DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

MAGNETICALLY LEVITATED INSECT FLIGHT MILL FOR FORWARD FLIGHT CONTROL ANALYSIS

CARL DELACATO
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Reviewed and approved* by the following:

Bo Cheng, Ph.D.
Assistant Professor of Mechanical and Nuclear Engineering
Thesis Supervisor

Zoubeida Ounaies, Ph.D.
Professor of Mechanical and Nuclear Engineering
Honors Adviser

* Signatures are on file in the Schreyer Honors College.
ABSTRACT

Insects are able to achieve unprecedented flight maneuverability and stability in highly dynamic and uncertain environments. This unique flight ability is made possible due to the intricate control of flapping wing motion and the use of unsteady aerodynamics through fast coordination of neural sensing, control, and muscular actuation systems. Gaining a better understanding of these highly stable, maneuverable and arguably energy efficient flying machines and how they interact with nature will be a key factor in developing future generations of unparalleled biomimetic robots with greater adaptability and maneuverability in complex and unstructured environments. Currently, there are limited resources available for conducting research that is capable of producing the analysis needed to develop engineering models of these complex flying machines in forward flight. The purpose of this thesis is to develop a magnetically levitated insect flight mill that will serve as a platform for acquiring the data necessary to conduct the analysis of insect forward flight. The novel magnetically levitated insect flight mill design is presented in the following thesis. In addition, sample data is presented to show the capabilities of using a magnetically levitated insect flight mill for extracting insect forward flight dynamics and control mechanisms.
# TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. iii

LIST OF TABLES ...................................................................................................................... iv

ACKNOWLEDGEMENTS ......................................................................................................... v

Chapter 1 Background Information ...................................................................................... 1

Chapter 2 Materials and Methods ......................................................................................... 6

- 2.1 Test Specimens .............................................................................................................. 6
- 2.2 Flight Mill Framing ...................................................................................................... 7
- 2.3 Flight Mill Arm ............................................................................................................. 8
- 2.4 Electric Circuit and Arduino Code ............................................................................. 12
- 2.5 Magnetic Levitation Model ......................................................................................... 14
- 2.6 High Speed Video Collection .................................................................................... 19
- 2.7 Tethering Station ........................................................................................................ 21

Chapter 3 Aerodynamic Loading Analysis ............................................................................ 25

- 3.1 Damping Analysis ....................................................................................................... 25
- 3.2 Small Damper ............................................................................................................. 27
- 3.3 Medium Damper ......................................................................................................... 29
- 3.4 Large Damper ............................................................................................................ 31
- 3.5 Summary of Damping Analysis .................................................................................. 33

Chapter 4 Data Analysis ........................................................................................................ 34

- 4.1 Small Damper Flight Results ..................................................................................... 34
- 4.2 Medium Damper Flight Results ................................................................................ 35
- 4.3 Large Damper Flight Results .................................................................................... 36
- 4.4 Data Analysis ............................................................................................................. 37

Chapter 5 Conclusion ............................................................................................................. 40

Appendix A Arduino Code .................................................................................................... 42

- A.1 Introduction ............................................................................................................... 42
- A.2 Magnetic Levitation ................................................................................................. 42
- A.3 Laser Timer and Camera Triggering ......................................................................... 44

Appendix B Circuit Components ......................................................................................... 45
LIST OF FIGURES

Figure 1: Low-Friction Pivot Flight Mill [41] ................................................................. 4
Figure 2: Magnetically Levitation Flight Mill ................................................................. 5
Figure 3. Blue Bottle Fly Used in Experiment ................................................................. 7
Figure 4. Flight Mill Arm ............................................................................................... 8
Figure 5. Axes Diagram for Magnet at the Center of Flight Mill Arm [43] ................. 10
Figure 6. Torque on a Magnetic Dipole [44] ................................................................. 11
Figure 7. Electric Circuit for Levitation and Camera [45] ............................................. 13
Figure 8: Angular Velocity and Camera Trigger Circuit [45] ......................................... 14
Figure 9: Free Body Diagram of Mag Lev Model [47] ................................................... 15
Figure 10: Model of Mag Lev System Using a PD Controller [47] ............................... 16
Figure 11: Magnetic Levitation Stability Comparison Plot ........................................... 17
Figure 12: Flight Mill Camera Triggering System ......................................................... 20
Figure 13. High Speed Video Collection Setup ............................................................. 21
Figure 14: Stationary Tethered Blue Bottle Fly ............................................................ 22
Figure 15: Flapping Tethered Blue Bottle Fly ............................................................... 23
Figure 16. Tethering Station Diagram ........................................................................ 23
Figure 17: Small Damper Penny Comparison ............................................................... 28
Figure 18. Small Damper Calibration Curve ................................................................. 29
Figure 19: Medium Damper Penny Comparison .......................................................... 30
Figure 20: Medium Damper Calibration Curve ............................................................ 31
Figure 21: Large Damper Penny Comparison ............................................................... 32
Figure 22: Large Damper Calibration Curve ................................................................. 33
Figure 23: Small Damper Wing Beat Captures ............................................................. 35
Figure 24: Medium Damper Wing Beat Captures ......................................................... 36
Figure 25: Large Damper Wing Beat Captures.................................................................37
LIST OF TABLES

Table 1: Small Damper Calibration Data .............................................................. 28
Table 2: Medium Damper Calibration Data ............................................................ 30
Table 3: Large Damper Calibration Data .............................................................. 32
Table 4: Damping Analysis Summary .................................................................. 33
Table 5: Blue Bottle Fly Flight Mill Data .............................................................. 37
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Chapter 1

Background Information

The study of insects has led to many interesting developments in the expansion of fundamental science and insect interaction with the environment. Narrowing down the study of insects to studying insect flight has the potential to open many doors to discoveries that will be useful in engineering applications. In the Locomotion Biomechanics and Control Lab, research is conducted to study the complex flight systems of insects at miniature scale from system and control perspectives. This field of study has several benefits and the potential to uncover many more in the future as many highly evolved flying insects have achieved superior flight stability and agility, a wide range of flight envelops, and miniaturization of their body size that human-engineered systems have not yet achieved. [1-7].

Gaining a better understanding of these highly stable, maneuverable, and arguably energy efficient flying machines and how they interact with nature will inspire designs in engineering robotics and engineering control systems. Studies on insect flight has received wide spread interests from both engineering and biology communities in the past decades. These studies range from experiments and simulations of flapping wing aerodynamics [8-11], flight dynamics [12-16] and neural sensing and control of flight [17-20].

A better understanding of insect flight will be a key factor in developing future generations of unparalleled biomimetic robots with greater adaptability and maneuverability in complex and unstructured environments. Insects are able to achieve unprecedented flight maneuverability and stability in highly dynamic and uncertain environments. This unique flight ability is made possible
due to the intricate control of flapping wing motion and the use of unsteady aerodynamics through fast coordination of neural sensing, control, and muscular actuation systems [21].

Currently, many of the studies conducted on insect flight have been centered on the hovering flight of insects in either tethered or free flight conditions. However, the forward flight of insects is an area of research that has received relatively less attention. It is important that a better understanding of insect forward flight is achieved as most insects fly frequently at a broad range of speeds while they are foraging, chasing for mating purposes, and escaping from potential predators [4, 22, 23]. It can also be argued from an evolutionary perspective that many of the flight characteristics of insects are adapted primarily for forward flight or at least for a compromise between forward and hovering flight performance.

Forward flight of insects has commonly been studied in wind tunnels [7, 24-27]. The primary goal of these studies range from the observation of wing kinematics during steady and unsteady flight and visual flight control. In the past, very few studies have focused on gaining a better understanding of the sensing, control, and energetics of forward flight. In particular, studies of forward flight have not allowed for rigorous mathematical modeling and system identification based on the observed kinematics of forward flight [28, 29]. Studies on the aerodynamics and power requirement of the insect forward flight have also been limited, as they have been mostly carried out using computational fluid dynamic (CFD) simulation [30, 31] and these experimental studies have been limited in comparison to the study of hovering flight [32, 33].

For insects in forward flight, visual flight control is one of the most widely studied topics. This is because a strong dependence of flight speed on the optical flow has been discovered in previous studies [29, 34]. The study of visual flight control also allows researchers to develop a powerful model of behavior to characterize optical flow processing [35, 36] and to inspire flight
control algorithms in engineered systems [37, 38]. Specifically, these studies have found that many insects, such as honeybees and fruit flies, are able to robustly extract their “ground speed”, also referred to as retinal slip velocity, from visual patterns with varying spatial and temporal frequencies. In particular, they are able to regulate their flight speed while maintaining a preferred ground speed invariant to substantial changes in headwind or different air speeds, which can be detected by air flow sensors such as antennas [34-38].

Interestingly, the above results have led to the hypothesis that insects will fly at their preferred speed independent of the aerodynamic power requirement as long as this speed is within their locomotor capacities. However, such a hypothesis has not been rigorously tested in past, and the results of this testing could lead to significant advances in understanding insect flight control and energetics. Therefore, the goal of this research is to systematically study the forward flight speed control of insects. More specifically, this research will study blue bottle flies under different aerodynamic loads by combining insect flight experiments, kinematics extraction and analysis, and aerodynamics calculations. In this thesis, a novel experimental setup has been developed, i.e., a magnetically-levitated insect flight mill, as the first step to accomplish this objective.

An insect flight mill is a device that restricts the flight path of an insect to a circle of a fixed radius around a fixed axis. The flight mill operates as a reliable platform for studying insect flight with the approximation that the radius of the flight mill is large enough to simulate straight line forward flight for the insect. Flight mills have commonly been used to determine the travelling distance of insects and study their dispersal potentials [39, 40]. To closely simulate the free forward flight of flies, the existing designs of flight mills employ a low-friction pivot. A traditional flight mill is shown below in Figure 1.
To improve the traditional flight mill design, the goal of this research is to develop a magnetically-levitated insect flight mill with two significant improvements over traditional flight mills; 1) the low-friction pivot is eliminated and 2) micro bearings are added to the flight mill that will allow the insect to rotate about their roll and pitch body axes. For the scope of this thesis, the first improvement has been achieved. However, incorporating roll and pitch about the insect body axes is an improvement that will be developed in the future. The improved flight mill developed in this thesis is shown below in Figure 2. With these two improvements, the magnetically-levitated flight mill will not only allow an improved simulation of free forward flight but also facilitate a variety of experimental studies on insect forward flight speed control.
In the following chapters, this thesis will explain the methodology used to develop a magnetically levitated insect flight mill and discuss data captured of a blue bottle fly in forward flight. The magnetic levitation insect flight mill developed for this thesis has been combined with a constant optical flow condition with varying aerodynamic loading to provide the opportunity for forward flight speed control analysis of insects. To conduct this analysis, high speed video equipment is used to quantify insect forward flight speed and also qualitatively analyze the wing kinematics of insects when subjected to varying aerodynamic loads. The materials and methods section will explain the flight mill design and control system, from which future insect flight mills can be developed with additional improvements to this novel iteration. Following this section, the analysis used to implement varying aerodynamic loads will be presented. Finally, a discussion of high-speed video data collected using this novel flight mill design will be presented.
Chapter 2

Materials and Methods

The flight mill system developed during this research and design process can be broken down into four main components. The four components are the flight mill framing, the flight mill arm, the controlling code and electronic circuitry, and the camera data collection system. In addition to the flight mill, a tethering stand is used to consistently harness the insects in order to attach them to the flight mill arm. These components work simultaneously to allow for high-speed video footage capture of the insects in tethered flight.

2.1 Test Specimens

A blue bottle fly was used for testing in this thesis. The blue bottle fly (Calliphora vomitoria) is a medium to medium-large size fly and has a typical body that is 125 mm long [42]. The blue bottle flies used for this research were purchased from mantisplace.com. The blue bottle fly is a relatively large fly, which made the tethering process employed in this research much easier. A blue bottle fly is shown below in Figure 3. The flies were purchased as Larvae and kept in a screened enclosure while maturing. Once mature, individual flies were removed from the screened enclosure for tethering and flight mill testing. One caution for purchasing flies online is that the weather affects the flies during shipping. Unfortunately, orders made during the winter months can cause the flies to die during shipping, and thus delay the research process. When
purchasing flies in the future, the weather should be considered and appropriate shipping supplies such as a heating pack should be purchased to keep the flies alive during shipping.

![Figure 3. Blue Bottle Fly Used in Experiment](image)

### 2.2 Flight Mill Framing

The flight mill framing serves to suspend the electromagnetic coil and flight mill patterned walls. The framing is all made using 80/20 T-slotted stock bar. T-slotted stock bar was chosen as it allows for easy adjustment and interchanging of components throughout the design process. In particular, positioning all required camera components and back lighting components required varying configurations until the best possible high speed video footage was recorded. The framing also supports the flight mill walls which are used to hold patterns to simulate varying optical flow conditions for the insect. The common pattern used to capture data of varying drag loads was a basic black and white striped pattern. The flight mill inner wall is made from 8-inch PVC pipe and the outer wall is made from 12-inch PVC pipe. PVC pipe was chosen as it is rigid and will not be affected by adhesives that hold the patterns used during data collection.
2.3 Flight Mill Arm

The flight mill arm is a critical part of the flight mill as it harnesses the insect, it is magnetically levitated, and it is the connection point for various drag loads. The flight mill arm is made from a 1.02 mm diameter carbon fiber rod cut to 260 mm in length. At the mid point of the arm, a D36-N52 permanent cylindrical magnet is rigidly fixed to the bar using Loctite 4305 light cure glue. At one end of the rod, a D12-N52 magnet is rigidly attached to provide surface to attach removable counterweights and the tethered insect. On the opposite end of the flight mill arm is a rigid flat plastic surface used to create a drag force on the flight mill arm. This plastic surface also acts as a counterweight to the harnessed insect at the other end of the flight mill arm. The flight mill arm is shown below in Figure 4.

![Figure 4. Flight Mill Arm](image)

The flight mill arm components can be selected to improve the simulation of straight-line flight, reduce the moment of inertia about the levitation axis, and to increase the stiffness of the
system about the axes perpendicular to the levitation axis. The criterion used to quantify the approximation of straight-line flight is the difference in wing tip velocities compared to the velocity of the insect’s center of mass. This means that a minimum flight mill arm length is required to achieve a certain percent difference in the wing tip velocities of the insect. For this thesis, the goal was to reduce this wing tip velocity difference to below ten percent. The calculation can be made using (1) below.

\[
\frac{V_{outer\ wing} - V_{inner\ wing}}{V_{body}} = \frac{\omega \left( \frac{L}{2} + W \right) - \omega \left( \frac{L}{2} - W \right)}{\frac{\omega L}{2}} = \frac{4W}{L}
\]  

(1)

In this equation, \(\omega\) represents the angular velocity of the flight mill arm, \(L\) represents the full length of the flight mill arm, and \(W\) represents the wing length, the distance from the center of mass to wing tip, of the insect. The wing length of a blue bottle fly is approximately 5 mm, meaning that a minimum flight mill arm length of 201 mm is required. However, for this thesis, a 260 mm flight mill arm was used to better fit the average diameters of the flight mill walls, which reduced the difference in wing tip speeds to 7.69% difference. As flight mill arm length increases, the straight-line flight approximation improves, but this increased length must be compromised with maintaining a reasonably small moment of inertia about the levitation axis.

The mass moment of inertia about the levitation axis can be found by summing the moments of inertia for each of the flight mill arm components. To clarify, the levitation axis, labeled \(z\)-axis in Figure 5, is the center of the electromagnetic coil, as well as the center of the magnet rigidly attached to the flight mill arm. The moment of inertia of the levitating permanent magnet is \(I_z = \frac{m}{2}r^2\), where \(r\) is the radius of the cylinder magnet. The moment of inertia of the carbon fiber rod about its center of rotation, also the \(z\)-axis, is \(I_z = \frac{m}{12}L^2\), where \(L\) is the full length.
of the carbon fiber rod. Finally, the counterweight and damping components of inertia can be found using \( I_c = m_c d^2 \), where the subscript \( c \) represents each individual component and \( d \) represents the distance of the component from the \( z \)-axis. All of these components can be summed to find the total mass moment of inertia of the flight mill arm about the \( z \)-axis. The mass moment of inertia should be minimized to allow the insect to accelerate as desired. However, as the purpose of this thesis is to gather data at steady state flight conditions, the moment of inertia of the flight mill arm becomes negligible once the insect reaches a constant speed. For the flight mill set up used for this thesis, the mass moment of inertia about the \( z \)-axis is \( I_z = 1.57 \times 10^{-6} \text{kgm}^2 \). The final purpose of the flight mill arm is to provide stiffness in the axes perpendicular to the levitation axis.

![Axes Diagram for Magnet at the Center of Flight Mill Arm](image)

**Figure 5. Axes Diagram for Magnet at the Center of Flight Mill Arm** [43]

To improve stiffness in the axes perpendicular to the levitation axis, in the \( x \)-axis and in the \( y \)-axis, the magnet used for levitation must be chosen carefully. Stiffness in the \( x \) and \( y \) axes is required to counteract the lift force produced by the insect to ensure the insect’s flight path is in a constant horizontal plane. The levitation magnet is a cylindrical magnet, which is the same as a magnetic dipole, having a north and south pole. The magnetic field from the electromagnet produces a torque on this magnetic dipole as seen in Figure 6.
The torque on a magnetic dipole in a magnetic field is $\tau = mLB\sin(\theta)$. In this equation, $m$ is the pole strength, $L$ is the distance between the poles or length of the magnet, $B$ is the magnetic field strength, and $\Theta$ is the angle between the alignment of the magnetic field and the magnetic dipole. This equation shows that the stiffness about the x and y axes increases proportionally to magnetic dipole length, assuming that each magnet has the same pole strength. Therefore, picking a magnet of equal strength and larger dipole length can increase the stiffness of the flight mill arm in the axes perpendicular to that of levitation. This increased torque improves the stiffness of the flight mill arm and will ensure the insect’s flight path is in a horizontal plane. Another advantage of increasing the length of the magnetic dipole is that the moment of inertia about the x and y axes also increases, $I_x = I_y = \frac{m}{12}(3r^2 + h^2)$, where $h$ represents the height of the magnet and the magnetic dipole length and the x and y axes can be visualized in Figure 5. This increased length will again help reduce movement in the flight mill arm to horizontal rotation only.
In summary, the components chosen for the flight mill arm are very influential on the quality of the data obtained. Components should be chosen to satisfy and improve the straight line flight simulation, reduce the moment of inertia about the levitation axis, as well as improve the stiffness in the x and y axes. Each component can effect multiple of these criteria. For example, a small reduction in the levitation magnet’s diameter and an increase in its dipole length can reduce the moment of inertia about the levitation axis and greatly improve the stiffness in the x and y axes.

2.4 Electric Circuit and Arduino Code

The electric circuit shown in Figure 7 includes all electric components used for magnetic levitation. The circuit is built using an Arduino UNO R3 and a breadboard. The important components in the circuit used for magnetic levitation include an electromagnetic coil and a Hall effect sensor. A complete break down and a list of exact components used in the circuit for the flight mill can be found in appendix B. However, many of these specified items can switched with similar components and a stable magnetic levitation system will still be achieved. There are several LED lights in the circuit that simply indicate when the flight mill arm is detected and levitating. These LED lights are therefore optional in the circuit. The code used to analyse the position of the levitating permananet magnet and return an appropriate output current to the electromagnet is written in Arduino code. The Arduino code can be found in appendix A.
Figure 7. Electric Circuit for Levitation and Camera [45]

The electric circuit and computer code control the levitation of the flight mill arm. Earnshaw’s theorem states that it is impossible to achieve static levitation using a combination of only permanent magnets and electric charges [46]. This concept can be made tangible by pushing the north poles of two permanent magnets towards each other. The results are that the magnets will attempt to move in a direction perpendicular to their magnetic dipole orientation or they will attempt to flip themselves around to align north-south to north-south. Therefore, the electric circuit and computer code above track the position of the levitating magnet using a Hall effect sensor then provide some output current through the fixed position electromagnetic coil to respond to any change in position of the levitating magnet. A complete model of the control system used and the resulting forces on the flight mill arm can be found in the following section.

Arduino code and an electronic circuit were also used to track the flight mill angular velocity and trigger the camera recording equipment. This circuit consists of two lasers pointing
on photoresistors. As the flight mill arm passes through the laser beam, the output signal from the photoresistor changes and triggers the camera and angular velocity recording system. The code used to control this recording system can also be found in Appendix A. Finally, the circuit used for the flight mill recording system is shown below in Figure 8.

![Figure 8: Angular Velocity and Camera Trigger Circuit](image)

2.5 Magnetic Levitation Model

The magnetic levitation system controller used for this thesis is modeled from a paper published by the Institute of Electrical and Electronics Engineers (IEEE). The following model equations and figures are from the IEEE paper and summarize the more in depth model explained in the paper [47]. The first portion of the IEEE paper model is a free body diagram of the magnetic levitation system seen in Figure 9.
The free body diagram force balance yields (2.1).

\[ m\ddot{x} = mg - K_1 \left( \frac{i}{K_2 + x} \right)^2 \]  

(2.1)

In (2.1), \(K_1\) and \(K_2\) are parameters characterized by the geometry and construction of the electromagnet and are found experimentally. As (2.1) is nonlinear, it must be linearized for the linear control system used to achieve single coil magnetic levitation. After linearization of the model around an operating point of \(i = i_0, x = x_0\), and \(\dot{x} = 0\), the governing equation of motion for the magnetic levitation system becomes (2.2).

\[ \ddot{x} = \frac{K_1}{m} \left( \frac{2i_0^2}{(K_2 + x_0)^3} \right) \delta x + \frac{K_1}{m} \left( \frac{2i_0}{(K_2 + x_0)^2} \right) \delta i \]  

(2.2)

The following constants, (2.2a) and (2.2b), are defined to condense the governing equation for simplicity and convenience when transforming (2.2) to the Laplace domain.

\[ k_x = \frac{K_1}{m} \left( \frac{2i_0^2}{(K_2 + x_0)^3} \right) \]  

(2.2a)
\[ k_i = \frac{K_1}{m} \left( \frac{2i_0}{(K_2 + x_0)^2} \right) \]  \hfill (2.2b)

With these condensed constants, the governing equation in the Laplace domain becomes (2.3) found below.

\[ s^2 X(s) = k_x X(s) - k_i I(s) \]  \hfill (2.3)

Finally, (2.3) in the Laplace domain can be rearranged to produce the open-loop transfer function of the system, (2.4), found below.

\[ \frac{X(s)}{I(s)} = \frac{-k_i}{s^2 - k_x} \]  \hfill (2.4)

A position-derivative controller is used to achieve stable levitation of the maglev system used in this thesis. If the levitating permanent magnet moves away from the set point, the Hall effect sensor measures this change and the PD controller adjusts the current passing through the electromagnetic coil accordingly to mitigate the position error. A block diagram of the position feedback controller can be found in Figure 10.

![Figure 10: Model of Mag Lev System Using a PD Controller](image)

This model allows for stable levitation of the flight mill arm. Stability of the flight mill can be improved by adjusting the gain values of the controller. To find the appropriate values necessary for the flight mill arm, trial and error was used to find values that were close to the gains that provided the best stability. Once levitation occurred using trial and error, the gains were varied in decreasing increments and the magnetic levitation stability was measured. To make this
measurement, the output signal from the Hall effect sensor was plotted and compared with the controller output signal to the electromagnetic coil. A comparison of the input and output signals can be found in Figure 11. As the gain values are varied, the plot of Hall effect signal gradually becomes more and more stable until the ideal operating gains are found. To avoid clipping of the controller output signal, the gain values should be minimized while still maintaining stability.

![Magnetic Levitation Stability Plot](image)

**Figure 11: Magnetic Levitation Stability Comparison Plot**

In Figure 11, the Hall effect sensor value has been converted to a distance in millimeters. The vertical position of the flight mill arm oscillates around the set point, with a maximum vertical displacement of 0.081 mm below the set point and a maximum vertical displacement of 0.087 mm above the set point. The total change in vertical position of the flight mill arm during data collection was 0.168 mm. This small change meant the flight mill arm was visually stable, yet the amplitude
of oscillations around the set point can be reduced in the future for improved stability. The output signal from the PWM controller oscillates around an average value of 207. The amplitude of oscillations of the PWM signal are much larger than that of the Hall effect signal, however this will change based on the electromagnetic coil and permanent magnet used for the levitation system.

For the flight mill system employed in this thesis, a linear Hall effect sensor was used to track the position of the levitating arm. However, there are numerous other types of sensors that can be used to achieve levitation. Sensor choice was a major bottleneck in the stability of the magnetic levitation system design. In particular, the Hall effect sensor used sends a signal to the controller based on magnetic field strength from the permanent levitation magnet and the controller responds by sending an appropriate change in current through the electromagnetic coil to maintain stability. However, as the controller output signal changes to supply an appropriate current through the electromagnetic coil to maintain stability, the magnetic field strength sensed by the Hall effect sensor changes both due to the position of the levitating flight mill arm as well as the strength of the required response current in the electromagnetic coil. The additional magnetic field from the electromagnetic coil adds noise to the position signal of the levitating object. This noise made it impossible to use a two-coil magnetic levitation system as the Hall effect sensor readings became saturated.

Other sensor options include using a camera or using a laser. Both of these options are substantially less noisy and are therefore clearly preferable for a standard magnetic levitation system. However, since the magnetic levitation system employed for this thesis requires that our levitating magnet is attached to the flight mill arm, several issues came to surface. In particular, the flight mill arm interferes with a camera’s ability to track the levitation magnet as it passes
through the frame and actually blocks the view of the camera. This could be solved by adding an extension to the magnet for tracking, but only in the presence of extreme stiffness in the x and y axes. If there is not extreme stiffness in the x and y axes, this extension arm would amplify rotation about those axes and thus amplify the change in position of the levitation magnet. This amplification can cause the controller to overcompensate for changes in position of the levitating magnet. Using a laser sensor would likely result in the same problem, as the laser can only focus in one place and small changes in the alignment of the z-axis of the levitation magnet from the z-axis of the electromagnetic coil would cause this laser sensor to respond with an incorrect signal. Camera and laser sensor options are much less noisy and are likely to produce better response if they can applied in a way that will eliminate the failures that have been previously identified. As time was a limiting factor for the design of this flight mill system, a simple one-coil Hall effect sensing system was used to obtain results for this thesis.

2.6 High Speed Video Collection

The high-speed video collection system consists of a triggering system, a high speed camera, and LED lighting. The triggering system is part of the electric circuit and uses lasers and photoresistors to begin and terminate the recording frame. As the flight mill arm passes through the first laser beam, the signal value from the photoresistor increases above a given threshold and starts the high speed camera recording. The high speed camera stops recording using the same laser and photoresistor triggering system. In addition, this triggering system also records the time the flight mill arm takes to pass through each laser beam, from which the angular velocity of the flight mill can be found. This triggering system is shown below in Figure 12.
For this thesis, a frame rate of 4000 frames per second was used to capture a blue bottle fly’s flight path from a perspective directly below the center of mass of the insect. Finally, the camera needs as much light as possible to capture usable footage for later wing and body kinematic analysis. To achieve this, two LED back lights were positioned around the flight mill to generate as much light as possible. A picture of the set up used for data collection is shown below in Figure 13. The positioning of lights and cameras can be varied to achieve a clean set up with a different framing configuration. To extract the best possible wing kinematic data, three high speed cameras should be focused on the recording region. These three high speed cameras should be strategically positioned to capture multiple angles of the insect as it passes through the recording region. Three cameras will ensure there is never a time when visual access to a wing is blocked by the flight mill arm or the body of the insect.
2.7 Tethering Station

In order to tether the insect to the flight mill arm, a small carbon fiber rod is rigidly glued to the back of the insect. On the other end of the small carbon fiber rod is a small metallic bead that is attracted to magnetic surfaces. The carbon fiber rod and metallic ball is shown in Figure 14.
The carbon fiber rod has a diameter of 1.02 mm to reduce any interference with the natural flight of the insect. In order to consistently and carefully handle the tethering rod and the sedated insects, a tethering station was designed. The sedation process will be discussed in the next paragraph. The tethering station consists of a modified aluminum rod. The aluminum rod is wrapped with copper wire and a current is passed through the wire to make the rod magnetic. The magnetic rod can then be used to hold the small carbon fiber rod and metallic ball while adhesive is applied and a sedated insect is positioned under the end of the carbon fiber rod. The rod is then lowered, allowing the tethering rod to be carefully fixed to the center of the back of the insect above its center of gravity. When the adhesive has dried, the current in the copper wire coil is reduced to zero and the aluminum rod becomes nonmagnetic again, freeing the insect from the tethering station. Figure 15 shows that the carbon fiber tethering rod does not interfere with the wings of the blue bottle fly while it is flapping its wings.
Finally, the insect is magnetically fixed to the flight mill arm. The process previously described is shown in Figure 16, which depicts the tethering station used for harnessing the insects.
The tethering process is a major source of inconsistency for the results of the flight mill used in this thesis. More specifically, the sedation process used can be greatly improved. Several techniques were attempted to sedate the insects for an appropriate amount of time, without causing permanent damage to their flight sensory systems. One method included using a sedating solution, but it was almost impossible to consistently administer the same quantity of sedating solution, and each insect had a different duration of sedation time. This led to numerous insects becoming active before their harnessing rods were rigidly attached to them. The same problem occurred when a refrigeration technique was used. The insects were refrigerated until they became inactive, then they were removed from the fridge to be tethered. However, for the refrigeration technique, numerous trials resulted in insects becoming active before a rigid tether had been achieved resulting in poor alignment of body angle. For this reason, the tethering process used by the University of California, Los Angeles, in which the insects are tethered in a low temperature environment should be used. This low temperature environment combined with intricate positioning tooling allows researches to consistently align a tethering rod to the back of each sedated insect [48].
Chapter 3

Aerodynamic Loading Analysis

This chapter will present the three flight mill arms that have been designed to produce varying loads of aerodynamic drag for an insect as it propels itself in the flight mill. In addition, this chapter includes the analysis process for determining the respective aerodynamic loads produced by each of the flight mill arms.

3.1 Damping Analysis

The damping surfaces used are rigid thin rectangular plastic sheets cut to varying dimension to produce different drag loads. Each of the damping surfaces were cut to produce damping surfaces of areas that increase by a factor of two for each surface. In other words, the small sized damper has a theoretical area of $A_0$, the medium sized damper has a theoretical area of $2A_0$, and the large sized damper has a theoretical area of $4A_0$. The actual dimension of each damper can be found in the following sections pertaining to each of the respective dampers.

In order to ensure accurate estimations of the damping caused by each of the respective flight mill arms, each flight mill arm was sped up to a maximum speed using a hair dryer to propel the flight mill arm with no insect attached. Once the flight mill arms were rotating at a constant angular velocity, the hair dryer was removed and the flight mill arm speed was recorded using the laser timer system at half rotation intervals until the flight mill arm’s angular velocity became zero.
For a flight mill arm without an insect attached, the governing equation of motion is (3.1), seen below.

\[ I \dot{\omega} = -c \omega \]  

(3.1)

In (3.1), \( I \) represents the moment of inertia of the flight mill arm, \( \dot{\omega} \) represents the angular acceleration of the flight mill arm, \( c \) represents the damping coefficient acting on the flight mill arm, and \( \omega \) represents the angular velocity of the flight mill arm. This governing equation can be converted into an exponential decay equation, (3.2), in the following format.

\[ \omega(t) = \omega_0 e^{(-\frac{c}{I})t} \]  

(3.2)

The values for \( \omega_0 \) and the exponent \(-\frac{c}{I}\) were found by plotting the angular velocity of each flight mill after the hair dryer was removed from the flight mill and using an exponential curve fit. Each of these plots and respective equations can be found in the following section for each of the three dampers used. In addition, the \( I \) value for each flight arm is assumed to approximately the same. This assumption means that the exponents found in the respective damper calibration plots is directly proportional to the damping coefficient only.

The governing equation of the flight mill arm changes when an insect is attached and is propelling the flight mill arm. The equation changes by the addition of the variable \( Tr \), which represents the torque produced by the insect. This torque is the thrust force of the insect multiplied by the distance from the z-axis of the flight mill arm. The fly also contributes a small amount of drag to the system. However, as the dampers used in this research are much larger than the fly, this additional damping is assumed to be negligible resulting in a new governing equation, (4.1), seen below.

\[ I \dot{\omega} = Tr - c \omega \]  

(4.1)
For each experiment, it is assumed that the insect is flying at a constant angular velocity, and thus the angular acceleration of the flight mill arm is zero. With this assumption, (4.1) can be simplified and the thrust produced by the insect can be found from (5), seen below.

\[ T = \frac{c\omega}{r} \]  

(5)

From the angular velocity of the flight mill measured during testing, (5) can be used to determine the thrust force produced by the insect. This also makes it possible to make an estimation as to if the insect picks a flight speed based on optical flow or power output. With a constant wall pattern, if the angular velocity for each test does not change with each respective damper, it is likely that the insect picks a speed according to optical flow. The power produced by the insect can be found using (6), seen below.

\[ P = c\omega^2 \]  

(6)

From (6), the power produced by the insect while tethered to each damper can be found based on the flight mill angular velocity. If the angular velocity reduces due to the increasing drag coefficients, the insect may pick a flight speed based on constant power output. Each of the dampers and their experimentally determined equations of motion can be found in the following sections.

3.2 Small Damper

The small damper used has a surface area of 200 mm² and can be seen in a comparison picture with a penny in Figure 17. The small damper has a small D11-N42 magnet glued to its
trailing surface to allow for attaching addition weight to make sure the moment of inertia of this rod matches that of the heaviest flight mill arm.

![Figure 17: Small Damper Penny Comparison](image)

This flight mill arm was placed in the flight mill and driven to a constant angular velocity using a hair dryer. Once the hair dryer was removed, the angular velocity of the flight mill arm was measured during every half rotation of the flight mill arm. The decreasing angular velocities can be found in Table 1.

<table>
<thead>
<tr>
<th>Revolutions</th>
<th>Distance (rad)</th>
<th>Time (ms)</th>
<th>Ang Vel (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.366</td>
<td>55.143</td>
<td>6.641</td>
</tr>
<tr>
<td>1</td>
<td>0.366</td>
<td>69.100</td>
<td>5.300</td>
</tr>
<tr>
<td>1.5</td>
<td>0.366</td>
<td>81.636</td>
<td>4.486</td>
</tr>
<tr>
<td>2</td>
<td>0.366</td>
<td>107.167</td>
<td>3.417</td>
</tr>
<tr>
<td>2.5</td>
<td>0.366</td>
<td>125.438</td>
<td>2.919</td>
</tr>
<tr>
<td>3</td>
<td>0.366</td>
<td>161.250</td>
<td>2.271</td>
</tr>
<tr>
<td>3.5</td>
<td>0.366</td>
<td>189.550</td>
<td>1.932</td>
</tr>
<tr>
<td>4</td>
<td>0.366</td>
<td>247.926</td>
<td>1.477</td>
</tr>
<tr>
<td>4.5</td>
<td>0.366</td>
<td>294.355</td>
<td>1.244</td>
</tr>
<tr>
<td>5</td>
<td>0.366</td>
<td>455.043</td>
<td>0.805</td>
</tr>
<tr>
<td>5.5</td>
<td>0.366</td>
<td>628.619</td>
<td>0.583</td>
</tr>
</tbody>
</table>
This data was plotted and an exponential curve was fit to the data. The plot of angular velocity as a function of revolutions is shown in Figure 18. The curve fit produced an exponent of 0.466, which corresponds to a damping coefficient of 7.32e-7 kgm²/s with a correlation coefficient of 0.9876. From this correlation coefficient, the experimentally determined damping is a statistically acceptable approximation for the flight mill arm with the small damper.

![Small Damper Calibration Curve](image)

**Figure 18. Small Damper Calibration Curve**

### 3.3 Medium Damper

The medium damper used has a surface area of 400 mm² and can be seen in a comparison picture with a penny in Figure 19. The medium damper also has a small D11-N42 magnet glued to its trailing surface to allow for attaching addition weight to make sure the rotational moment of inertia of this rod matches that of the heaviest flight mill arm.
This flight mill arm was placed in the flight mill and driven to a constant angular velocity using a hair dryer. Once the hair dryer was removed, the angular velocity of the flight mill arm was measured during every half rotation of the flight mill arm. The decreasing angular velocities can be found in Table 2.

Table 2: Medium Damper Calibration Data

<table>
<thead>
<tr>
<th>Revolutions</th>
<th>Distance (rad)</th>
<th>Time (ms)</th>
<th>Ang Vel (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.366</td>
<td>55.625</td>
<td>6.583</td>
</tr>
<tr>
<td>1</td>
<td>0.366</td>
<td>67.667</td>
<td>5.412</td>
</tr>
<tr>
<td>1.5</td>
<td>0.366</td>
<td>92.385</td>
<td>3.964</td>
</tr>
<tr>
<td>2</td>
<td>0.366</td>
<td>113.133</td>
<td>3.237</td>
</tr>
<tr>
<td>2.5</td>
<td>0.366</td>
<td>170.550</td>
<td>2.147</td>
</tr>
<tr>
<td>3</td>
<td>0.366</td>
<td>214.200</td>
<td>1.710</td>
</tr>
<tr>
<td>3.5</td>
<td>0.366</td>
<td>299.394</td>
<td>1.223</td>
</tr>
<tr>
<td>4</td>
<td>0.366</td>
<td>491.440</td>
<td>0.745</td>
</tr>
</tbody>
</table>

This data was plotted and an exponential curve was fit to the data. The plot of angular velocity as a function of revolutions is shown in Figure 20. The curve fit produced an exponent of 0.610, which corresponds to a damping coefficient of 9.58e-7 kgm²/s with a correlation coefficient
of 0.9874. From this correlation coefficient, the experimentally determined damping is a statistically acceptable approximation for the flight mill arm with the medium damper.

![Medium Damper Calibration Curve](image)

**Figure 20: Medium Damper Calibration Curve**

### 3.4 Large Damper

The large damper used has a surface area of 800 mm² and can be seen in a comparison picture with a penny in Figure 21. The large damper is the heaviest of the three damping surfaces, and therefore does no need additional weight to match the other flight mill arms use for testing.
This flight mill arm was placed in the flight mill and driven to a constant angular velocity using a hair dryer. Once the hair dryer was removed, the angular velocity of the flight mill arm was measured during every half rotation of the flight mill arm. The decreasing angular velocities can be found in Table 3.

Table 3: Large Damper Calibration Data

<table>
<thead>
<tr>
<th>Revolutions</th>
<th>Distance (rad)</th>
<th>Time (ms)</th>
<th>Ang Vel (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.366</td>
<td>62.900</td>
<td>5.822</td>
</tr>
<tr>
<td>1.0</td>
<td>0.366</td>
<td>81.091</td>
<td>4.516</td>
</tr>
<tr>
<td>1.5</td>
<td>0.366</td>
<td>137.778</td>
<td>2.658</td>
</tr>
<tr>
<td>2.0</td>
<td>0.366</td>
<td>175.480</td>
<td>2.087</td>
</tr>
<tr>
<td>2.5</td>
<td>0.366</td>
<td>306.968</td>
<td>1.193</td>
</tr>
<tr>
<td>3.0</td>
<td>0.366</td>
<td>527.714</td>
<td>0.694</td>
</tr>
<tr>
<td>3.5</td>
<td>0.366</td>
<td>1035.126</td>
<td>0.354</td>
</tr>
</tbody>
</table>

This data was plotted and an exponential curve was fit to the data. The plot of angular velocity as a function of revolutions is shown in Figure 22. The curve fit produced an exponent of 0.925, which corresponds to a damping coefficient of 1.45e-6 kgm²/s with a correlation coefficient
of 0.9812. From this correlation coefficient, the experimentally determined damping is a statistically acceptable approximation for the flight mill arm with the medium damper.

![Figure 22: Large Damper Calibration Curve](image)

**y = 10.873e^{-0.925x}
R^2 = 0.9812**

### 3.5 Summary of Damping Analysis

In summary, the damping coefficients increased with increasing damper surface area. These experimentally determined damping coefficients can be used to analyze how the insect’s forward flight speed changes with varying aerodynamic loads. A summary of the damper cross sectional areas and damping coefficients can be found in Table 4.

<table>
<thead>
<tr>
<th>Damper</th>
<th>Cross Sectional Area (mm$^2$)</th>
<th>Damping Coefficient (kgm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Damper</td>
<td>200</td>
<td>7.32e-7</td>
</tr>
<tr>
<td>Medium Damper</td>
<td>400</td>
<td>9.58e-7</td>
</tr>
<tr>
<td>Large Damper</td>
<td>800</td>
<td>1.45e-6</td>
</tr>
</tbody>
</table>
Chapter 4
Data Analysis

In the following chapter, the data captured using the previously described insect flight mill will be present and analyzed. The following data was captured for a blue bottle fly while flying with the three varying aerodynamic loads and a constant flight mill wall pattern. The data consists of figures of wingbeat patterns of the blue bottle fly, the forward flight speeds of the blue bottle fly, and the wingbeat frequencies of the blue bottle fly while subjected to each aerodynamic load. From this information, the thrust and power generated by the blue bottle fly will be analyzed. The blue bottle fly was tethered to the large damper aerodynamic load first, the medium damper aerodynamic load second, and lastly to the small damper aerodynamic load. This sequence of loading was used to prevent the fly from becoming fatigued. More specifically, in previous trials, when a fly was subjected to increasing aerodynamic loads, the fly was less likely to fly as the load increased. The following data is for one blue bottle fly to show the capabilities of this iteration of the magnetically levitated flight mill and to draw some initial conclusions about the forward flight speed control of the fly during varying aerodynamic loading.

4.1 Small Damper Flight Result

The blue bottle fly achieved a maximum flight speed while tethered to the small damper aerodynamic load. The fly achieved a velocity of 0.39 m/s, which corresponds to a flight mill angular velocity of 2.9 radians/s. Using the analysis presented in section 3.1, this forward flight
speed combined with the damping coefficient of the small damper flight mill arm found in section 3.2, means that the fly produced a thrust force of $2.16 \times 10^{-6}$ N and a power of $6.18 \times 10^{-6}$ W. In addition, the fly maintained a wingbeat frequency of 149 Hz. The wing beat pattern for the fly while attached to the small damper aerodynamic load is shown below in Figure 23.

![Figure 23: Small Damper Wing Beat Captures](image)

**4.2 Medium Damper Flight Results**

While tethered to the medium damper aerodynamic load, the blue bottle fly achieved a velocity of 0.28 m/s which corresponds to a flight mill angular velocity of 2.1 radians/s. Using the analysis presented in section 3.1, this forward flight speed combined with the damping coefficient of the medium damper flight mill arm found in section 3.3, means that the fly produced a thrust force of $1.98 \times 10^{-6}$ N and a power of $4.10 \times 10^{-6}$ W. In addition, the fly maintained a wingbeat frequency of 141 Hz. The wing beat pattern for the fly while attached to the medium damper aerodynamic load is shown in Figure 24.
4.3 Large Damper Flight Results

The forward flight speed of the blue bottle fly was at a minimum while tethered to the large damper aerodynamic load. The blue bottle fly achieved a velocity of 0.22 m/s, which corresponds to a flight mill angular velocity of 1.6 radians/s. Using the analysis presented in section 3.1, this forward flight speed combined with the damping coefficient of the large damper flight mill arm found in section 3.4, means that the fly produced a thrust force of 2.33e-6 N and a power of 3.75e-6 W. In addition, the fly maintained a wingbeat frequency of 115 Hz. The wing beat pattern for the fly while attached to the large damper aerodynamic load is shown in Figure 25.
4.4 Data Analysis

Table 5: Blue Bottle Fly Flight Mill Data

<table>
<thead>
<tr>
<th>Damper Size</th>
<th>Damping (kgm²/s)</th>
<th>Angular Velocity (rad/s)</th>
<th>Velocity (m/s)</th>
<th>Wingbeat Frequency (Hz)</th>
<th>Thrust (N)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>7.32E-07</td>
<td>2.9063</td>
<td>0.3886</td>
<td>149.07</td>
<td>2.126E-06</td>
<td>6.180E-06</td>
</tr>
<tr>
<td>Medium</td>
<td>9.58E-07</td>
<td>2.0691</td>
<td>0.2768</td>
<td>140.85</td>
<td>1.982E-06</td>
<td>4.100E-06</td>
</tr>
<tr>
<td>Large</td>
<td>1.45E-06</td>
<td>1.6063</td>
<td>0.2151</td>
<td>115.27</td>
<td>2.333E-06</td>
<td>3.747E-06</td>
</tr>
</tbody>
</table>

The flight mill data collected is summarized above in Table 5. The data contains several interesting trends. The velocity of the blue bottle fly decreased dramatically with increasing aerodynamic load. The forward flight speed of the fly reduced by almost a factor of two from the small damper aerodynamic load to the large damper aerodynamic load. This large change in forward flight velocity directly contradicts the hypothesis that this flight mill will test more rigorously in the future. This hypothesis stems from findings that fruit flies and honeybees determine a forward flight speed based on optical flow instead of power requirements, however the large change in forward flight speed for the blue bottle fly found here suggest this hypothesis may prove to be incorrect for the blue bottle fly with a larger sample of data.
The next important trend is the reduction in wingbeat frequency with increasing aerodynamic loading. This change in wingbeat frequency suggests that the blue bottle fly is able to change the signal sent to its flight muscles. This change in wingbeat frequency may likely be attributed to reduced forward flight speed, and thus a proportionally reduced optical flow. In other words, the fly may change its wingbeat frequency based on the optical flow it is experiencing. Another possible explanation of this change in wingbeat frequency is that the fly is compensating for the larger aerodynamic load. The reduced wingbeat frequency could be attributed to an aerodynamic load that is beyond the muscle capabilities of the fly.

The thrust force of the blue bottle fly remained approximately constant for all aerodynamic loads. This is an extremely interesting finding, as the thrust force does not follow the trends of the other forward flight parameters. More specifically, the constant thrust force produced for each aerodynamic load implies that the blue bottle fly controls its forward flight speed based on a constant thrust force instead of optical flow or power regulation. Slight variations in the thrust force between each aerodynamic load likely resulted from inconsistencies in this iteration of the insect flight mill. Justification that the thrust force is a potential deciding factor for forward flight speed is that the slight variations in thrust force do not follow any other trends found in forward flight velocity, wingbeat frequency, or power requirement.

Finally, the power produced by the blue bottle fly follows a similar trend to that of forward flight velocity and wingbeat frequency. The power produced by the blue bottle fly decreased as aerodynamic load increased. This result may be another suggestion that the blue bottle fly does not use optical flow to determine a forward flight speed. This decreasing trend for power production also counters the hypothesis that forward flight speed is chosen based on a constant
power output. Variations in power output should be analyzed more rigorously with a larger sample of data gathered using future iterations of this insect flight mill.
Chapter 5

Conclusion

Researching the complex flight systems of insects at miniature scale from system and control perspectives has the potential to inspire designs in robotics and control systems of the future. Gaining a better understanding of these highly stable, maneuverable and arguably energy efficient flying machines and how these flying machines interact with nature will be a key factor in developing future generations of unparalleled biomimetic robots with greater adaptability and maneuverability in complex and unstructured environments. Insects are able to achieve unprecedented flight maneuverability and stability in highly dynamic and uncertain environments. This unique flight ability is made possible due to the intricate control of flapping wing motion and the use of unsteady aerodynamics through fast coordination of neural sensing, control, and muscular actuation systems.

The goal of this thesis was to contribute to the overarching goal of researchers in the field of insect flight, which is to gain a better understanding of these complex flying machines. More specifically, the goal of this thesis was to develop the foundation for a systematic method for testing the forward flight speed control of insects. To this end, a novel magnetically levitated flight mill was designed and tested to show the potential ability of this tool in gaining a better understanding of insect forward flight speed control.

The data presented in this thesis contains many interesting trends regarding insect forward flight speed control. Though the sample of data is small, the data collected for the blue bottle fly
directly contradicts forward flight speed control hypotheses that have been developed for other insect flying machines such as the fruit fly and honeybee. More specifically, the approximately constant value of thrust for varying aerodynamic loading presents a trend that has not previously been explored. In future iterations of the insect flight mill, researches will be able to systematically test these hypotheses and draw conclusions regarding the forward flight speed control of insects. The novel magnetically levitated insect flight mill developed throughout the course of this research shows that future iterations of this flight mill system will be a powerful platform for analyzing the forward flight speed control of insects.
Appendix A

Arduino Code

A.1 Introduction

The following codes were used for magnetic levitation and laser timer and camera trigger purposes. The code for the magnetic levitation is a simplified version of example code from an Arduino Forum on the topic of magnetic levitation [49, 50]. The code is tailored to use PD control with a Hall effect sensor to levitate a permanent magnet. Several lines of code were added to make the system more stable. Specifically, a running average was added to the code to help reduce effects of noise due to saturation from the Hall effect sensor. Code for the laser timer and camera triggering system can be used for capturing more consistent video footage. The following codes must be adjusted to work with varying physical components and electric circuits.

A.2 Magnetic Levitation

//Single Coil Mag Lev with Hall Effect Sensor
const int TOP_COIL_PIN = 11;
const int HALL_EFFECT_SENSOR_PIN = 0;
const int LED_INDICATOR_PIN = 13;
const int COIL_MAX_VALUE = 255;
const int PWM_BIAS = 135;
const int SET_POINT = 710; //distance from Hall effect sensor
const int ERR_INTEGRAL = 10000;
const int TOP_COIL_IDLE = 0;
const int MIN_CONTROL_RANGE = 610;
const int MAX_CONTROL_RANGE = 800;

//PID Controller Values
const float pGain = 2.0;
const float dGain = 10;
const float iGain = 0.0;

int TOP_COIL_PWM_COMMAND;
int CUR_HE_VALUE;
int PREV_HE_VALUE;
int COMMAND;
#include <RunningMedian.h>

RunningMedian samples = RunningMedian(50);

void setupCoilPWM()
{
    // Setup the timer 2 as Phase Correct PWM, 3921 Hz.
    pinMode(TOP_COIL_PIN, OUTPUT);
    // Timer 2 register: WGM20 sets PWM phase correct mode, COM2x1 sets the PWM out to channels A and B.
    TCCR2A = 0;
    TCCR2A = _BV(COM2A1) | _BV(COM2B1) | _BV(WGM20);
    // Set the prescaler to 8, the PWM freq is 16Mhz/255/2/prescaler
    TCCR2B = 0;
    TCCR2B = _BV(CS21);
}

void setup()
{
    setupCoilPWM();
    // put your setup code here, to run once:
    Serial.begin(115200);
    pinMode(HALL_EFFECT_SENSOR_PIN, INPUT);
    pinMode(LED_INDICATOR_PIN, OUTPUT);
    pinMode(TOP_COIL_PIN, OUTPUT);
}

void loop()
{
    int SET_POINT_DELTA;
    int LAST_READING_DELTA;
    CUR_HE_VALUE = analogRead(HALL_EFFECT_SENSOR_PIN);
    if (CUR_HE_VALUE > MIN_CONTROL_RANGE && CUR_HE_VALUE < MAX_CONTROL_RANGE)
    {
        Serial.print(CUR_HE_VALUE);
        Serial.print(" , ");
        digitalWrite(LED_INDICATOR_PIN, HIGH);
        SET_POINT_DELTA = (SET_POINT - CUR_HE_VALUE);
        LAST_READING_DELTA = (PREV_HE_VALUE - CUR_HE_VALUE);
        COMMAND = PWM_BIAS + (int)(pGain*SET_POINT_DELTA) +
        (int)(dGain*LAST_READING_DELTA);
        TOP_COIL_PWM_COMMAND = constrain(COMMAND, 0, COIL_MAX_VALUE);

        analogWrite(TOP_COIL_PIN, TOP_COIL_PWM_COMMAND);
        Serial.println(TOP_COIL_PWM_COMMAND);
        //Running Average
        {          
            int CUR_HE_VALUE = analogRead(HALL_EFFECT_SENSOR_PIN);
            samples.add(CUR_HE_VALUE);
            long AVERAGE = samples.getAverage();
            PREV_HE_VALUE = AVERAGE;
        }
    }
    else
    {          
        digitalWrite(LED_INDICATOR_PIN, LOW);
        TOP_COIL_PWM_COMMAND = TOP_COIL_IDLE;
    }
}
A.3 Laser Timer and Camera Triggering

//Laser Timer and Camera Trigger
const int ON_CAMERA_PIN = 2;
const int OFF_CAMERA_PIN = 3;
const int ON_VALUE = 85;
const int OFF_VALUE = 95;
const int LED_CAMERA = 4;

int START_TIME;
int STOP_TIME;
int CAPTURE_TIME;

void setup() {
    Serial.begin(115200);
    pinMode(LED_CAMERA, OUTPUT);
}

void LaserTrip() {
    int CameraOn = analogRead(ON_CAMERA_PIN);
    if (CameraOn > ON_VALUE)
    {
        digitalWrite(LED_CAMERA, HIGH);
        START_TIME = millis();
    }
    int CameraOff = analogRead(OFF_CAMERA_PIN);
    if (CameraOff > OFF_VALUE)
    {
        digitalWrite(LED_CAMERA, LOW);
        //STOP_TIME = 0;
        STOP_TIME = millis();
        CAPTURE_TIME = (STOP_TIME - START_TIME);
        Serial.println(CAPTURE_TIME);
    }
}

void loop() {
    LaserTrip();
}
Appendix B

Circuit Components

Magnetic Levitation

TEKPOWER PP-3003D-3 0-30V/0-3A
Arduino UNO R3
Solder-less Breadboard (84X54X9mm)
A1326 Linear Hall Effect Sensor
XRN-XP 18kg 12VDC Magnetic Coil
10 kΩ and 22 kΩ Resistors
470 nF Ceramic Capacitor
iN 4007 Diode
TIP31C 6054 A-126X10 Transistor

Camera Triggering

Photoresistors
Lasers
10 kΩ Resistors
FASTCAM Mini UX100 800K-M-16G8


Academic Vita

EDUCATION

The Pennsylvania State University

Graduation: May 2016
Bachelor of Science in Mechanical Engineering
Schreyer Honors College

The University of Cape Town

Study Abroad 2015

WORK EXPERIENCE

The Boeing Company – North Charleston, SC

June – Aug 2015
• Design Engineering – Recurring Structural Design (EAHI)
• 787 Dreamliner engineering change creation and implementation
• Composite handling and machining defect control and correction
• Material interaction to improve structural integrity and corrosion resistance

L.F. Driscoll Co., LLC – Philadelphia, PA

May – Aug 2014
• Project Management and Construction Management
• Building Information Modeling
• RFID tracking and Tableau Software implementation
• Comcast Innovation and Technology Center – 8th Tallest building in the US

Penn State Math Department – State College, PA

Sept 2013 – Aug 2014
• Calculus Learning Assistant for Differential Equations, Integrals, and Series

Aquatic Marine Limited – Philadelphia, PA

May 2012
• Marine Engineering custom boat design and build process
• TIG welding aluminum electric winch platform design project

RESEARCH

• Locomotion Biomechanics and Control Lab
• Aerial locomotion and biologically inspired micro air vehicles
• Flight systems of insects and birds

SKILLS

• Public Speaking
• Computer Aided Design - CATIA and SOLIDWORKS
• Data Analysis – EXCEL and TABLEAU
• Welding: MIG, TIG, and SMAW
• Programming: FORTRAN, MATLAB, and PYTHON

LEADERSHIP, COMMUNITY SERVICE, AWARDS

• TeachOUT – Academic Assistance for Disadvantaged South African Students
• Executive Board and Judicial Board – ATΩ – America’s Leadership Development Fraternity
• Penn State IFC/Panhellic Dance Marathon – Leading Greek Organization – $375,000 raised each year
• Penn State Varsity Club Squash – Vice President
• President’s Freshman Award – Pennsylvania State University
• Graduated Cum Laude with High Honors from Chestnut Hill Academy