ was added to get a operability distance of 500 mm.

**Linear Actuator**

The linear actuator is a servo motor from Moons’ industries that can be programmed using a Q-programmer. It can be programmed to operate at different revolutions per second as shown in Table 3-1. The laser range finder coupled with the linear actuator is used to measure the velocity at which the patterned wall moves.

<table>
<thead>
<tr>
<th>Q-programmer [rev/s]</th>
<th>v [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.063</td>
</tr>
<tr>
<td>1</td>
<td>0.126</td>
</tr>
<tr>
<td>2</td>
<td>0.252</td>
</tr>
<tr>
<td>4</td>
<td>0.514</td>
</tr>
<tr>
<td>8</td>
<td>1.028</td>
</tr>
</tbody>
</table>
3-4 Optic flow Experiments

Figure 3-14: ADNS 9800 optical flow sensor setup with the lens system

Figure 3-15: Working of the optic flow setup. Images from left to right depicts the translational motion of the patterned wall.

3-4-2 Result

The experimental setup was built successfully and the optic flow was determined for a translation motion of a patterned wall as seen in Figure 3-15. Several measurements were taken by varying the velocity of the moving wall (v), see Table 4-1 and by varying distances to the wall, see Table 3-2. In a single measurement the optic sensor reads several optic flow vectors (from different pixels) but the average of the magnitude of the optic flow vectors is used in the results.
Table 3-2: Varying distances to the wall

<table>
<thead>
<tr>
<th>r [m]</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.113</td>
<td>Minimum</td>
</tr>
<tr>
<td>0.138</td>
<td></td>
</tr>
<tr>
<td>0.238</td>
<td></td>
</tr>
<tr>
<td>0.313</td>
<td></td>
</tr>
<tr>
<td>0.388</td>
<td></td>
</tr>
<tr>
<td>0.463</td>
<td></td>
</tr>
<tr>
<td>0.538</td>
<td>Optimum</td>
</tr>
<tr>
<td>0.663</td>
<td></td>
</tr>
<tr>
<td>0.813</td>
<td></td>
</tr>
<tr>
<td>0.963</td>
<td></td>
</tr>
<tr>
<td>1.113</td>
<td>Maximum</td>
</tr>
</tbody>
</table>

Figure 3-16 shows the optic flow measured in (counts/s) plotted with the distance (measured in meters) for varying velocities and the confidence coefficient $R^2$ is maintained above 0.99. It is evident from the plot that the distance is inversely proportional to the optic flow which satisfies the Equation 3-13. In the Figure 3-17, the optic flow is plotted with the velocity for varying distance and a linear relation is achieved. As the velocity is increased the magnitude of optic flow increases, thereby satisfying the Equation 3-13. The data points have a confidence interval of 99%. However, Figure 3-17 shows small irregularities in smaller and larger $r$. Outside the depth of field there will be a loss of the focus, leading to smaller optic flow. On infinite $r$ with infinite depth of field, the optic flow will be zero.
3-4 Optic flow Experiments

0 0.2 0.4 0.6 0.8 1
0.5
1
1.5
2
2.5
3 x 10
4
Velocity [m/s]
Magnitude of Optic Flow [counts/s]

... R^2 = 0.99997
0.663m, R^2 = 0.99999
0.813m, R^2 = 0.99998
0.963m, R^2 = 0.99998
1.113m, R^2 = 0.99998

Figure 3-17: Magnitude of optic flow vs velocity for varying distances

3-4-3 Conclusion

Equation 3-13 is a valid description for optic flow around the depth of field. At distances outside the depth of field, the equation will describe the optic flow less well because of the optical effects. In practice, the optic flow is more likely to go to zero because of the contribution of certain effects, other than the finite depth of field, such as:

- low light intensity leading to insufficient contrast.

- As we move towards greater distances with the same opening angle, the viewing area increases. This causes the contrast lines to be averaged over the pixels.

Remark

The results show that the optic flow to the ADNS-9800 in pure translations behave accurately with a confidence interval of 99%, provided that you remain within a certain range. This range is dependent on a number of factors, such as the properties of the lens, the contrast of the surface and the amount of light which is reflected by the surface.

These experiment results show that the mouse optical sensor can be used to determine the translation motion of an object. This provides motivation to extend this research to translational and rotational motion across multi-dimensions.
Chapter 4

Simulator

4-1 Introduction

Simulation is the imitation of a real-world process or a system. In a simulator, a numerical computational model is developed taking into account the characteristics and key features of the real world system and the simulation is the operation of this model over time. The external factors and conditions with which the Atalanta interacts with the physical world is taken into consideration in the simulator developed in this thesis. Scenarios and events are replicated with sufficient reality to ensure that this simulator provides sufficient insight for the researchers.

The simulator approach is chosen taking into account the following considerations,

- Test bed- The simulator developed in thesis is a testing platform for the research proposal by Goosen[4]. The optic flow control algorithm for flight stabilization proposed by Goosen has to be tested and validated before building the flying sensor platform (refer section 3-3-2).

- Experimental complexity - The Atalanta is a delicate, complex and a highly unstable flying system. It is a multidisciplinary project with various master students and PhDs working on different aspects of the system like the body, wings, engine and electronics. The research is ongoing, so the simulator approach is a good practice to test the functionality of a subsystem before integrating all the systems.

4-2 Three Dimensional Model

The simulator consists of Motion, Flying Environment, Optic flow and Controller modules. In this chapter we will discuss the modules of motion, flying environment and optic flow as highlighted in Figure 4-1. The motion module consists of submodules to define the path and the motion for the Atalanta to fly within the environment. Position (s), orientation (θ),
velocity ($v$) and the angular velocity ($\omega$) are the outputs obtained from the motion module. The flying environment consists of submodules to construct the room like environment and calculate the distance to the walls ($r$) from the Atalanta during its flight. The optic flow module generates the optic flow as perceived by the six optic flow sensors of the Atalanta based on the outputs from the motion and the flying environment modules. The optic flow (OF) is fed to the controller as an error signal. The controller operates on the basis of an algorithm that uses the optic flow values to stabilize and control the flight of the Atalanta in space which will be discussed in detail in the Chapter 5.

![Figure 4-1: Modules in the simulator](image)

**4-2-1 Flying Environment**

A flying environment is necessary to test the flight of the Atalanta. As the Atalanta is intended for indoor use, a room like environment as seen in Figure 4-2 is developed and simulated. The environment is constructed in a three dimensional cartesian coordinate system and each plane is represented in cartesian form. 2056 cm × 2056 cm × 2056 cm is the default dimensions of the flying environment and it can be reconfigured depending on the flying area. The environment is stationary throughout the simulation and is defined in the global coordinate system (G).

**4-2-2 Flying Sensor platform**

A simplified three dimensional model of the Atalanta is used as shown in Figure 4-3. It has dimension 2 cm × 2 cm × 2 cm and the mouse optical sensor is placed at 1 cm from the centre in each of the six directions. The Atalanta has its own rotating frame of reference (R) with 6 degrees of freedom. To begin with, the Atalanta is placed at a certain known point in the environment with a specified orientation after which it moves along a pre-defined path as determined by the motion module. At the initial state of flight, the rotating frame of reference of the Atalanta is aligned with the fixed frame of reference of the environment. The optic flow sensor in the positive x direction will be facing the wall in the positive x direction, etc.
The motion of the Atalanta within the flying environment is tested for a few defined three dimensional motions. The path to be followed by the Atalanta is defined for a period of 20 seconds. These tests were primarily done to verify the six degrees of freedom of the Atalanta.
In our analysis we have considered the paths as shown in Figures 4-4, 4-5. The velocity components are obtained by differentiating the position vector $s(x, y, z)$.

- **Linear Motion**

![Figure 4-4: Linear motion of the Atalanta](image1)

\[
\begin{align*}
x &= 2 \\
y &= 2 \\
z &= 2(t)
\end{align*}
\]

- **Circular Motion**

![Figure 4-5: Circular motion of the Atalanta](image2)

\[
\begin{align*}
x &= 2. \cos(t) \\
y &= 2. \sin(t) \\
z &= 2
\end{align*}
\]

The initial orientation angles (roll, pitch and yaw), time of flight and the path are fed as inputs to the systems. The linear velocity in three directions ($v_x$, $v_y$ and $v_z$), the angular velocity in three directions ($w_x$, $w_y$ and $w_z$) are obtained as the output of the system.

**4-2-4 Distance measurement**

The distance to the wall ($r$) is an important component to determine the optic flow as seen in Equation 3-1. This is a mathematically generated three dimensional model and the distance to the walls from the Atalanta can be mathematically derived. It is to be noted that there are two coordinate systems are used in the simulator. The environment is
• **State (N)**

It is the state of the Atalanta at $N^{\text{th}}$ second. In the Figure 4-6, the green stick diagram represents the Atalanta, which is positioned in the environment at point $\mathbf{O}(x_0, y_0, z_0)$, defined in global coordinate system (G). $\mathbf{C}(x_c, y_c, z_c)$ is the position of the optic flow sensor oriented along negative y-axis. $\mathbf{W}_p(x_w, y_w, z_w)$ is the point on the wall, defined in (G), where the optic flow sensor is focused on. The distance from the point $\mathbf{C}(x_c, y_c, z_c)$ to $\mathbf{W}_p(x_w, y_w, z_w)$ has to be measured. A similar set of position vectors will be available for the remaining five optic flow sensors in different directions, but for the ease of understanding of the concept we limit the description to one sensor in the negative y-axis. However, in the simulator the translation and rotation of all the position vectors has been included.

![Figure 4-6: Initial flying state of the Atalanta](image)

**Determining the Wall point, Wp**

The intersection of a line and a plane results in a point. The point of focus on the wall $\mathbf{W}_p$, by the optic sensor in the negative y-axis is formed by the intersection of the line joining the centre of the Atalanta $\mathbf{O}$, the position of the mouse optic sensor $\mathbf{C}$ and the wall formed by the three points $\mathbf{P}_1$, $\mathbf{P}_2$, and $\mathbf{P}_3$, defined in G. We have implemented the parametric form of line plane intersection method to determine the point $\mathbf{W}_p$ on the wall, as explained in [25].

**Distance between the sensor and the wall**

Now that we know the coordinates of the wall point $\mathbf{W}_p(x_w, y_w, z_w)$, we can determine the distance ($r$) between the sensor $\mathbf{C}(x_c, y_c, z_c)$ and the wall by,
\[ r = \sqrt{(x_c - x_w)^2 + (y_c - y_w)^2 + (z_c - z_w)^2}. \]  \hspace{1cm} (4-1)

The position vector of the sensor depends on the translation and rotation of the Atalanta so in the following section we will illustrate the transformation involved while moving from one position to another.

**Translation and Rotation from state (N) to state (N+1)**

State (N) is determined based on the output from the motion block (see section 4-2-3). Let us consider an example where the Atalanta translates from state (N) to state (N+1) and performs a rotation about y-axis. This motion is depicted in the Figure 4-7. The change in displacement is given by \( \Delta x \), \( \Delta y \), \( \Delta z \). In order to translate the position vector of the sensor \( C \) from state (N) to state \((N+1)\), we multiply the point \( C \) with the translation matrix \( 'T' \). The new point of the sensor before rotation will be \( C_t(x_c + \Delta x, y_c + \Delta y, z_c + \Delta z, 0) \) as represented by the equation 4-2.

\[
T = \begin{bmatrix}
1 & 0 & 0 & \Delta x \\
0 & 1 & 0 & \Delta y \\
0 & 0 & 1 & \Delta z \\
0 & 0 & 0 & 1
\end{bmatrix},
\]

\[
C_t = T \ast C.
\] (4-2)

The rotations of the Atalanta has to performed about its own rotating frame (R). The axis of rotation is given by the line joining the origin \( O(x_o, y_o, z_o) \) and a point on the axis of rotation \( P(x_p, y_p, z_p) \). A direction vector can be obtained by \( <u, v, w> = <x_p-x_o, y_p-y_o, z_p-z_o> \). The transformation for the rotation of a point \( C_t(x_c + \Delta x, y_c + \Delta y, z_c) \) about this line by an angle \( (\theta) \) is represented by a matrix, ‘TR’. The detailed derivation can be viewed at [26].

\[
TR = \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix},
\]

where,

- \( X = x_o.(u^2+w^2) - u.(y_o.v+z_o.w-w.C_t(1)-v.C_t(2)-w.C_t(3)).(1-cos(\theta)) + L.C_t(1).cos(\theta) + \sqrt{L}.(-z_o.v+y_o.w-w.C_t(2)+v.C_t(3)).sin(\theta)/L \)

- \( Y = y_o.(u^2+w^2) - v.(x_o.u+z_o.w-w.C_t(1)-v.C_t(2)-w.C_t(3)).(1-cos(\theta)) + L.C_t(2).cos(\theta) + \sqrt{L}.(z_o.u-x_o.w+w.C_t(1)-u.C_t(3)).sin(\theta)/L \)

- \( Z = z_o.(u^2+v^2) - w.(x_o.u+y_o.v-v.C_t(1)-w.C_t(2)-w.C_t(3)).(1-cos(\theta)) + L.C_t(3).cos(\theta) + \sqrt{L}.(-y_o.u+x_o.v-v.C_t(1)+u.C_t(2)).sin(\theta)/L \)
L = u^2 + v^2 + w^2 (for equation simplicity). \( \textbf{TR} \) represents the new position vector of the point C.

- **state (N+1)**
  
  It is the state of the Atalanta at \((N + 1)^{th}\) second which has covered a distance from point O to point O' along with a rotation about an axis. \( W_p' \) is the new position of the the wall point of focus and it is determined by repeating the steps discussed in section 4-2-4.

  For the ease of understanding, the translation and rotation of the optic sensor oriented in the negative y-axis is explained. In the actual simulator, the entire Atalanta with the six sensor configuration is taken into account. Therefore at every instant of time there will be a translation and rotation of seven position vectors (including the centre (O of the Atalanta). The distance to the walls from the six optic flow sensors is obtained. Any motion with six degrees of freedom within the environment can be tracked and the distance to the walls at every instant of time can be calculated in the simulator. A function to determine which wall (out of the six walls) the optic flow sensor views (i.e. sensor X+ is facing wall 3, etc) is also implemented.
Example of linear motion

A linear motion along the z direction as shown in Figure 4-4 is considered where the Atalanta is placed at equal distances from all the six walls and rises vertically upwards along the z-axis (see Figure 4-8). The distance measured from the six sensors during the flight of the Atalanta is plotted. Consider the Figure 4-9, during the 20 second flight of the Atalanta the distance measured from the X+ and X- sensor remains the same as the motion is only along the z direction. The sum of the distances measured gives the length of the flying environment (2054 cm). The same applies to the sensors Y+ and Y- as shown in Figure 4-10. In the Figure 4-11,

![Figure 4-8: Distance measurement for a linear motion](image)

as the Atalanta rises up vertically along z-axis, the distance to the walls gradually reduces and the distance from the Z- sensor increases. The above example is a proof to illustrate that the distance measurement in the simulator is accurate.

4-3 Optic Flow

The Optic flow module consists of a system of equations as derived in the section 3-3-3. The velocity components in three directions \((v_x, v_y, v_z)\), the angular velocity components in the three directions \((\omega_x, \omega_y, \omega_z)\) and the distance to the walls from the six optic flow sensors \((r_1, r_2, r_3, r_4, r_5, r_6)\) are inputs to the module. Throughout the simulation \(\beta\) is chosen to be 100. The output is a set of twelve optic flow values from the six sensors. \(O F_{x+}^y\) is the optic flow as perceived by the optic flow x+ sensor in the y direction and \(O F_{z+}^z\) is the optic flow as perceived by the optic flow x+ sensor in the z direction, etc. At every instant of time we obtain these set of twelve optic flow values that are fed to the controller module which will discussed in detail in Chapter 5.
Figure 4-9: Distance measured from X+ and X- sensor

Figure 4-10: Distance measured from Y+ and Y- sensor

Figure 4-11: Distance measured from Z+ and Z- sensor
Optic flow measurement for a circular motion

To test the module, several tests have been run. These consisted of moving the Atalanta along a pre-defined 3D path and plotting the optic flow. In the test presented here, the Atalanta flies in a circular motion as described in the Figure 4-5. The velocity \( v \) and the angular velocity \( \omega \) in \( x \), \( y \) and \( z \) directions are plotted, see Figure 4-13. Note that the velocity \( (v_z) \) remains zero as the motion is along \( x \) and \( y \) direction. They are the derivatives of the vectors \( s \) and \( \theta \) generated in the motion module, see section 4-2-3. Since it is a pure translational motion, the angular velocity component is zero as seen in Figure 4-13. The wall distance measured from the \( X+ \) sensor is a reflected duplication of the wall distance measured from \( X- \) sensor as shown in Figure 4-14. This is due to the fact that the \( X+ \) and \( X- \) sensors are placed 180° apart. The same applies to the sensors in \( y \) and \( z \) directions. The distance to the walls from the \( Z+ \) and \( Z- \) sensors as shown in Figure 4-16 remains unchanged as the Atalanta flies in the \( x-y \) direction (see Figure 4-5). Figures 4-17 and 4-18 shows the optic flow as perceived by the \( X+, X-, Y+ \) and \( Y- \) sensors. These plots are generated based on the equations derived in section 3-3-3. Since there is no motion in the \( z \)-axis the optic flow values observed by the sensors \( X+, X-, Y+ \) and \( Y- \) in the \( z \) direction is zero. The optic flow perceived by the \( Z+ \) and \( Z- \) sensors are obtained based on the Equations 3-5 and 3-6. Optic flow is observed both in \( x \) and \( y \) direction as shown in Figure 4-19.
4-4 Parameter Estimation

In a real life scenario, the translational, rotational components and the distance to the obstacle will not be known to the Atalanta. It has to determine meaningful information out of the optic flow signals. In this section, we attempt to explore the possibility of parameter estimation by solving the nonlinear system of optic flow equations in order to estimate the velocity \((v_x, v_y, v_z)\), angular velocity \((\omega_x, \omega_y, \omega_z)\) and the distance to the six walls \((r_1, r_2, r_3, r_4, r_5, r_6)\) based on the optic flow values alone. The system consists of twelve equations with twelve knowns and twelve unknowns. It cannot be solved directly since it is nonlinear. The following
Distance measurement from Sensor X+ and X-

Figure 4-14: Distance measured from X+ and X- sensor

Distance measurement from Sensor Y+ and Y-

Figure 4-15: Distance measured from Y+ and Y- sensor

Distance measurement from Sensor Z+ and Z-

Figure 4-16: Distance measured from Z+ and Z- sensor
Optic flow from X+ sensor along y and z axis

Optic flow from X- sensor along y and z axis

Figure 4-17: Optical flow from X+ and X- sensor

Optic flow from Y+ sensor along x and z axis

Optic flow from Y- sensor along x and z axis

Figure 4-18: Optical flow from Y+ and Y- sensor
steps were followed to solve the issue,

- An assumption must be made with regards to at least one of the parameters. Here the dimensions of the environment are chosen.
- A matrix is formed by combining the set of known values of the system, see Table 4-1.
- A MATLAB function is defined using the system of nonlinear optic flow equations as explained in section 3-3-3. It is required that the number of equations be precisely the same as the number of variables being solved for. The set of equations are rewritten in the form \( f(x) = 0 \). The known values (optic flow) are substituted in the system of equations.
- The system of nonlinear optic flow equations were solved using the MATLAB function \textit{fsolve}.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
\textbf{Known values} & \textbf{Unknown values} \\
\hline
Optic flow & \( v_x, v_y, v_z \) \\
Dimensions of the Flying environment & \( \omega_x, \omega_y, \omega_z \) \\
\hline
\end{tabular}
\caption{Parameter estimation : Known and unknown entities}
\end{table}

The velocity and angular velocity components were estimated for the circular motion of the Atalanta as shown in Figure 4-5. In the Figure 4-20, the actual velocity and the estimated
velocity in the x direction is plotted along with the error histogram plot. It can be seen in the error histogram plot that the error between the actual and the estimated velocity is of order $10^{-3}$ which is extremely low so an accuracy of almost 100% is achieved.

Figure 4-20: Estimation of velocity in the x direction

Since there is no rotation involved the actual and the estimated angular velocities are zero as seen in Figure 4-21 but the solver estimates the angular velocities to values of order $(10^{-3})$ approaching zero as seen in the error histogram of angular velocity.

Figure 4-21: Estimation of angular velocity in x direction
**Remark**

This estimator module is an attempt to show that meaningful information can be extracted out of optic flow. Estimating the velocity and the angular velocity components to such high accuracy and the distance to the wall is vital as far as the flight stabilization and obstacle avoidance is concerned. From this information, the position and the speed of the Atalanta can be controlled and can prevent it from collision. However, the optic flow signals are scalable i.e. if an object is flying towards an obstacle which is 3 cm away at a velocity of 3 cm/s, the optic flow will be 1 as per the formula, \( OF = \frac{v}{r} \). If the same object flies along an obstacle which is 100 cm away at a velocity 100 cm/s, the optic flow will still be 1. So the estimation of motion parameters and distances is not sufficient if the scale of the flying environment is not known. We have included the dimensions of the environment in the estimator to determine the motion parameters.

In this chapter, the various modules of the simulator (motion, flying environment and optic flow) were discussed and the following conclusions can be made,

- The results in the section 4-2-4 proved that the distance measurement inside the flight arena were accurate.
- The plots in section 4-3 proved that the derived optic flow equations work fine.
- It was evident from section 4-4 that the state of the Atalanta can be estimated if the scale of the flying environment is known.

In the following chapter, the three dimensional kinematic module that is developed to generate the flight of the Atalanta, controller and its controlling strategy using optic flow will be discussed.
Chapter 5

Control Strategy

5-1 Introduction

Insects use many techniques to achieve flight stabilization in spite of limited brain power, by automatically responding to inputs from sensory organs such as ocelli, halteres, compound eyes as discussed in chapter 2. They achieve stabilization in hovering, forward flight and also obtain a collision free flight without the need for complex control systems. In this chapter we will be discussing a simple control strategy to control the flight of the Atalanta and to achieve a stable hovering state. The control algorithm is an optic flow based proportional control as proposed by Goosen [4] based on the observations of insect behaviour and information on insect senses and neurological responses. The Figure 5-1 represents the modules of the simulator which is similar to Figure 4-1 with a small difference. The motion module is replaced by a three dimensional kinematic model to obtain the translational and rotational parameters. The optic flow signals from the optic flow module are fed to the control module which uses the optic flow algorithm to generate roll, pitch and height control signals.

![Figure 5-1: 3D kinematic model and controller module in the simulator](image-url)
5-2 Three dimensional kinematic model

Flight dynamics of Flapping Wing Micro Aerial Vehicle (FWMAV) is an open area of research and this is due to the difficulties in measuring the aerodynamic forces on flying insects. The motion block (see section 4-2-3) discussed in the previous chapter used predefined path as shown in Figures 4-4 and 4-5 which is followed by the Atalanta. However, in this section a more realistic approach to motion generation is adopted. In this simulator we have considered the Atalanta as a rigid body of centre of mass ‘m’ subject to external disturbances and we have assumed that the insect motion evolves according to the rigid body motion equations subject to external forces.

from the second law of motion:

\[ F = m \cdot a \]  \hspace{1cm} (5-1)

\[ a = \frac{dv}{dt} \]  \hspace{1cm} (5-2)

substituting equation 5-2 in 5-1 we get:

\[ F = m \cdot \frac{dv}{dt} \]  \hspace{1cm} (5-3)

\[ dv = \frac{F}{m} \cdot dt \]  \hspace{1cm} (5-4)

\[ \int_{v_0}^{v} dv = \int_{0}^{\Delta t} \frac{F}{m} \cdot dt \]  \hspace{1cm} (5-5)

On solving equation 5-5 we get:

\[ v = v_0 + \frac{F}{m} \cdot \Delta t \]  \hspace{1cm} (5-6)

where \( v_0 \) is the initial velocity and \( \Delta t \) is the time step. In the kinematic module, disturbances in the form of force vector is applied to a mass ‘m’ of the Atalanta and the resultant velocity vector \( v \) is obtained. The Atalanta is a four winged MAV as shown in Figure 5-2 and in the simulator we have considered it as a fixed wing platform and not a flapping wing platform. Moment applied around the centre of mass result in the rotation of the Atalanta. The external forces acting on the Atalanta are the lift force generated by the wings, the gravity and the body viscous drag, see Figure 5-3. In order to obtain rotations (roll and pitch) the moment, \( \tau \) is applied around the centre of mass.

From the equations of rotational motion:

\[ \tau = I \cdot \alpha \]  \hspace{1cm} (5-7)
\[ \alpha = \frac{d\omega}{dt} \]  

(5-8)

where \( \tau \) is the Moment applied to the wings and \( I \) is the moment of inertia of the rotating body frame around the centre of mass of the Atalanta.

substituting equation 5-8 in 5-7 we get:

\[ \tau = I \frac{d\omega}{dt} \]  

(5-9)

\[ d\omega = \frac{\tau}{I} dt \]  

(5-10)

\[ \int_{\omega_0}^{\omega} d\omega = \int_{0}^{\Delta t} \frac{\tau}{I} dt \]  

(5-11)

On solving equation 5-11 we get :

\[ \omega = \omega_0 + \frac{\tau}{I} \Delta t \]  

(5-12)

From the above derived equations, the translational and rotational components of motion are obtained. The velocity vector \( v = [v_x, v_y, v_z] \) and the angular velocity of the Atalanta \( \omega = [\omega_x, \omega_y, \omega_z] \) are relative to the rotating body frame of the Atalanta.
5-3 Flight Control

The controller developed in this section is a simple feedback controller and the optic flows correspond to the error signal. The twelve optic flow signals obtained from the optic flow module is fed to the controller module which are then combined arithmetically to generate control signals, see Figure 5-4. The roll/pitch control signal generated by the controller is equivalent of a moment applied around the centre of mass. The controller also generates a height control signal which is equivalent of variations of power applied to the main actuator of the Atalanta.

5-3-1 Wing control

The four wing configuration of the Atalanta is symmetrical in nature. Any control or disturbance applied to one wing will have an equal and opposite effect on the other wing.
Rotation control

Basic stability of the platform is obtained by subtracting the optic flow in the z direction from the cameras along the x and y axis as represented by,

\[ C_{1}^{X+}_{\text{wing}} = a_{\text{rot}} \cdot (OF_{z}^{X+} - OF_{z}^{X-}), \]  
(5-13)

\[ C_{2}^{Y+}_{\text{wing}} = a_{\text{rot}} \cdot (OF_{z}^{Y+} - OF_{z}^{Y-}), \]  
(5-14)

\( C_{1}^{X+}_{\text{wing}} \) is the drive signal to the wing actuator in the X+ direction and \( C_{2}^{Y+}_{\text{wing}} \) is the drive signal to the wing actuator in the Y+ direction. \( a_{\text{rot}} \) is the amplification factor multiplied to the optic flow to obtain the control signal.

Let us consider an example as seen in the Figure 5-5. A disturbance in the form of a moment is applied about y-axis causing a rotation in x direction. An optic flow is sensed by the sensors in the X+ and X- direction along the z-axis. The difference in these signals is applied as a rotational control signal to the wings as described in the equation 5-13 to bring it back to the initial non-rotating state.

Displacement control

Consider a linear motion in the x direction. Maximum optic flow is obtained from the cameras in y and z direction. Displacement control in the x direction is obtained by summing the optic flow in the x direction of the camera facing along y and z axis as shown in Figure 5-6. It is represented by the following equation,
$C^3_{wing} = a_{displr}(OF_x^+ + OF_x^- + OF_y^+ + OF_y^-)$, \hspace{1cm} (5-15)

$C^3_{wing}$ is applied as a moment about y-axis to control the displacement in the x direction. The displacement control for a linear motion in the y direction is given by,

$C^4_{wing} = a_{displr}(OF_y^+ + OF_y^- + OF_z^+ + OF_z^-)$, \hspace{1cm} (5-16)

where $a_{displr}$ is the amplification factor.

**Figure 5-6:** Displacement control on the wings

### 5-3-2 Height control

Height control is essential for the hovering state of the Atalanta. The height control signal is given as force whose magnitude translates to the change in power applied to the main actuator of the Atalanta to keep the platform at a certain height. The displacement control in the z direction is achieved by summing the optic flow outputs in the z direction of the cameras facing the x and y axis as shown in the Figure 5-7. It is represented by the following equation,

$C^7 = a_{displt}(OF_z^+ + OF_z^- + OF_x^+ + OF_x^-)$. \hspace{1cm} (5-17)

The equation 5-17 is a control signal for the altitude stabilization and does not determine the altitude.

Master of Science Thesis  
Abhimanyu Selvan
5-3-3 Obstacle avoidance

When the Atalanta is closer to a wall or an obstacle, the optic flow perceived by the camera near to the obstacle will yield an optic flow of greater magnitude. By turning the Atalanta away from these flows an obstacle avoidance behaviour without complicated image processing can be achieved. A simple rotation by the difference in flow between opposite looking cameras will introduce this desired effect as they are represented by the following equations,

\[
C_{5_{wing}}^{X^+} = a_{avoid} \cdot (|OF_{y}^{X^+}| - |OF_{y}^{X^-}|), \quad (5-18)
\]

\[
C_{6_{wing}}^{Y^+} = a_{avoid} \cdot (|OF_{x}^{Y^+}| - |OF_{x}^{Y^-}|). \quad (5-19)
\]

The avoidance control is a part of the altitude stabilization and is achieved by finding the difference in the absolute values of the optic flows in the x and y direction of the cameras facing in the z direction as represented by the equation,

\[
C8 = a_{avoid} \cdot (|OF_{y}^{Z^+}| - |OF_{y}^{Z^-}|) + a_{avoid} \cdot (|OF_{x}^{Z^+}| - |OF_{x}^{Z^-}|). \quad (5-20)
\]
5-3-4 Control signals

The control signals that correspond to moments and force is obtained by combining the equations derived in the previous section. The moment about y (see equation 5-21) is obtained by summing the equations 5-13, 5-15 and 5-18 and the moment about x (see equation 5-22) is obtained by summing the equations 5-14, 5-16, 5-19.

\[
\text{Moment}_y = \Delta C^y \left( X^+ - X^- \right) + a_{\text{rot}} \left( OF^Y_z + OF^X_x + OF^Z_z \right) + a_{\text{displ}} \left( |OF^X_y| - |OF^X_y^-| \right),
\]

\[
\text{Moment}_x = \Delta C^x \left( Y^+ - Y^- \right) + a_{\text{rot}} \left( OF^Y_z + OF^X_x + OF^Z_z \right) + a_{\text{displ}} \left( |OF^X_y| - |OF^X_y^-| \right),
\]

These moments are the control signals applied to the respective wing actuators of the Atalanta. Altitude stabilization control signal \( \Delta \text{Force} \) is determined by combining equations 5-17 and 5-20 and is represented by the equation,

\[
\Delta \text{Force} = a_{\text{displ}} \left( OF^X_z + OF^X_z^- + OF^Y_z + OF^Y_z^- \right) \]

\[
+ a_{\text{avoid}} \left( |OF^Z_x^+| - |OF^Z_x^-| \right) \]

\[
+ a_{\text{avoid}} \left( |OF^Z_y^+| - |OF^Z_y^-| \right),
\]

where \( a_{\text{displ}} \) and \( a_{\text{avoid}} \) is the amplification factor. These amplification factors are obtained by trial and error. The \( \Delta \text{Force} \) obtained is fed to the 3D kinematic block which calculates the resulting motion of the aircraft.

5-4 Results

In the previous section we discussed about the control logic and in this section we will be analyzing the working of the controller for a few sample flights of the Atalanta.
Table 5-1: Parameter settings for Case I, II and III

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{\text{rot}}$</td>
<td>50</td>
</tr>
<tr>
<td>$a_{\text{avoid}}$</td>
<td>4</td>
</tr>
<tr>
<td>$a_{\text{displr}}$</td>
<td>50</td>
</tr>
<tr>
<td>$a_{\text{displt}}$</td>
<td>4</td>
</tr>
</tbody>
</table>

Choice of amplification factor settings

The amplification parameter values as shown in Table 5-1 were chosen by trial and error. The factors were tuned for a constant control period, in this case $[t=5s]$. The obtained values for the amplification factors yielded good control and stability. Let us discuss effects of each parameter on the flight control.

- $a_{\text{rot}}$ - Rotation of the Atalanta about x and y axis yields a very low optic flow value when compared to the displacement so a comparatively higher value is chosen. Choosing a value $[a_{\text{avoid}} < = 50]$ will result in a delayed control and is not suitable for a control period of $t = 5s$. Care has to be taken while choosing the value as this will have a significant impact on the displacement control, i.e. Optic flow $OF_{x}^{\pm}$ and $OF_{y}^{\pm}$ will be affected resulting in delayed displacement control.

- $a_{\text{avoid}}$ - Wall avoidance is not tested in this thesis, so a low arbitrary value is assigned to the avoidance factor.

- $a_{\text{displr}}$ - The displacement factor in the wing control is assigned a value equal to that $a_{\text{rot}}$ because the wing should be able to generate a counter moment after the rotation control becomes zero in order to prevent the Atalanta moving along x/y axes.

- $a_{\text{displt}}$ - Since the displacement yields higher optic flow as far as altitude stabilization is concerned, the amplification factor is assigned a low arbitrary value.

Remark: Larger rooms will result in a low optic flow as the distance to the walls increases leading to higher values of the parameters. These values have to be finely tuned as they are interrelated and the values assigned to the parameters might change depending on mass of the system and the magnitude of external disturbances etc. For instance, a disturbance of larger magnitude on a mass of less magnitude will cause instability.

5-4-1 Case I: Height control for a pure translational motion

Let us consider an example where a disturbance is applied in the form of an initial velocity in the z direction which results in an upward motion along z-axis as shown in Figure 5-7. The optic flow based controller starts to control the flight as soon as it receives the optic flow sensor outputs. Figure 5-8 illustrates the output of the controller. The control moments are zero as there is a pure translational motion. The Figure 5-9 illustrates the effect of the controller on the velocity of the Atalanta. Gradual reduction in the velocity can be witnessed...
as the controller tries to stabilize the Atalanta. The displacement plot (see Figure 5-10) illustrates the displacement control in z direction. Since it is a pure translational motion, the angular displacement remains zero.

**Figure 5-8:** Height Stabilization-Controller output, Case I

**Figure 5-9:** Height Stabilization-Velocity control, Case I
5-4-2 Case II: Wing control - Roll and Pitch stabilization

A disturbance in the form of a moment is applied about the y-axis as shown in Figure 5-5 which causes a pitching motion of the Atalanta. In this scenario we investigate the pitch stabilization of the Atalanta based on the optic flow control as illustrated in the Figure 5-11.

The moment applied to the wings causes an angular velocity about y-axis. The controller
reduces the angular velocity and brings it back to the stable state within the control period. The controller output for pitch stabilisation is illustrated in the Figure 5-12.

![Figure 5-12: Pitch Stabilization-Controller output, Case II](image)

Figure 5-12 illustrates the roll stabilization of the Atalanta for a disturbance (moment) about x-axis. The controller output for roll stabilisation is illustrated in the Figure 5-14.

![Figure 5-13: Roll Stabilization-Angular velocity control, Case II](image)
5-4 Results

5-4-3 Case III: Hovering

One of the key objectives of this thesis is to attain a hovering state of the Atalanta using the optic flow control strategy. In this case we will be combining case I and II i.e. A disturbance that generates and upward motion along with a disturbance to one of the wings causing roll/pitch (see Table 5-2) and analyze the response of the controller. The initial velocity of the Atalanta is in the z-direction along with the moment applied to the Atalanta about y-axis, which generates a motion in x direction causing the Atalanta to take a curved path as shown in Figure 5-15. This explains the velocity of small magnitude in the x direction ($v_x$) as shown in Figure 5-17.

Table 5-2: Initial disturbances

<table>
<thead>
<tr>
<th>Disturbances</th>
<th>Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Velocity, $v_0$ [cm/s]</td>
<td>[0 0 3]</td>
</tr>
<tr>
<td>Angular Velocity, $\omega_0$ [deg/s]</td>
<td>[0 4 0]</td>
</tr>
</tbody>
</table>

Figure 5-16 illustrates the controller output for the hovering state. The optic flow controller gradually reduces the velocity in z direction $v_z$ as shown in the Figure 5-17 simultaneously controlling the pitch of the Atalanta as shown in Figure 5-18. The translation in x direction is evident from the rise in $v_x$ in the Figure 5-17. At Time $t=1.7$[s], the angular velocity reaches zero thereby resulting in pitch stabilization but continues to rotate about y-axis (results in overshoot) till the Atalanta comes to a standstill in the x direction and returns to zero as explained in the displacement control under the section5-3-1. From the Figure 5-20 we can verify that the Atalanta has attained a stable state as the angular displacement($\theta$) reaches zero within the control period. Hovering state of the Atalanta is achieved at $t=4$[s], where
the displacement in x and z direction remain constant.

Path followed by the Atalanta

![Atalanta flight path](image)

**Figure 5-15:** Atalanta flight path

![Control signals](image)

**Figure 5-16:** Controller output, Case III
5-4 Results

Height Stabilization

![Graph showing Height Stabilization](image)

**Figure 5-17:** Height stabilization-Velocity control, Case III

Pitch Stabilization

![Graph showing Pitch Stabilization](image)

**Figure 5-18:** Pitch stabilization-Angular velocity control, Case III
5-4 Results

Figure 5-19: Displacement control, Case III

Figure 5-20: Angular Displacement control, Case III
Conclusions and Recommendations

6-1 Inference

In this thesis work a ‘flight simulator’ was developed to analyse the optic flow based flight control system. The results presented in the section 5-4 and the remarks therein, provided an explanation and validity of the simulations. However, it should be noted that these observations were made while working with certain assumptions on selected issues that the author feels deserves more investigation than was possible in this project. In a scientific attempt to explore the possibilities of using optic flow to stabilize the flight of a Flapping Wing Micro Aerial Vehicle (FWMAV) the following were concluded,

- The experimental results presented in section 3-4 demonstrated the confirmation of the theoretical relationship between optic flow, velocity and distance to the obstacle.

- The flight simulator developed, acts as a test bed to analyse the flight behaviour of the FWMAV in a three dimensional space. The flight path of the FWMAV is tracked and its proximity to the walls of the room is determined successfully. An insight on the effect of external disturbances, the power required by the wing actuators and the main actuators to stabilize its flight is provided by the simulator.

- The six optic sensor configuration is an effective sensor system arrangement to establish hovering and slow indoor flight.

- A control system purely based on optic flow can be used to stabilize the FWMAV in space in a controlled simulated environment.

- Parameter estimation provided an insight on how the optic flow values are not 100% reliable as the values can be scaled based on the dimensions of the flying environment. Hence, the optic flow based control system is dependent on the indoor environment.

The author believes that the points summarized above would allow the reader to connect the individual ‘modules’ of this thesis together and hopefully obtain the final answer to the research question of this thesis.
6-2 Future Recommendations

Being a pilot project in this direction, the author has the following suggestions for the future,

- The optic flow experiments were conducted for a linear motion. In order to gather more insight in the optic flow behaviour, rotational motion has a good scope for further research.
- The optic sensor simulated is a single point camera i.e. it determines the optic flow at only one point. However, in reality the optic sensor can capture a frame of $16 \times 16$ to $30 \times 30$ pixels at every instant of time so a simulated camera model based on the real world sensors is worth researching.
- The flying environment developed in this thesis is a room-like area. A flying environment with obstacles, different sizes, different paths can be modelled and tested.
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- The flying environment developed in this thesis is a room-like area. A flying environment with obstacles, different sizes, different paths can be modelled and tested.
- The simplified stick model of the Atalanta is modelled and tested in this thesis. However, a more realistic model of the Atalanta with real world dimensions and other specifications can be modelled and tested.
- Exploring the possibilities of reducing the number of sensors is worth researching as it further reduces the power consumption, effect on weight, etc.
- In this thesis, we were able to test the wing control, height control and the hovering flight of the Atalanta. Obstacle avoidance has been implemented in the controller and it can be tested.
- The parameters $a_{rot}$, $a_{displ_r}$, $a_{displ_l}$, $a_{avoid}$ used in the control algorithm were determined based on trial and error. However, tuning the parameters using other approaches is an interesting field to study and analyse.
- The influence of the scaling of the environment on the control system can be analysed.
- Implementing the six optic sensor configuration on a quadcopter to test the control strategy is worth being considered.
Bibliography


Glossary

List of Acronyms

FWMAV    Flapping Wing Micro Aerial Vehicle
MAV      Micro Aerial Vehicle