DEVELOPMENT OF A LOW-COST THREE-AXIS ANEMOMETER FOR ANALYSIS OF VARIOUS WIND PHENOMENA

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John M. Hirano
I dedicate this to my Father, who is no longer with us. He is the one who pushed me to be the very best that I could be, even beyond what I could see or believe.
ACKNOWLEDGMENTS

The journey to completion of this dissertation has been long and trying. I do not believe I would have made it here without the guidance and faith of my lead adviser, Dr. David Garmire. He provided me the opportunity to research a wide breath of topic and use it to find a topic to dive into for this dissertation. There is also the Renewable Energy and Island Sustainability group, under the leadership of Dr. Anthony Kuh, who provided the means for my research and allowed me to devote my time to the University. There is also I would like to also thank my committee, whose guidance has allowed me to expedite the completion of my research and dissertation. In addition, I thank my family for supporting me through my journey and especially through the completion of this dissertation. They allowed me to spend the past season of my life, spending late nights in the lab, long hours writing, and countless days away from them. I would also like to thank Jaclyn, for having the faith in me to finish my dissertation and the love to keep pushing through the hard times.
Distributed three-axis anemometers are needed for high spatial resolution networks to understand the flow of wind for the study of various phenomena. In order to achieve high spatial coverage, the cost of each three-axis anemometer must be reduced while maintaining accuracy and durability. I achieved a low-cost three-axis anemometer by implementing guided-parallel beam structures and incorporating infrared (IR) sensor technology. The sensor can measure wind speeds over 100 mph with an accuracy under 0.2 mph while costing a fraction of existing commercial anemometer prices.

Three parallel beam structures are oriented and designed to decompose the wind force along each axis and eliminate cross-coupling between each axis. The IR sensor pair converts the physical displacement to a voltage to determine the velocity of the wind. The initial prototypes showed the concept to be favorable and led to further design iterations. Through the emergence of 3D printing and in-house printed circuit board (PCB) milling, I transitioned to a faster design-build-test methodology. This thesis details several of the challenges I encountered during this process.

One such challenge was the openly exposed IR phototransistor which caused misreading due to its exposure to external infrared light sources. This challenge was addressed through the profiling of the IR sensors and evaluating methods for mitigating the effects of external interference. The findings of the IR profiling and subsequent research led to the development of a new force transducer to convert the displacement of the parallel suspensions to a force measurement. The force transducer uses principles of total internal reflection and frustrated total internal reflection to measure the amount of force applied to the transducer. The force transducer was fabricated using polydimethylsiloxane (PDMS) as the material for the optical waveguide. The optically-based force transducer performs with similar characteristics as available force sensors and can be implemented into a low-cost three-axis anemometer. The research has led to the development of technology that can be implemented in a variety of situations to measure fluid flow.
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CHAPTER 1
INTRODUCTION

Over the past 20 years, we have seen an increase in electricity consumption of nearly 12%, requiring a greater need for energy generation. During this period, there has been an increase in renewable energy installations into the nation’s power portfolio. The fastest growing of these sectors is wind generation with a growth of 300% over the past 5 years [1]. The majority of this energy is being generated via large scale wind farms, but there is a growing sector of urban distributed wind generation, which takes advantage of a phenomenon called architectural wind. The common method of studying this phenomenon is through numerical models which can help to understand the flow of the wind, but does not lead to actual wind measurements. It is our interest to acquire real-time wind measurements near and around buildings to develop models that will help us to better understand architectural wind and to create a return of investment model for various distributed wind generation installation. To achieve this type of study, we needed to find an anemometer, wind sensor, that will measure wind in a three dimensional vector, allowing for measurements of winds traveling up a building, as well as having a low cost point, making it possible to implement a large number of sensors over a given area.

1.1 Current Anemometer Technology

Our initial investigation into an anemometer that would meet our requirements lead us to the following technologies and conclusions about each. We have found that the current landscape of anemometers have not changed significantly over the last thirty years. The market is primarily saturated with three primary technologies: cups, propellers, and ultrasonic anemometers. The following subsections will describe each of these technologies, how they are implemented, and their shortcomings.
1.1.1 Cup Anemometers

Cup anemometry is one of the more commonly used technologies in measuring wind speed. The device often consists of three cups equally spaced around a single vertical rod. The wind velocity is determined by converting the measured revolutions per second to a chosen unit of velocity, such as miles per hour. Alone, cup anemometers are not able to determine the direction of the wind which is why they are often paired with a wind vane. The cups have an even response with respect to planar winds, but suffer from a cosine response to winds with a vertical incident angle off the normal axis of the face of the cups [2]. Another shortcoming of the technology is due to its mechanical design; the anemometer will often output higher wind speeds during gusty conditions. This fact is due to the ability of the cup anemometer’s to rapidly respond to increases in wind speed, but not to slow down at the same rate as the wind [3]. There are no implementations of cup anemometers for three-axis wind measurements.

1.1.2 Propeller Anemometers

The propeller anemometer has gone through various blade designs, but most modern devices use a four helicoid blade design [3]. The propeller anemometers operate under similar principles as the cup anemometers, but is more sensitive to winds traveling normal to the face of the device. They are often paired and mounted onto a wind vane which allows the the face of the propeller to stay perpendicular to the direction of the wind. The non-linear response to the direction of the wind in relation to the normal axis of the face of the propeller can be approximated initially as $\cos(\theta)$ and $\cos^{1/2}(\theta)$ as the angle approaches 90 degrees.

Compared to cup anemometers, propeller anemometers can be oriented to measure wind along all three axes. A three-axis propeller anemometer places three propellers perpendicular to each other, two along the planar axis and one in the vertical axis. Each of the propellers cause a turbulent wind stream as they move due to the wind, this wind stream can distort the reading of the other propellers if they are caught in the wind stream. To reduce this affect each of the three propellers need to be positioned a few feet from the others [4]. This causes the overall structure of the device to be large in size, creating challenges with installation and placement. Another
downside of the device is the coupling that will occur between each of the propeller due to their individual cosine response. In addition the vertical axis, suffers from a greater amount of bearing friction, which causes a slower response to the wind and a decrease in lifespan due to deterioration.

1.1.3 Ultrasonic Anemometers

Ultrasonic anemometers measure wind speeds by measuring the time it takes for a sonic pulse to be transmitted back and forth along a single axis. The device uses the difference in time to calculate the speed of the wind traveling along that axis. This approach allows for easy decoupling of the wind with the use of a pair of ultrasonic sensors along each of the three axes. The difficulty of this technology is its reliability on high precision installations due to its sensitivity to misalignment. They can also suffer from interference due to the accumulation of dust, ice, or other weather elements on the sensors. This technology has a higher price than the other technologies which makes the cost for high-spatial resolution network not feasible with these sensors.

1.2 Conclusion

We have examined three of the current anemometer technologies available on the market today. Each anemometer comes with its own benefits and shortcomings. The cup anemometer has a great response to planar winds, but does not provide an available method to measure the vertical component of the wind, which is particularly important when studying architectural wind. The propeller anemometers are able to gather measurements along all three axes, but requires a large spacial footprint and can create its own turbulence to distort measurements [4]. The ultrasonic anemometers have a smaller footprint than the three-axis propeller anemometers with a higher precision, but it comes with a higher price point which limits the spacial resolution based on the project budget. Based on these findings, we decided to develop our own low-cost three-axis anemometer for the purpose of studying architectural wind and distributed wind generation systems.
CHAPTER 2
LOW-COST THREE-AXIS ANEMOMETER

2.1 Introduction

This chapter will discuss the implementations of a low-cost three-axis anemometer. These possible areas of application include, but are not limited to the study of distributed wind energy generation, architectural winds in urban areas, use in assisting with the stabilization of power grids through large-scale wind farm predictive models, increasing airport safety with predictive models for wind shear events, and personal hand-held units. This chapter will also include a breakdown in the development of the low-cost three-axis anemometer. It will discuss the journey from a proof of concept design through the miniaturizing of the design and finally to a fourth prototype. Much of the findings and testing for this chapter were first published in Sensors and Transducer Journal [5].

2.2 Application of Low-cost Three-axis Anemometer

As mentioned in the previous chapter, many of the modern devices offer reliable one to two-axis measurements for a low-cost, but the cost for a three-axis anemometer is not conducive to a high-spatial resolution data acquisition network. The three-axis anemometers are essential to our models due to the vertical component of the architectural wind. The areas of application include the development of predictive models for the study of architectural wind and small-scale distributed wind generation. Also real-time predictive models of large-scale wind farms to assist with the stabilization of the power grid and for wind shear prediction to increase airport safety. In addition the technology can be used to design a three-axis handheld anemometer.

2.2.1 Distributed Wind Energy Generation and Architectural Wind

The growth of distributed wind energy generation is not isolated to rural communities, but have expanded in the urban space. [6] This new area of growth is accompanied by the development of special wind turbines that harvest the energy of the wind traveling parallel to the surface of the earth
at high altitudes and the energy of architectural wind. The term "architectural wind" refers to the wind generated due to the natural channeling created by the topology of a building [7] [8]. These turbines are designed to take advantage of the accelerated wind speeds in the vertical direction created by this phenomena. The use of a low-cost three-axis anemometer in multiple point data network will allow for the generation of real-time models for architectural wind that take into account actual wind measurements. These models can be used to create better architectural wind turbines that can be applied in both urban and residential environments [9] [10]. The data should be measured at a high-frequency to reduce the effects of turbulence in the air [11]. This data can be combined with existing numerical models to predict energy generation potential and conduct feasibility studies.

2.2.2 Large-scale Wind Farms and Grid Stabilization

The continued increase in the development of large-scale renewable energy generation farms creates a challenge of power companies. A primary concern is the power company’s ability to maintain the quality of their power output. In the United States of America, this quality refers to the ability to deliver a constant 120/240 volts at 60 Hz. This was accomplished by traditional power plants through large turbines being fed with either a type of fossil fuel, natural gas, coal, or other combustible. These generators were able to output power at a constant rate, helping to maintain the power quality. In contrast, renewable energy sources can vary their output greatly over the span of hours or even minutes [12]. This variability in energy output creates a challenge to the stabilization of the overall power grid. Therefore, as the percentage of the renewable energy generation on a power grid increases the effects of the variation in power output will increase, causing more instability. To compensate for these changes in energy production, power companies will run traditional fossil fuel turbines to assist in power production. This method is currently the most effective to compensate for changes from minute to minute and the changes from hour to hour, but not as much in the intermediary range. The reason that intermediate changes are such a challenge is due to the start up time for the larger turbines currently being used by power companies. Of all of the renewable energy sources, wind generation has some of the most variability
in power output [13] [14].

The need for grid stabilization is one of the biggest priorities for the power company, as well as consumers who use it. The use of a low-cost three-axis anemometer array and predictive models in conjunction with the current stabilization methods can increase the stabilization of the grid. The sensors can be deployed in a high spatial resolution network, surrounding a wind farm installation, for data acquisition. This data in conjunction with wind and power predictive algorithms will give the power company’s controller more information sooner allowing them to make decisions that are proactive rather than reactive. Since these sensors have a lower price point, it will allow for the data network to have a higher density of information and create better predictive models based on the land’s topology surrounding the farm.

2.2.3 Wind Sheer Events at Airports

In August of 1985, Delta Airlines Flight 191 was on approach to Dallas-Fort Worth International Airport when it experienced a wind shear event, causing the airplane to crash. The accident caused 8 crew members and 126 passengers to die [15]. During a wind shear event, the aircraft experiences a strong headwind, slowing the plane down and pushing the noise up, which causes the pilot to react by pushing the noise down and increasing the engines. During a wind shear event, the headwinds are followed by a downdraft and tailwind. This causes the aircraft to increase in velocity and pushes the nose of the plane into a further downward position [16]. This combination of events is what caused Flight 191 to crash approximately 6,300 feet north of its original runway and causing fatalities [15]. This event was the catalyst to the research in determining and predicting wind shear for the purpose of preventing further accidents. The current implementation of wind sheer detection are located on the aircraft. These on board systems alert the pilot if a wind shear event is occurring, but not if the environmental factors will cause wind shear. This means that the plane and the passengers will experience the turbulence involved with such a meteorological event. But with an implementation of the three-axis anemometers around the air field, similar to that of the large scale wind farms, pilots and air traffic controllers may be able to have a proactive rather than reactive response to wind shear. The data network created by these sensors can allow for more data
to be inputted into predictive models to help predict when wind shear events may occur. This will allow for the air traffic controller to divert or delay incoming flights to avoid possibly dangerous situations.

2.2.4 Handheld Anemometer

The most common off the shelf hand-held anemometer technology is the propeller anemometer. Just like other propeller anemometers, they require the face of the device to be facing the on coming wind to get an accurate measurement. This requires the user to hold the sensor up and turn until the unit outputs the highest measurement. This becomes more difficult when the wind is gusty or if the wind speed is changing rapidly. Most of these sensors do not contain a compass function, so it then requires the user to take out a compass and then measure the direction of the wind. These two shortcomings make site evaluations both time consuming and less accurate [5]. This market is ripe for an alternative three-axis anemometer. By combining our three-axis anemometer and a digital compass, a handheld anemometer can be designed. This new design would allow the user to just hold the device in the air or have it attached to a pole/tripod to reduce user error. The display for these units would be able to output the direction and velocity of the wind in reference to the position of the user. For a simplified design, the hand held unit can eliminate the third axis, the vertical axis, from the design and just measure the planar wind speed and direction.

2.3 Device Theory

The low-cost three-axis anemometer uses the principles of mass-spring physics and infrared distance sensors. The conceptual design looks to determine the velocity of the wind by looking at the force it applied to device. The device will have a proof mass that will eventually surround the spring structure, with inherent spring constant, $K$, and an infrared system. This sensing element will have a physical mass, $M$, and a drag coefficient, $D$, which is linearly dependent to the velocity of the wind for low Reynolds number (ratio of inertial forces to viscous forces). It will also have a spherical shape and surround the internal structure and electronics. The overall size of the sensing element will have to be small to reduce its Reynolds number and resultant turbulence.
2.3.1 Parallel-guided Suspension

The internal spring structure will consist of a three-stage parallel-guided suspension designed to decouple the wind velocity vector into each of its three components. Each of the stages are designed to have the same stiffness in each of the three axes. This is intended to increase the rotational stiffness of the structure, (see appendix for equations). Due to the properties of a parallel-guided suspension, the wind energy will be decoupled as each set of beams are only allowed to move along its axis. Based on the manufacturing restraints, the width, length, and thickness of the beams can be adjusted to optimize the deflection and resonant frequency for the best signal-to-noise ratio [17]. The three-stage parallel-guided suspension is designed to have approximately the same stiffness in all three directions and high rotational stiffness. For a parallel-guided suspension, the stiffness, K, can be described by the formula:

\[ K = 2w(t/L)^3E \]

Where t, w, and L are the thickness, width, and length of each beam in the suspension and E is the Young's Modulus of the material (roughly 2.3GPa for plastic).

2.3.2 Infrared Sensors

The displacement along each axis is measured using an infrared (IR) sensor pair. Each pair consists of an IR emitter which outputs an IR light, and an IR phototransistor used to detect IR light and varies the amount of current allowed through the transistor based on the IR intensity. Paired together, the emitter and phototransistor will help to determine the displacement of the suspension system. For each of the three axes, an IR sensor pair will independently measure the displacement of the suspension along the axis. The device then uses the data to determine the wind speed along each axis.

2.4 Prototype I: Proof of Concept

Prior to Prototype I, we attempted a variety of different approaches to the spring suspension system. The approaches included the use of off-the-shelf springs to fabricated springs, to the use of fiber
optics as suspensions. This section discusses the first working prototype, which was labeled the proof of concept, as it verified many of the predictions we had about a mass-spring and IR-based three-axis anemometer.

2.4.1 Design

The design of Prototype I has taken cues from the many mistrials that came before it. The key technology that was adapted was the use of parallel-guided suspensions and the IR sensors for measuring displacement. Prototype I, see Figure 2.1, can be separated into three parts: the proof mass, the center structure, and the base. Much of the construction for the proof of concept used material readily available in our lab space. This allowed for a very low-priced mock up and a device that we were able to test.

The initial proof mass was a block of soft Styrofoam in the shape of a cube shape because it allowed for the most amount of force to be applied along each axis. The Styrofoam is also a light weight material that minimized its affects on the base structure. The center structure was

![Figure 2.1: The shows the construction of Prototype I, the proof of concept device. The three major sections of the prototype are labeled: the proof mass, center structure, and base structure.](image-url)
modified from previous designs to incorporate the parallel guided suspension. For the proof of concept, we used balsa wood and a plastic ruler. The plastic ruler was used as beams for the parallel guided suspension because of their flexibility across its thickness and its rigidness against its width. The center structure consisted of two parallel guided suspensions, stacked on top of each other with a 90 deg rotational offset. This structure allows for decoupling of the wind force in two directions, the x and y axis. The third part is the base structure, this was taken directly from previous designs. In this design, the base structure is a double parallel guided suspension in an "X" shape configuration. This design prevents twisting and therefore, reduces the stress on the device and prevents malfunctions. The beams were constructed using fiber-optic lines to control the consistency of the beams [5].

2.4.2 Testing

The test for Prototype I was designed to determine if it could be used as a valid method for measuring a wind vector along all three axes. The voltage produced by the phototransistor was normalized by using an operational amplifier in negative feedback configuration, as seen in Figure 2.2. The voltage was sampled using a National Instrument DAQ at 1k Hz using MATLAB as the controlling program. To secure Prototype I for testing, it was mount an optics table using screws and tie-down cables. The purpose of the first test was to analyze the decomposition of the wind forces along each axis. The wind source for this test was supplied by a can of compressed air. The wind source was first calibrated using an off the shelf hand-held propeller anemometer. The hand-held unit was positioned 1 cm from the output of the can’s nozzle and consistently displayed a value of 50 mph. With a controlled wind source at a known value, the test was setup with the mass of Prototype I placed 1 cm away from the can’s nozzle along the x-axis. The can was triggered for approximately 2 second increments.

The second test was designed to test the physical limitations of the device. With the prototype still attached to the optics table, a push and pull system was added. For each of the three axes, force was applied in the positive direction, then allowed to return to its initial state, followed by force being applied in the negative direction and allowed to return to its initial state. The forces
Figure 2.2: Symbolic representation of the circuit used to measure the change in voltage due to the displacement of the parallel suspensions.

were applied in the opposite direction for the z-axis.

2.4.3 Results

The results from the first test were very favorable to our design. The data showed that for a rapidly generated wind of 50 mph, the voltage output of the circuit was 45 mV at its peak. Further, by examining the noise of the circuit when no wind force was being applied, we found the circuit noise had a standard deviation of 0.18 mV. When comparing the noise to the voltage output at a wind speed of 50 mph, we concluded that under these conditions the prototype would have a precision of 0.2 mph.

The graph also shows the device’s time response to the change in wind speed. For both the acceleration and deceleration of the wind, the anemometer performed better than conventional propeller and cup anemometers. This is largely due to the fact that those sensors need to physically speed up and slow down to react to the changes in wind velocity. The graph also showed coupling between the voltage outputs of the three axes. This coupling is caused by the imperfections in the construction of the prototype and possibly the IR sensor pair sensitivity to misalignment. These factors will be addressed in future designs. The second test also lead to favorable conclusions. The data suggested that the average max voltage outputs were around 100 mV. This is approximately twice the voltage output of the the first test with wind speeds of 50 mph. This leads us to conclude that the device should be able measure wind speeds up to 100 mph. The variance in the max values along each axis can be contributed to the condition of the prototype at the time of the test.
2.5 Prototype II: Miniature 3D Printed Model

Due to the success of the Prototype I, research continued to further the development of a low-cost three-axis anemometer. The next step in the design process was to reduce the size of the overall structure in order to reduce the Reynolds number of the device. Prototype II addressed this by using a three-dimensional printer to print a computer aided design (CAD) model of the anemometer.

2.5.1 Design

The goal of prototype II, as seen in Figure 2.3, was to reduce the size of the overall structure while maintaining its physical properties. First, a CAD model of Prototype I was recreated at a half scale model. To maintain the mechanical properties of the Prototype I, adjustments to the beams needed to be considered. Since the lengths and widths of the beams were reduced, the thickness of the parallel suspension arms for the center structure needed to be increased. For the base structure, the round fiber-optical beams were replaced with thin flat beams similar to those on the center structure. This allows for an increase in its resistance to twisting in the base structure. Based on the results from the initial test, sensors and electronics remained the same. Further adjustments to the IR sensor mounts needed to be taken into consideration to fit the 5 mm sensors. The CAD model was then three-dimensionally (3D) printed using a fused deposition-modeling (FDM) machine. The FDM process will be further explained in Chapter 3. Based on the manufacturing process and its tolerances we found many weaknesses in the new design. The primary cause for concern was suspension arms of the center structure. Since the the FDM process printed a line for each layer of the arms as they extended vertically, this caused points of weakness and breakage if enough force was applied. Also adjustment were needed to be made to the IR mounting points because of the tolerances of the printing process was not taken into consideration.

2.5.2 Testing

The tests were designed to find out if the reduced size of the Prototype II was able to maintain the properties of Prototype I. The first test examined the relationship between voltage output of the
phototransistor and the displacement of the proof mass. An optical staging platform was attached to the optics table. Attached to the platform was a probe set to the height of the proof mass of Prototype II. This probe was used to apply a force to the proof mass to move it a set distance. Prototype II was then attached to the optics table adjacent to the probe. The probe was set to move the mass in the positive x-direction; this was meant to simulate the wind in one direction. Similar electronics were used in the testing from Prototype I. The DAQ was set to measure at a rate of 1kHz for 4 seconds. The measurements were taken at 1 millimeter increments from zero to seven millimeters.

The second test examined Prototype II’s response to a controlled wind source. For this test, the wind source was a valve controlled air compressor. From the air compressor, a long tube was run up to the optics table and connected to a valve and then a T-split. From the T-split, equal length tubes were run to an optics mount to position the outlets of air. The concept behind this setup was that the air, if given identical paths to an exit, would travel at the same velocity, creating two wind sources, one to be measured by a control and the other by our anemometer. To calibrate the
wind sources, a hand held anemometer was placed at each of the two outlets to measure the wind velocities. As the system outputted wind to each of the anemometers, adjustments were made to the placements of the outlets until the sensors were displaying the same values. To account for differences in the sensors, the two hand held units switched places and retained matching values. At this point, one of the hand held anemometers was replaced by Prototype II and the testing of the prototype commenced. A variant of wind speeds were applied to both, the hand held unit, as well as the prototype. For each test, the wind would start in an off state and be turned on rapidly to a fixed level then turned off after a duration.

The final test of Prototype II was a limitations test. This test was used to determine the physical limitations of the anemometer’s design and construction. The test was executed in the same manner as that of Prototype I.

2.5.3 Results

The first test for Prototype II was to understand the relationship between the displacement of the proof mass to the voltage output of the IR sensors. From the graph, we are able to see that there is a linear relationship between the displacement of the proof mass and the voltage output of the phototransistor. The output of the circuit maintained a linear output for the first 4 mm of displacement with a voltage output of 0 mV to 10 mV.

The second test conducted on the device displaced the capabilities of the design based on a variable simulated wind source. The graph in Figure 2.5, shows the outputs of the various wind speeds
Figure 2.5: The graph shows the results from test 2 of prototype II. The graph represents the change in voltage output due to wind produced by a compressed tank of air due to time. The wind speeds vary from 5.0 to 23.8 mph and were measured using a hand help anemometer.

layered upon each other. We were not able to attain controlled steps of wind velocity changes, but rather the following five max speeds in miles per hour: 5.0, 10.2, 13.5, 18.4, 23.8. Due to the limited size of our compressor tank, we needed to output the wind from our system in bursts to maximize the speeds the test could attain. Similar to results of the first test, there was a steady increase in the output voltage as the measured velocity of the wind increased. Also based on the data from the test, we concluded that the max wind speed for Prototype II was approaching 100 mph. This was calculated based on the approximation that at a max test speed of 23.8 mph, the voltage output was approximately 6 mV. When the 6 mV output is translated to the max voltage output of the first test, 20 mV, we can estimate that the max speed approaches 100 mph. This can be especially true because at higher speeds, the propeller anemometer takes a longer time to reach its max speed. There is also the presence of turbulence in the graph; this turbulence is due to the use of an air compressor with a limited size tank. The turbulence is created by the motor trying to generate more air to be outputted by the system.

In the final test, we examined the physical limitations of the prototype. For this test we primarily studied the x and y axis of movement. Table 2.1, displays the voltage outputs of the test. For the x-axis, the max voltage output was roughly the same, based on the biasing of the voltage output to zero for the zero state. For the y-axis, the negative direction of motion was similar to the max values in the x-direction, but the positive direction was significantly less. This discrepancy is due to damage the prototype endured in the previous test and through general handling. These max
Table 2.1: The data in the table displays the output limitations of Prototype II. The test pushed the structure to its limits along the two primary axes and measured its output voltage values. The data support the claim that the sensors should be able to operate at speeds in excess of 100 mph.

Prototype II has shown much promise from the tests performed upon it but there are many shortcomings as well. One of these areas is the suspension system for both the center tower and the base. This is to be addressed through adjustments that take into account the manufacturing process and tolerances. The beams also need to be redesigned to increase the flex in the measurement direction and stiffened in its counter direction. The final shortcoming of the design is the non-linear response to displacement. This can be addressed by designing the structure to operate in a given displacement region and through the assistance of software.

2.6 Prototype III: Multi-part Structure

Based on the results from the Prototype II and the lessons learned from the 3D printing process, a new design for the anemometer was created. The goal for Prototype III was to reduce the size of the internal structure and eliminate the manufacturing weaknesses. This new design took into consideration the 3D printing process and looked to take advantage of the length of the lines for the arms of the suspensions. Prototype II, seen in Figure 2.6, shows that each of the three axes are its own individually printed part. This was important because it allowed for us to print each individual axis flat with the width of the suspension arms being printed vertically. This allows for the parallel guided suspension to retain their structural integrity as force is applied perpendicular to the width of the beams. Prototype III continues to use the same IR sensors and electronics.

Prototype III was manufactured by another fabrication company, who claimed that they would have better tolerance and prints than Prototype II. When the printed parts were received back from the company they looked excellent and very professional. But once back in the lab, the parts again suffered from tolerance issues, making installing components nearly impossible. With the
improved build construction, making alterations to the design was difficult. Also, the process left the beam structure much more stiff than originally calculated. These combined challenges, along with the long turn around time, left Prototype III untested and left us looking for new solutions.

2.7 Prototype IV: Rapid Prototype Implementation

Following the challenges with Prototype III, we took time away from the anemometer design and investigated the topic of rapid prototyping and managing our own 3D printer, see Chapter 3 for more information. Prototype IV was the resulting design from our ability to create multiple iterations of the same design until we found a design that met our previous design performance.

2.7.1 Design

With the ability to create several iterations of the same design until all of the parts fit together, we experimented with several different designs. As we experimented with different beam designs, we found that a folded parallel guided suspension, see Figure 2.7, provided the best flexibility along the length of the structure in one direction, while maintaining stiffness in the perpendicular direction. The folded structure allowed for a smaller overall design, with easier positioning of the IR sensors. With the new design came the shifting to a different IR sensor pair, VSMG2700 and VEMT3700,
Figure 2.7: The image is a CAD rendering of an initial design for a folded suspension. It has a hole in its center mass to connect to the outer shell of the anemometer. The folded suspension allows for the structure to maintain the stiffness of a taller structure in a more compact package.

emitter and phototransistor respectively. These new sensors were chosen because of their matched IR operating frequency and PLCC-2 surface mount packaging, making them roughly 3 mm by 3 mm. Due to the smaller packaging, the challenge was no longer making room for the sensor but finding a way to connect to the sensor.

With these two changes to the design, the new design was called Prototype IV. It kept the modular construction due to the FDM process of manufacturing each piece. This allowed for the strands of plastic to be in the same direction as the arms of the parallel beams helping to maintain the structural integrity of the component. We also kept the nested design of the center structure from the previous prototype. The base of the designed evolved into a double parallel guided suspension due to some of the limitations of the 3D printer that we had at the time. This design also prevented the base structure from becoming too thick, as in Prototype III, to the point that it would not provide any motion.

The final component of Prototype IV was the implementation of an external shell as a proof mass, see Figure 2.8. The shell was constructed from pentagons and hexagons, similar to the pattern of a soccer ball. This shape was used instead of a sphere due to its simplicity in manufacturing through the 3D printing process and the size of the printer's build platform. The outer shell was assembled piece by piece, bonded together with cyanoacrylate and accelerate. The shell was attached to the center of the suspension system with a single rod. There was a hole at the bottom of the shell allowing for inner suspension to be attached to a stand and for the wiring to exit the device.
2.7.2 Flaws and Shortcomings

Once the design was assembled, several design flaws and other shortcomings started to arise. The first shortcoming is with the implementation of the new IR sensors. The PLCC-2 package for the new IR sensors presented contact points that we were able to connect to initially, but due to their low surface area the wires did not stay attached for very long. Also, related to the IR sensors is their mounting points on the suspension structure. Due to the resolution of the 3D printer and the warping of the plastic that occurred, the mounting points were not very well defined, causing the IR sensors to not sit properly. The sensors would also become detached from the mounting point due to the adhesive and the plastic not being able to bond to each other properly. Another shortcoming of Prototype IV was the method in which we connected the outer shell to the center structure. We implemented the use of a single rod to the center of the suspension structure. This rod did its purpose of translating the force of the wind upon the shell to the inner structure, but would experience twisting on the rod that could distort some of the translated energy.

This design was not tested due to its innate issue and the challenges with the implementation of the new IR sensors. Instead, research shifted to the understanding of the IR sensors and methods to reduce effects of external IR interference on the sensor’s measurements. This and other IR related research will be discussed in Chapter 4.
CHAPTER 3
RAPID PROTOTYPE

3.1 Introduction

The term “rapid prototyping” traditionally refers to any additive manufacturing process derived from a Computer Aided Design (CAD) data [18]. These processes include stereolithography, fused deposition modeling, laser cladding, and laminated object manufacturing [19]. The term has since evolved to describe a design process. This process challenges the tradition ”systems approach” which has a focus on the effectiveness of a product over the efficiency of designing one [20]. The rapid prototyping design process looks at quickly developing working prototypes, through the use of various computer aided tools, to verify the works for the design. The tools that brought this change to our design process was the 3D printer and the PCB milling machine.

3.2 3D Printing

The rapid growth of 3D printing has been staggering over the past several years. It has created the ability for anyone, hobbyist and professionals alike to change the way they design. Prior to the wide acceptance of desktop 3D printers, such as the Makerbot Replicator, 3D printing was reserved for special purposes and large companies that could afford the large price tag. The cost for many of these printers ranged from $35,000 to upwards of $100,000. These printers use various methods of printing from stereolithography to ink jet printing. Each method has its advantages over the others but the method most desktop printers use is fused deposition modeling.

3.2.1 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is an additive process for 3D printing. The process begins with the designing of a model using one of the various Computer Aided Design (CAD) programs. The design then needs to be exported to a stereolithography format (STL). When a file is converted to an STL format, all of the geometry in the design are tessellated into triangles and simplified
geometry. The STL file format is used because it is a universal format, which most software can export and can be used by the printer’s supporting program. The software then takes the model and slices it into layers with a thickness based on inputs by the user and characteristics of the printer. Each layer represents a top-down view of the area that the printer needs to fill with material. The software then takes the layers and creates a machine instruction on how to construct the model [21]. Based on the machine instruction, the printer will take plastic filament material and heat it to its semi-melting state and then the plastic is force through a smaller nozzle and out of the print head. As the print head moves along the X-Y plane of the build platform, the extruded plastic is laid out in the same pattern as determined for each layer by the the slicing program. As the program moves to the next layer, the build platform is lowered to allow the plastic to be placed upon the previous layer. Since the plastic is in a semi-molten state, as the new layer is placed on the previous, it fuses with the previous layer, creating a single piece. This process is repeated until the whole model is completed [21].

3.2.2 Makerbot Thing-O-Matic

The first 3D printer used was the hobbyist grade Makerbot Thing-O-Matic, which costs less than $1,500. The printer was constructed primarily out of laser cut wood and assembled with nuts and bolts. The printer was designed to be used with Acrylonitrile butadiene styrene (ABS) plastic. This requires the use of a heated build platform that was xxx by xxx in size. The build platform was also designed to be automated, as each printed piece could be slid off with the built-on conveyor belt. In comparison to the FDM process described above, the build platform would move along the X-Y plane and the printer head would move along the Z-axis. The original print head, MK5, was driven using a DC motor, which limited control of the extrusion of the filament. This made building multiple stand alone structures during a single print session a challenge. The print head was later replaced with the MK7, which was driven by a stepper motor, increasing the control of the extrusion.
3.2.3 Makerbot Replicator 2x

As the interest in desktop 3D printers increase, so did the quality of the products, as the second printer purchased was the Makerbot Replicator 2x. This printer represented a large leap forward from the Thing-O-Matic as the Replicator 2x consisted of a steel frame design and higher quality components. The Replicator 2x still prints using the FDM process. The new printer consisted of dual extruder, allowing the use of multiple filaments in a single print. The extruder is driven similarly to the MK7 with the stepper motors and heat sink cooling for the components. The Replicator 2x prints as described in Section 3.2.1, with the extruder moving along the X-Y plane and the build platform moving along the Z-axis. The prints produced by the Replicator 2x are of a higher quality, as the minimum layer height is 100 microns, and larger, as the build platform is 24.6 x 15.2 cm.

3.2.4 Challenges

There were a various number of challenges and lessons that were learned with the use of a hobbyist 3D printer. The first is directly related to the FDM process and understanding the limitations of the fabrication method. Since FDM uses a fixed size filament and nozzle, the material laid down is not one to one between width and height. This means that the prints may have a 100 micron resolution in terms of its height, but this may not be true for its length and width. Also, the nature of the ABS is to shrink as the plastics cools to room temperature. These factors create challenges in the tolerances of the prints. For example, a hole designed to be 5 mm in diameter may be 4 mm by the time the model sets. This was even true with industrial machines, such as the parts we had printed for Prototype III. But with having a desktop unit, corrections can be quickly redesigned, reprinted, and retested in a matter of hours compared to the weeks when it is done by an external company.

The Thing-O-Matic has a particular issue with stability. Due to its primarily wooden design, it often experienced error in prints due to the translation of vibrations from the rapid movement of the build platform to the machine as a whole. As a result prints would get misaligned and taller structures would begin to angle to one direction. This made it difficult to create larger pieces in a
single print and resulted in creating multi-part pieces. This challenge developed the skills to design in parts and ability to design with the manufacturing process in mind.

3.3 Printed Circuit Board Fabrication

The second tool that changed the way we designed was a Printed Circuit Board (PCB) mill. Compared to the hobbyist grade 3D printer, the T-Tech QCJ-5 is a commercial grade Computerized Numerical Control (CNC) mill designed specifically for creating PCB. The design of the PCB is first generated using a CAD schematic and layout program, such as Eagle CAD. In the software, the circuit is first designed using symbolic icons that represent all of the components that will be included in the circuit. From the symbolic design, a PCB layout is created. It is at that this point the designer needs to check to see if the proper packaging for each component is used and have a basic understanding of layout design. Since the PCB is planar design, the placement and orientation of each component is a major consideration to assist with the routing process. The routing process is where the individual wire traces need to be placed to create an electrical connection between two points on the board. The mill is able to produce two sided PCB, this allows for a larger number of components to be placed in a given area. Once the design is completed, it is exported as a Gerber file format. These files contain all of the information for the design of the PCB as an individual layer. The Gerber files are then imported into the milling software, where the user can set the configuration for the print. These configurations include placement of the circuit on the copper board, the widths and depths of the traces, as well as the individual bits used in the process. Similar to the 3D printer, the software converts the design into a machine instruction for the mill to produce the PCB. The CNC mill is able to mill the board and change its own milling bits; the only assistance needed is for a double layer design that requires the copper board to be flipped over during the job.
3.4 Advantage to Development and Implementation

The biggest advantage to rapid prototyping and the acquisition of the 3D printer and CNC PCB mill is time. The tools allow us to generate and adapt our designs in a single day compared to what would have taken weeks or even months. For example, the suspension beam structures of Prototype III was designed in our lab and then sent out to a third-party to be printed. Based on our communication with the company they did not address any of the tolerance of their machines and printing process, so we designed the models to have a tight fit. When we received the components back, several weeks later, they did not share the same mechanical properties as we expected. Also, the fitting was not correct and none of the components fit together. In comparison, Prototype IV was designed in our lab and printed using the Thing-O-Matic. The 3D printer provided the ability to designing and testing the individual suspensions prior to designing the structure as a whole. This was also how we were able to get our fitting to be tight, through a process of trial and error. The quality of the prints were not as high as the ones produced by the third-party but we were able to create another functional prototype in a fraction of the time. In the time it took for us to get a single print back from the manufacturer, we were able to construct a full working model. This also holds true for the creation of PCB, as the turn around time for most PCB fabrication houses is anywhere from 4 to 6 weeks. Our system is currently limited to the production of double sided boards, but this fits most of our needs. In the same 4 to 6 week time span, we are able to design, print, and test several iterations of a design as a single board can be printed and populated in a single day.

This leads us to the second advantage and change in design process. The traditional method of designing is seen as an engineer sitting down and thinking out all of the possible situation and attempt to create a perfect design on paper before sending it off to be manufactured as a prototype. In comparison, the ability to quickly create models of the design, an engineer does not need to think about all of the problems, but rather construct their first idea, print it, and physically handle the device to find its flaws. This tactile approach to designing lends itself to collaborative work flow, models allow the thoughts of the designer to be expressed in a more tangible manner. For example, the parallel suspensions for Prototype IV were designed by printing a variety of suspension designs
and testing each individually before designing the center structure. This has shifted the design process from a thought-consuming to a tactile approach.

The approach of rapid prototyping has changed the way we search for solutions to a problem. From our first design of Prototype I, you see the idea of rapid prototyping by the use of material commonly found around the lab and using them in ways they may have not originally been intended to be used. With the wide spread acceptance of desktop 3D printers such as the Replicator 2x, which produces a more reliable print each time, the first step to creating is the computer and CAD software. This allows the engineer or designer to transfer their concepts to a fully tangible print in a matter of hours rather than weeks. With the shorter delay between concept to reality, designers are able to stay motivated and engaged in the project due to the lack of down time. Due to the lower cost of time and money, incremental changes can be applied to the design to allow the designer to examine each issue individually, rather than a vast number of changes at a single time. In the end, rapid prototyping is changing the methodology to designing and redesigning devices.
CHAPTER 4
INFRARED TECHNOLOGY PROFILING AND VARIOUS IMPLEMENTATION

4.1 Introduction

In this chapter, we take an in-depth look at the application of IR sensors in the development of a low-cost three-axis anemometer. This includes a study of the correlation between the displacement of the IR emitter and IR phototransistor and the effects that an external source can have on the measurements. This study also Examines a possible solution for the effects of external interference. Also included in this chapter are various other applications of the IR sensor pair for use in determining displacement of two structures. The other methods include using a reflective surface to allow the sensors to be placed adjacent to one another. We also attempted to develop a method for using low-cost circular waveguides to measure displacement and allow for the IR sensors to be mounted to the data acquisition PCB.

4.2 Direct Line of Sight with Interference

The access to rapid prototyping tools has allowed for the development of custom testing apparatuses. These testing setups are used to test the individual sensors implemented in the anemometer design. One implementation of this technique was our testing of the IR sensor pair and how they were affected by external environmental interference. This experiment examined the voltage output changes of the phototransistor circuit due to the changes in displacement between the emitter and phototransistor. In addition, the experiment also looked at the effects that a simulated external IR source would have on the output of the phototransistor. These findings were first published at the Cleantech Conference in 2013 [22].
4.2.1 Test Setup

The test setup was designed to allow for the variable displacement of the IR emitter and phototransistor and the recording of data. The design for the test setup takes into consideration the need for a mobile or field testing implementation. The test setup, see Figure 4.1, is separated into three parts: positioning platform, IR external interference, and circuit control and data acquisition.

Figure 4.1: The image shows the testing setup for the direct line of sight test of the IR sensor pair. The three parts are labeled as follows: 1) Positioning Platform, 2) Circuit Control and Data Acquisition, and 3) Infrared External Interference

Positioning Platform

The positioning platform allows the user to set a zero state and change the displacement between the IR emitter and phototransistor. This system is designed to allow the tested to be repeated while reducing the concern for misalignment between tests. There are three major components to this section, which includes the optical stage, IR sensor mounts, and the IR sensor pair.

The main component is the optical stage, two Melles Griot precision single-axis stages. The use of
these optical staging components allowed for the use of 20 mm micrometers to control the position of the IR sensors in relation to each other. The micrometers used in the system allowed for 0.01 mm of precision. The stages were mounted directly to a one inch thick wooden board, which allows the setup to be portable and taken out of the lab for a field test.

The second part of the positioning platform is the IR sensor mount. These mounts were custom designed and printed using the second evolution of the 3D printer. The IR mounts were designed to be easily attached to the optical stages while IR sensors would be positioned over the edge of the stages to reduce the interference the stages would have on the IR positioning. Due to the limitation of the 3D printer, the IR mount needed to be broken down into three separate printed pieces. The first is the base, this part is designed to attach the mount to the optical stages through the mounting threads on the stages. The base is also designed with an open port and positioning groove under the surface for the second piece, the vertical arm. The vertical arm allows IR sensor to be positioned above the precision stages and angled toward each other. This allows for the IR sensor to be set at an initial state where the sensors are touching face-to-face. The final piece to the IR mounts are the IR holders that mount to the vertical arm. The IR holders are designed to allow the IR sensors to be positioned properly and aligned with each other. The holders are slotted to allowed the PCB mounted IR sensors to be easily positioned into place.

The IR sensors being tested are the same components used in Prototype IV of the low-cost three-axis anemometer, VEMT3700 and VSMG2700. In order to simplify the use the surface mount component custom PCB breakout boards were designed. At the time we did not own a PCB mill, therefore the PCB were made using an etching process. The resulting PCB produced an easier method for attaching the IR sensors to and for wiring to be attached to the accompanying circuit.

**Infrared External Interference**

The IR external interference provides a source of controllable IR light to act upon the IR sensors to cause inaccurate measurements. The system consists of four 5 mm high-intensity IR LEDs operating at 850 nm wavelength, close to the 830 nm wavelength operating frequency of the IR sensor pair. The four IR LEDs are mounted onto a 3D printed circular mount. The circular mount
is placed on top of a cardboard channel used to block out any other external sources of light, as well as to direct the IR interference toward the IR sensor pair.

**Circuit Control and Data Acquisition**

The circuit control and data acquisition is responsible for responding to the commands from MATLAB and controlling the electronics in the system. The National Instrument USB-6211 (DAQ) is the core component for system, as it is able to communicate directly with MATLAB through the Data Acquisition Toolbox. The schematic, see Figure 4.2, shows an external five volt power supply because of the current output limitations of the DAQ and the large power draw of the IR emitter and the high-intensity IR LED. To control the IR emitter, the DAQ is connected to the base connection of a TIP31, NPN transistor, which is in series with the IR emitter. The IR external interference is controlled using the same circuitry with the LED in parallel to each other. The DAQ takes the voltage output reading across the biasing resistor for the phototransistor.

![Figure 4.2: Schematic of the circuit control for data acquisition. Circuit is used to control the IR emitter and record the output of the phototransistor under various conditions.](image)

**4.2.2 Testing Calibration**

Prior to testing the IR sensors, a set of calibrations were applied to the test setup. The first calibration set the initial position of the IR sensors into a zero state. By setting a zero state, it allows the test to run multiple times with the the same precision and displacement. The first step was to position the stage with IR emitter to its starting position by setting the attached
micrometer to zero. Then, lock the stage down so that it does not move while setting up the other precision stage. Next, while observing the gap between the two sensors under a microscope, the phototransistor stage was slowly positioned closer to the IR emitter until their faces just begin to touch. At this point, the micrometer for the phototranistor stage was turned back very slightly to relieve any force that may have been applied to the arm structure as the faces touched. The phototransistor stage is then locked down and the zero state for the sensor pair is set for all of the tests.

The second calibration determined the noise floor for the circuit across the various displacements. To find the noise floor, we measured the output of the phototransistor with the IR emitter and IR interference off. In addition, we performed the test in a dark room to eliminate the affects of the room lights. The voltage output was recorded while the IR emitter off for displacements from 0 to 10 mm at increments of 0.5 mm. The data was also used as the zero condition, emitter off and interference off, for analysis.

The final calibration test is to measure the light intensity of the IR LED interference array. The light intensity was measured using an Apogee SP-110 pyranometer attached to the USB-6211. The IR interference array was placed on the cardboard channel mount, which was placed over the pyranometer. The output of the pyranometer was recorded while the interference array was turned on. The average output of the pyranometer was 2.4 mV, which translates to about 12 W/m² of solar irradiation.

### 4.2.3 Testing Procedures

The test was designed to examine the affects of external interference on the performance of the IR displacement sensor implemented in a low-cost three-axis anemometer. To accomplish this goal, the test was performed under three conditions, in addition to the zero state condition. The first condition requires the IR emitter to be turned on during the test and the IR interference to be turned off. This condition provided a baseline performance of the IR sensor through a various range of displacements. The second condition requires the IR emitter to be off and the IR interference to be turned on. This state represents the IR inference contribution to the output of the system.
The measurement needed to be taken over the range of displacement because it allows any physical shielding of the interference to be accounted for in the data. The third and final condition requires both the IR emitter and IR interference to be turned on. This state shows the combined effect that the two inputs have on the output of the IR phototransistor.

For each condition, the test sequence remained the same. The MATLAB program is initialized and gives the user instructions for the current position. The test starts at the zero state, where the IR emitter is set to 0 mm. The program waits for the user to press any button and then commences its capturing and recording of the data at 1000 samples per second for 5 seconds. After the data is collected for the given displacement, it will increment its counter and display the next position to be recorded and the process is repeated. For each condition, measurements were taken from 0 mm to 10 mm at increments of 0.5 mm.

4.2.4 Results

The data collected from each condition were converted and overlaid into a single graph. To attain the new voltage output vs displacement curves, the average voltage for each displacement was taken and placed into a new array paired with its displacement value. This process was repeated for each of the four conditions, the three mentioned in the testing procedures and the zero state mentioned in the calibration section. All four of the resulting curves overlaid with each other in Figure 4.3. In addition to data collected from the four conditions, a fifth curve, condition four, was added to the graph, this curve represented the difference between condition three, both IR emitter and IR interference on, and condition two, just the IR interference on and IR emitter is off.

To further analyze the strength of our data, we example the signal to noise ratio of the data collected. To attain the signal to noise ratio, a power spectral analysis needed to be preformed on the data collected at each displacement for each condition. Two cases that we will look at in particular are the 0 and 1 condition at 1 mm of displacement. These two cases were selected because the zero condition case gave the signal to noise ratio for the circuit noise in the system. The second case, condition one provided the signal to noise for a large signal verifying the low noise floor as well as an interesting artifact at 120 Hz.
Figure 4.3: The graph shows the outputs of the IR direct line of sight test overlaid with each other in a single plot. The graph suggest that the difference between condition three and two closely resembles the output of condition one.

4.2.5 Discussion

The results of our test lead us to a few conclusions about the IR sensors and their reaction to external interference. The first is drawn from the results of condition one, emitter on and interference off. It shows that the ideal range of operation is from 0 to 3 mm of displacement. This is largely due to the linearity of the correlation between the displacement and the voltage output of the circuit. The advantage of a small linear region in combination with a low noise floor, as deducted from the condition zero results, allows for the design of smaller and stiffer suspension structures for the three-axis anemometer.

The second conclusion leads us to a method for reducing the effects of an external interference. As you look at the plots for condition one and curve five, they both line up with each other with a small difference. This leads us to conclude that for a limited amount of interference, we can take samples with the IR emitter turned off and subtract it from samples with the IR emitter on and the result should reduce the effects of the external interference. One method to achieve this is to pulse the IR emitter at a slower rate than the sampling rate of the system and handle the calculation in post-analysis.

The next takeaway is based on the results from the power spectral analysis completed on the collected data. The power spectral analysis converts the data collected as a function of time and then converts it to function of frequency and in terms of decibels. This conversion allows us to determine at what frequency most of the signal is attributed. The signal to noise ratio is calculated
by taking the source power density and dividing it by the noise power density. The source power
density is determined by taking the peak value across the frequencies of operation. The noise
power density is calculated by integrating across all other frequencies across the band of interest.
For the zero condition at 1 mm, the signal power was $1.1 \times 10^{-3}$ dB and the noise power density is
$2.89 \times 10^{-4}$ dB. The resulting signal to noise ratio is 3.81, this low value is accredited to the lack
of signal applied to the phototransistor. The low signal to noise does support the low noise floor of
the circuit and the lack of circuit noise across all frequencies. For the first condition at 1 mm, the
signal noise is $1.29 \times 10^{3}$ dB and the noise power density is $1.56 \times 10^{-2}$ dB, this results in a signal
to noise ratio of $8.3 \times 10^{4}$. The higher signal to noise ratio suggests that majority of the output
signal is directly contributed to the input of the circuit. This again confirms the low noise floor
and confirms that the use of a smaller suspension structure is viable in future designs.

The final takeaway is related to the total of solar irradiation produced by the IR array in relation
to the amount of irradiation produced by direct sunlight. From the calibration procedures, the
total solar irradiation for the IR LED array was 12 W/m$^2$. The total amount of solar irradiation
that is produced by direct sunlight is 1100 W/m$^2$ across the full spectrum of light. Since the IR
phototransistor has an effective band of 600 to 1000 nm wavelength, the effective amount of solar
irradiation from direct sunlight is 450 W/m$^2$ [23]. Based on the effective band and not taking into
account the IR phototransistor’s spectral sensitivity away from its ideal wavelength of 850 nm, the
IR array only represents about 2.7 % of the total amount of effective solar irradiation. Even with
2.7 % of the total solar irradiation the trend of the fifth curve should hold true. Also, the use
of shading techniques can reduce the greater effects of the external interference and the pulsing
technique, mentioned earlier, can mitigate the remainder of the interference.

### 4.3 Paired Sensors and Reflective Surface

Based on the results from the previous test, we continues to look for ways to implement the IR
sensors into the design of a three-axis anemometer. At this point, the accessibility to a PCB mill
became available and the ability to create more precise PCB. This lead to researching other methods
to determine displacement through the IR sensors. One implementation was the placement of the
two IR sensor components adjacent to each other on the same PCB and use of a reflective surface as the moving element. The same setup from the previous IR sensor test was used to test the new theory. The only change is the IR sensor component mount: the phototransistor side was made wider to fit the new PCB with the two sensors and the IR emitter side was replaced with a reflective surface. The reflective surface was a 3D printed mount with a flat vertical surface with aluminum tape attached as the reflective material. The test procedures were the same as the test performed in condition one of the direct line of sight configuration.

4.3.1 Results

![Graph](image)

Figure 4.4: The graph shows the outputs of the IR reflected test. The graph is a single plot of the voltage output of the IR sensor in relation to the displacement of a movable reflective surface.

The data collected from each displacement was processed by taking the average $V_{out}$ for each of the displacements and combining them into a single array of data points and plotting them on a graph, see Figure 4.4. As shown in the graph, the resulting curve has a favorable range of operation from 2.5 to 6 mm of displacement. In comparison to the direct line of sight configuration, this setup produced a linear response along a greater range of displacement.

4.3.2 Discussion

The results are very favorable in assisting with the development of a low-cost three-axis anemometer. One benefit of the new design is the reduction of the concern of misalignment. The misalignment could be due to errors in construction or due to the effects of multi-directional wind acting upon the anemometer. The slight misalignment can have a greater effect on the output of the phototransistor.
than the displacement between them. The second advantage to the reflective design is the larger and more linear range of operation. This increase in range can allow for a higher sensitivity and precision by reducing the stiffness of the suspension structure. It could also result in an increase in the range of operation by maintaining stiffness and allowing a larger range of motion.

4.4 Circular Waveguide for IR Transmission

In an attempt to further reduce the size of the anemometer structure, I studied and tested various methods for removing the IR sensors from the structure itself and channeling the IR light through the use of custom circular waveguides. The material used for the waveguide was PDMS due to its optical properties as well as the ability to create it in any shape as long as it was set in a mold. The following subsections describe the attempts at implementing this method and the challenges that they presented. The three methods used are direct-to-sensor mounting, proximity to IR sensor, and direct-to-glass.

4.4.1 Direct to Sensor Mounting

The first method was to directly mount the waveguide to the IR sensor prior to soldering them to the PCB. The best method for creating a circular waveguide using PDMS was to place the PDMS and curing agent mixture into a thin straw and allow it to set. In order for the straw to be placed directly on to the IR components, a mold was needed. Using the 3D printer, a two part mold was created that allowed straws to be inserted and placed directly over the face of the IR sensors. In addition, two plastic bands were printed to help hold the whole mold together.

We were able to successfully place the parts together and insert the PDMS for curing. It was at this point that challenges presented themselves. The first was the spreading and seepage of the PDMS into the gaps due to its viscosity prior to it setting. To counter the seepage, we created a negative pressure at the top of the straws by removing some of the air and placing a stopper to prevent the PDMS from spreading. To reduce the time the PDMS had to spread in to gaps, it was placed in a low temperature oven to increase the curing rate. These two adjustments allowed the waveguides to be created and set, but another issues arose. As the mold was separated and
the IR components were removed, they were not bonding to the PDMS. Therefore leaving us with IR sensor components not attached to the waveguides in a manner that they could be handled or implemented. This resulted in a nonviable method for implementing low-cost circular waveguides into the system.

4.4.2 Proximity to IR Sensor

To address the result from the previous attempt, a simpler approach to the implementation was attempted. This time, we wanted to see if we could just use the custom made waveguides and have them positioned onto the IR sensor components and have them emit and receive the IR light. The circular waveguides were constructed using the same method as in previous design, the use of thin straws and stoppers to keep the PDMS inside of the straws and curing as a circular waveguide. A custom PCB was designed to implement this placement of three sets of IR sensor pairs. A mount was made to encapsulate half of the PDC and allow for the waveguides to be positioned on top of the IR sensor components. The mount also contained small compartments for each of the PLCC-2 package to sit inside to prevent IR leakage between the three sets of sensors.

Once completely assembled, the setup showed some promise as IR light was detected from the outlet of the IR emitter waveguide, using a phone camera to visually detect the IR light. With a digital volt meter attached across the biasing resistor of the phototransistor, the two ends of the circular waveguides were placed face to face and a voltage output resulted. This is evidence that the method of transmitting the IR light through the PDMS waveguide is a viable solution. But when the two faces were separated from each other, the voltage output drops to no signal, invalidating the method for the purpose of our application. A possible reason for the lack of transmission through space is due to the condition of the ends of the waveguide. Since the ends needed to be cut, the imperfections along that surface does not make for an ideal optical transmitter or receiver.

4.4.3 Direct to Glass

In a final attempt to find a method to have the circular waveguides transmit and receive the IR signal from the emitter to the phototransistor, we cured the waveguide directly to a glass slide.
This was achieved by designing a mount for the glass slide that had two holes for the straws to be positioned up against the slide. Applying the reflective method of measuring the displacement, a second component was designed to reflect the IR signal back to the glass slide and the IR sensor components. Using the same methods as before, the circular waveguides were set and cured. The two pieces were placed on the precision stages to be tested based on their displacement. To verify the design, a digital volt meter was attached to the circuit to measure the system output. Even with the IR emitter set to output near 100 mA there was no output, except when the reflector was positioned right up against the glass slide. The suspected reasoning for the lack of any transmission is due to the method we used to make the two waveguides. Since they were poured with the glass slide facing down while it set, this gave the PDMS the time and room to seep between the glass slide and the 3D printed mount. When the piece finally cured, the waveguides became one with the glass slide. As a result, the dispersion of IR light from the glass seemed to be diluted and intensity greatly attenuated. This prevented any light to properly be reflected back to the receiving waveguide to be transmitted back to the phototransistor.

4.4.4 Conclusion

Based on the three attempts using custom circular waveguides to transmit the IR signal, we decided to abandoned the concept. It seemed as if the only way to make it work would be a higher financial investment into higher quality optical components. Even in the wake of the failure of the circular, the process validated the use of rapid prototyping tools, such as 3D printing and CNC milling, as a means of quickly testing and evolving a concept. This particular series of designs happened over a period of several weeks rather than several months. The shorter time investment allows us to move forward from a bad idea, rather than feeling like we need to make it work.
CHAPTER 5
INFRARED FORCE TRANSDUCERS FOR APPLICATION WITH LOW-COST THREE-AXIS ANEMOMETER

5.1 Introduction

As the challenges of implementing IR sensors into the design of a low-cost three-axis anemometer compounded, we searched for other methods of measuring the force being applied to the anemometer. With this search, we determined that the current offering did not meet the needs of the design and looked to develop a solution. This solution took us back to the IR sensors, but a different method of implementation. It was at this point that we began to develop a force transducer that used total internal reflection to measure the force being applied to the device. The research and findings were first published in IEEE Sensor Journal [24].

5.2 Current Force Sensor Technology

This section is a brief description of the currently available force sensor technologies. The descriptions will include how the technology is implemented and the shortcomings of each as it relates to our anemometer development. These technologies include the following: capacitive, piezoelectric, piezoresistive, strain gauges, and optical force transducers.

5.2.1 Capacitance

Capacitance force sensors are based on the principles of a parallel plate capacitor. These sensors consist of four primary components: a fixed plate, a shim, a movable plate, and a diaphragm or plug. The fixed plate is separated from the movable plate by the shim. The shim is a dielectric material that is able to store the charges between the two plates. The diaphragm or plug is the component of the sensor to absorb the force and translate the energy to the movable plate. There are two methods to causing a change in capacitance. The first method is pressing the movable plate toward the fixed plate to reduce the gap between the two plate effectively increasing the
capacitance of the capacitor. The second method, a plug is attached to the movable plate and the plate can shift over the fixed plate, while maintaining the distance between the two plates. As the surface area that overlaps the fixed plate increases, the capacitance will increase.

There are two primary disadvantages of using a capacitor based force sensor and they are both anchored in the method for measuring the change in capacitance. The primary method to measure capacitance is through a capacitance bridge of reference capacitors. Therefore, the accuracy of the capacitance measurements is only as reliable as the reference capacitors. Since the cost of the reference capacitors exponentially increase with their accuracy and precision, this can cause dramatic increases in the cost of the final design of our anemometer. The second major disadvantage is due to the capacitor’s sensitivity to changes in temperature, even at room temperature. The capacitance changes due to temperature are significant to the point that reference bridges are often needed to be stored in a temperature controlled box external of the force sensor. The need for a temperature controlled environment makes using a capacitance sensor in outdoor environments not feasible. These two reasons, individual of each other, are enough to make capacitance-based force sensors not viable as a solution for our low-cost three-axis anemometer.

5.2.2 Piezoelectric

Piezoelectric force sensors function under the principles of the piezoelectric effect. The piezoelectric effect occurs when a special material is pressed and causes an electrical potential difference across the material. These special materials are called piezoelectric materials. There are both natural and synthetic materials with piezoelectric properties. The naturally occurring piezoelectric material have a anisotropic crystalline molecular structure that allows for a change in electrical voltage when force is applied. These natural piezoelectric includes quartz and tourmaline, which can be manufactured for a low cost but lacks sensitivity. The second type of piezoelectric material is a synthetic ceramic, not crystalline-based material. The ceramic material maintains many of the properties of the natural piezoelectric material, but is able to be made into various shapes and thicknesses. The piezoelectric properties of the ceramic material can be controlled though its shape and thickness. The primary disadvantage of the piezoelectric force sensor is related to measuring
the output of the sensor. One of the properties of these sensors is the high output impedance of a piezoelectric material. The output resistance is usually of the magnitude of $10^{15}$Ω in comparison to the typical value of $10^{3}$Ω. This creates a challenge with data acquisition; because of the high output impedance, the measurement needs to be taken by a device with a higher input impedance, which requires special measuring device that can increase the cost of the sensor system. The other option is having a data acquisition unit that is able to read the voltage across the output before it is dissipated.

5.2.3 Piezoresistive and Strain Gauge

A piezoresistive-based force sensor operates under the premise that its relative resistance changes as it is stressed by an external force. Another device which operates by the same premise is a strain gauge. These devices change output resistance as the device is stressed and deformed. There is a linear relationship between the force applied to the sensor and its change in resistance. This relationship can be represented by the formula

$$\frac{\delta R}{R} = G \times \frac{\delta L}{L}$$

Whereas piezoresistive sensors take the form of a semiconductor made from a piece of silicon, a strain gauge is designed in a form of a pad consisting of a metal substructure. These pads are often used to measure the stresses on a beam by being attached to its surface [25].

The major disadvantage of piezoresistive sensors have is the cost associated with maintaining a high precision from sensor to sensor. This is due to the fact that piezoresistive sensors are silicon based and require a doping process to be manufactured. In order to maintain the level of precision, more money and more time is needed to be spent for each sensor. Secondly, the physical properties, primarily the silicon’s rigidity, reduces the amount of deflection that can be measured. In comparison to piezoresistive sensors, strain gauges do not suffer from the same high cost and rigidity, but rather a lower gauge factor. A lower gauge factor results in a limited sensitivity of the sensor. Another issue with the metal strain gauges is that they do not flex with the same properties as the material it is measuring, resulting in errors between the measured strain and actual strain on the
material [25].

5.2.4 Optical

Optical-based force sensing devices are often referred to as force transducers because they use optics to determine the displacement of a mechanical structure experiencing the force. A force transducer, according to Dan Mihai Strfanescu, is a device that converts a measured force and outputs it as an electrical signal [26]. Similar to our previous use of IR sensors, most optical force transducers use both an IR emitter and a light sensor to determine displacement. One example of this research was conducted by Palli and Pirozzi. They utilized the off-axis light intensity dispersion pattern to determine the change in the angle of the two components and therefore determined the forces applied [27]. Other optical force transducers use reflective surfaces to direct the light back to the light sensor located adjacent to the emitter [28].

A common weakness for these optical transducers is their sensitivity to misalignment. The misalignment of a sensor can have a larger effect on the output of the sensor than the displacement of the mechanical mechanism. This is also true for devices such as the one developed by Palli. The data can still incur errors due to misalignment at installation or even due to external distress once deployed [27]. The second means of error is related to our past research on IR profiling (see Chapter 4), external light sources. These external interferences can cause higher readings than expected.

Total Internal Reflection and Frustrated Total Internal Reflection

A subset of optical-based force transducers use the principles of total internal reflection (TIR) and frustrated total internal reflection (FTIR) as a means of determining force. Total internal reflection is a phenomenon in which light waves traveling within a waveguide becomes trapped due to the properties at its boundaries. Further details about total internal reflection can be found in the Appendix A.

Frustrated total internal reflection is less defined, as there is two differing explanations to the phenomenon. The first definition states that FTIR occurs when a third medium comes into contact with the waveguide, causing the propagating wave to penetrate the new medium and then changes
the trajectory of the wave as it returns to the waveguide and exits at the opposing boundary [29]. The second explanation states that frustration occurs when another surface of a higher reflective index is introduced and causes the wave to exit the waveguide [30]. The following is a description of Han’s implementation of FTIR as a mean of measuring multiple points of force for tracking multiple points on a multi-touch surface. In his research, he used a solid planar waveguide to trap IR waves in a state of TIR. As a user applied their finger to the surface of the waveguide, the trapped IR waves would begin to divert from the waveguide and exit opposite the point of contact. These stray waves would be detected by an IR camera and the resulting image is processed to determine the points of contact and the relative amount of force applied [30]. While it is an effective application of the technology it did come with a high overhead cost and a size much beyond the needs of our project.

5.3 Device Theory

Similar to the other designs of a TIR and FTIR based force sensor, our force transducer is designed to measure the force applied normal to the face of the device. The primary structure of the sensor is a translucent waveguide designed with a higher reflective index than air, but maintaining a low wave power attenuation through the material. These characteristics allow the IR waves to be trapped in the waveguide through TIR. The material choice of our waveguide needs to differ from the other approaches because it needs to be flexible to allow for deformation. The second component device is a solid probe designed to apply the force to the upper bounds of the waveguide. The probe will cause the surface to deform and depress into the waveguide. This depression causes a change in the geometry of the upper boundary of the waveguide, which changes the angle of incident of the IR waves traveling through the structure. This change of angle of incidents will change the mount of IR waves that will exit the waveguide through the upper boundary and the amount of IR energy propagated through the waveguide. The probe itself causes a disruption in the boundary condition of the waveguide, this disturbance alters the IR wave trace, as well as absorbs some of the energy at the point of contact through FTIR. The final component of the transducer is the IR sensor pair, which converts the mechanical forces on the probe to an electrical voltage that can be
easily measured and recorded.

Figure 5.1: A theoretical model of the IR wave trace with no disturbance to the surface of the waveguide. The two sample waves are in a state of total internal reflection causing them to remain in the waveguide.

Figure 5.2: A theoretical model of the IR wave trace with a disturbance to the surface of the waveguide. IR wave trace with initial angle 1 demonstrates the effects of deformation of the incident angle of a TIR wave. IR wave trace with initial angle 2 demonstrates the FTIR effects of a different medium coming into contact with the waveguide boundary. Here the wave is altered by the new medium causing the wave to be absorbed by the probe.

5.4 Computational Analysis

In order to verify our concept and design for a TIR and FTIR based force transducer, we performed a computational simulation for a simplified device design. The simulation test analyzed the energy
transfer through a waveguide with various amounts of upper surface deformations. The simulation was simplified by looking at the waveguide as a two-dimensional parallel boundary structure.

5.4.1 Simulation

Based on the material requirements of the waveguide, PDMS was chosen because it has a reflective index of 1.4, low signal attenuation, and a variable Young’s modulus [31]. The waveguide was set to 15 mm in height and 30 mm in length. The IR emitter was located at the right side of the waveguide and its energy dispersion pattern was modeled after the VSMG2700. The simulation assumed that all surrounding boundaries was air with a reflective index of 1.0, allowing for TIR to occur at all of the boundaries. The program performed a ray trace simulation for the waves emitted from the IR emitter at increments of 0.5 deg from −90 deg to 90 deg off the center axis. Each ray trace was stored in an array with its initial angle, point of contact at the propagating end, and its energy level. The program ran the ray traces for various deformations to the upper surface ranging from 0 to 7.5 mm of deformation at steps of 0.25 mm. The simulation estimated the deformations as an inverse half sine function across the upper surface at the given various max depths.

5.4.2 Analysis

The simulation produced favorable results for the device theory. The results showed a linear relationship between the increase in deformation and reduction of IR wave energy reaching the opposing end of the waveguide. The force needed to cause the deformation was not included in the simulation due to the variability of the PDMS’s Young’s modulus. These results did lead us to believe that in a three dimensional structure the device would maintain similar linear properties between the deformation of the waveguide and the voltage output of the phototransistor.

5.5 Testing Setup

Based on the findings of the computational analysis, a testing setup was developed to test the design and see if the device would fulfill our application needs in a low-cost three-axis anemometer. The following is a description of the testing setup that was developed for the force transducer test.
The parts of the setup includes a manually controlled staging setup, the waveguide, the force probe and the electronics for data acquisition.

5.5.1 Staging Setup

The staging setup is responsible for holding the waveguide in place and controlling the deformation probe. The staging setup was previously designed for IR profiling test, see Chapter 4. The primary component are two Melles Griot linear translation stages, positioned facing each other. They are positioned facing each other to allow the 20 mm micrometers to set a zero state with one platform, while using the other to adjust a given distance. The stages are mounted to a wooden platform to allow for mobile and environmental testing.

5.5.2 Waveguide

The primary component of the device is the waveguide structure. For the reason stated in the computational analysis, the material chosen for the waveguide was PDMS. PDMS is known as a viscoelastic material; this means that it behaves as a highly viscous material at room temperature. The PDMS is hardened by combining it with a curing agent and allowing it to sit and harden. The Young’s modulus of the PDMS can be varied by adjusting the ratio of PDMS and the curing agent [31].

Waveguide Mold

Due to the properties of the PDMS and the required curing process, a mold is needed to create the form of the waveguide. The waveguide mold was designed using a 3D modeling program and printed using a 3D printer, as described in Chapter 3. The material choice for the 3D print was ABS at 100 % infill. Even with the lower layer heights available with the newer printers, the need for our waveguide to have smooth walls was a priority. ABS was the preferred material choice because of the ability to smooth the external surface after the part was printed. Since ABS can be dissolved with acetone, they are combined to create a mixture. The mixture is applied to the surface of the mold and as the acetone begins to evaporate, the ABS binds to the surface and filling
the ridges on the surface. This mixture was applied to the inner walls of the mold to smooth the surface and reduce the effect of the printing process.

The waveguide mold is primarily designed to set the size of the PDMS waveguide. The dimensions of the waveguide are 15 mm high by 15 mm wide and 30 mm long, to match the dimensions of the simulation waveguide. The mold was also responsible for mounting and properly positioning the IR sensors onto the waveguide. To help with the consistent positioning of the IR sensor, they were positioned prior to pouring the PDMS mixture to be cured. The IR sensors are located on PCBs and therefore, slits are made in the mold to for the boards to slide into position. The slits are positioned 1.75 mm back from the squared sides of the waveguide so that the IR sensor’s faces lineup with the sides of the waveguide. There is an included stopper to fill the space above the IR sensors at both ends of the waveguide. The final design component is an extrusion along the length of the waveguide, designed to fit into a socket mount attached to one of the staging platforms. This peg-and-socket design allows for simplified printing as well as the ability to test multiple sensors with the same setup.

Figure 5.3: The primary image is an isometric view of the alignment of the Waveguide Mold and Force Probe. In the top right corner is a top view of the setup and the direction that the probe moves.
Waveguide Fabrication

For the lab test we used a 20 : 1 concentration ratio, PDMS to curing agent. This allowed for a significant amount of deformation, while maintaining the structure of the waveguide.

5.5.3 Force Probe

The force probe was designed to model the mechanical force being applied to the upper surface of the waveguide structure. To better mirror the computational analysis, the probe was designed to have a length that spanned the width of the waveguide rather than a single-point probe. This provided an even deformation across the width of the waveguide, just as a two-dimensional waveguide would look. The tip of the probe was a rounded edge to provide an even force and help with creating even deformation. The rounded end is also important because it helps to prevent the probe from puncturing the surface of the waveguide and damaging the transducer as a whole.

5.5.4 Electronics and Data Acquisition

The IR sensors used in this design is a matched pair: VSMG2700, an IR emitter, and VEMT3700, a phototransistor. The VSMG2700 is a high speed IR emitter with a wide intensity dispersion pattern, which has a half power intensity of ±60 deg. The emitter has a max power of 160 mW at 100 mA. The VEMT3700, the frequency matched phototransistor to the VSMG2700, is an NPN phototransistor optimized for 830 nm wavelength. Each sides of the IR pair has its own designed PCB. The PCB allows the sensors to be placed in the same location, at either ends of the waveguide, to reduce errors due to misalignment. The PCB also makes connecting the sensors to the additional electronics for data acquisition more reliable. The sensors are initially soldered into place while sitting in the mold to optimize the placement and then soldered into place on a separate surface. The National Instrument USB-6211 was used as the data acquisition unit (DAQ) for the test of the transducer. The USB-6211 has a various amount of both analog and digital input and output ports and can be powered completely through USB. This particular unit has a built-in 16 bit analog to digital converters, which allows for recording of data at 0.1 mV resolution. The DAQ allows for the use of an external program such as MATLAB to control and record a various number of inputs and
outputs through its Data Acquisition Toolbox. This allows programs to be written in MATLAB to both collect the needed data and analyze the data in a single program.

The additional electronics for the data acquisition is laid out in the schematic in Figure 5.4. On the left side of the schematic is the IR emitter circuit: this includes the IR emitter, a resistor, and a TIP31. The resistor is a 200 Ω resistor used to limit the output intensity of the IR emitter. The TIP31, a silicon NPN transistor, is used to control the IR emitter through the controller. This circuit allows the controller to turn the IR emitter on and off through software while maintaining the higher amperage compared to the controller output. At the right of the schematic is the phototransistor circuit, which includes a biasing resistor. The resistor is a 2 kΩ resistor to keep the transistor in saturation throughout the range of input from the IR emitter. As the device is designed to be a force transducer, a force sensing resistor (FSR) or strain gauge was added to the circuit. The FSR used in our test setup was an Interlink Electronics FSR. This sensor was placed on the surface of the waveguide just beneath the probe to measure the force that the probe applied to the waveguide. The FSR functions as a potentiometer; as the force applied to the sensor increases, the output resistance decreases. To measure the change in resistance, the FSR is placed in series with a 10 kΩ resistor to create a voltage divider circuit. Due to the size of the 10 kΩ resistor, a voltage follower configured operational amplifier was added to reduce its effects of the resistor on the input resistance of the DAQ.

Figure 5.4: The circuit schematic for the force transducer including the basic electric components and the ports on the NI-DAQ that they are connected to.
5.6 Test

The testing procedures can be broken down into two parts. The first being the calibration testing setup. It is here that the zero conditions are set and the staging platforms are configured to operate as needed for the test. The second part are the procedures used to test the force transducer and record the displacement of the probe, force applied to the device, and the voltage output due to the displacement change.

5.6.1 Calibration

The calibration portion of the testing procedure is designed to set the starting positions for the staging platforms. By setting one of the platform to zero and the other set to a fixed initial position, this allows for the displacement test to be quickly repeated. The force probe platform’s micrometer is set to 10 mm, this will allow for the probe to have 10 mm of depression into the waveguide. Then, the mold platform is adjusted till the probe is making contact with the upper surface. To attain an accurate starting point, a voltmeter is attached to the FSR circuit and the output is observed to be just above zero. The position on the mold stage micrometer was recorded and the process was repeated two more times. The average position of the three test determined the fixed position of the mold stage.

5.6.2 Testing Procedure

The test is primarily controlled by the program written in MATLAB. The internal parameters of the programs allows the user to set the max displacement and the size of each incremental step toward that max displacement. The user initiates the program and the screen will display the deformation depth to be measured, starting with the initial state of zero. A cover is then placed over the mold and the probe to help eliminate any external interference of IR light. Upon setting the probe to the correct depth, the user presses any key on the keyboard and the program will begin to take measurements. Each set of measurements are taken at 1000 samples a second for five seconds. The first set of measurements is with the IR emitter off and then it will take a second set of measurements with the IR emitter on. The measurement sets are then stored into a dynamic
matrix to be processed after all depths are recorded. Once the data is stored, the program will increment the output on the screen to the next deformation depth and the process is repeated until the max depth is reached.

5.7 Results

My results and analysis is broken down into three sections. The first examines the direct correlation between the deformation depth and the voltage output of the phototransistor. This will most closely be compared to the computational analysis, as it only took into account depth deformation and not force. The second section will compare the deformation depths to the force values derived from the FSR. The final section will infer conclusions based on a comparative look at the force values and its correlating voltage output from the phototransistor.

5.7.1 Displacement vs. Phototransistor

The first set of data to be examined is the deformation displacement to phototransistor voltage output, see Figure 5.5 for a plot and best fit line of the data gathered. The plot shows that the correlation between the displacement and the voltage output is not perfectly linear as in the computational analysis, but it does show linear performance regions. The best fit line for the overall set of displacements is:

\[ V(x) = -0.00059x^3 + 0.01001x^2 - 0.07651x + 0.9672. \]

The plot can be broken down into three linear regions: 0 to 1.5 mm, 1.5 to 3.5 mm, and 3.5 to 7.5 mm. These regions can be used as isolated regions for linear performance in later designs. The non-linearity between the displacement and voltage output can be contributed to several different factors. One contributing factor is the nonlinear response of the phototransistor to the change in IR intensity. The nonlinear response of the phototransistor was first revealed during our research of IR sensor profiling, see Chapter 4. Another contributing factor could have been the placement of the FSR on the top of the waveguide. Just as the probe can provide FTIR, the circular disk
Figure 5.5: The best fit line for the displacement-voltage data with the FSR in place and the data point collected for each displacement step. The equation of the best fit line is 

\[ V(x) = -0.00059x^3 + 0.01001x^2 - 0.07651x + 0.9672. \]

The footprint of the FSR could have an effect on the voltage output of the phototransistor.

Since the final application of the sensor would not include an FSR, the test were then repeated without the FSR installed. The data from this retest is shown in Figure 5.6, the plot displays all of the points collected and the best fit line for the data points. The best fit line for the overall voltage output to displace without the FSR is:

\[ V_{out}(x) = -0.0009464x^3 + 0.01388x^2 - 0.08259x + 1.063. \]

The new plot does not initially show a dramatic difference between the first and second test, except for the graph having a more dramatic change at the initial point of contact. The second difference was a more linear decay in relation to the change in displacement from 3 to 7.5 mm, see Figure 5.7. The best fit line for this region is

\[ V_{out}(x) = -0.01945x + 0.9758. \]

This may provide an ideal region of operation for the future design of the force transducer. The final analysis of this set of data was a power spectrum analysis for each displacement deformation for both tests. The average signal to noise ratio for both tests were very favorable with \(4.425 \times 10^6\) and \(5.645 \times 10^6\), respectively. This shows that the data acquired through the test was not affected
Figure 5.6: The best fit line for the displacement-voltage data and the data point collected for each displacement step without the FSR in place between the probe and the device surface. The equation of the best fit line is \( V(x) = -0.0095x^3 + 0.01388x^2 - 0.08259x + 1.063 \).

Figure 5.7: The linear region of the IR phototransistor output from 3 to 7.5 mm displacement without the FSR present. The equation of the best fit line is \( V(x) = -0.01945x + 0.9758 \).

by external noise.

5.7.2 Displacement vs. Force

The next set of data was the deformation displacement to force measured by the FSR. This data was plotted out and a best fit line was found for the data point, as shown in Figure 5.8. The best fit line for the plot is

\[
F(x) = -1.561x^3 + 4.79x^2 + 177.5x - 6.649.
\]
The results of the plot was not as expected. It was initially believed that the relationship between the displacement and force would be either linear throughout or exponentially increase as the deformation increased. Instead, we have a linear region from 1 mm to 4 mm, which correlates to roughly 0 to 700 g of force. But after 4 mm, the force value does not increase exponentially, but rather converges.

After looking back at some images of the test, we concluded that this behavior after 4 mm of deformation can be contributed to the large amount of flex the FSR experienced at the greater depths of deformation. The bending can cause the dispersion of the force away from the force sensor and result in lower reading and less sensitivity to the force being applied. Just as with the previous set of data, a power spectrum analysis was conducted on the data set for each displacement. The results show that there is little to no effect of external noise on the system with a signal to noise ratio of $6.3 \times 10^7$. These values validate the precision of the data gathered from the circuit.

### 5.7.3 Force vs. Phototransistor

The final set of data is an indirect comparison between the voltage output of the phototransistor and the FSR measurements for the force applied to the waveguide. The data correlating data points
Figure 5.9: The primary image shows the deformation of FSR and the upper surface due to the large displacement. In the top right corner is an image of the printed circuit boards that mount the IR emitter and IR phototransistor.

are plotted in Figure 5.10, and the best fit line for the points plotted is

\[
V(g) = (-4.82 \times 10^{-10} g^3 + (8.024 \times 10^{-7})g^2 - 0.0006g + 0.978.
\]

The plots shows a semi-linear relationship between voltage output and force up to 700 g of force. This ties directly to the linear correlation that we had in the previous force to displacement data. The inconsistencies in the values as the force increases can be contributed to the errors from the greater displacement values in both of the two tests.

Figure 5.10: The best fit line and the data point for the forces recorded from the FSR in correlation to the voltage output of the IR phototransistor. The equation of the best fit line is \( V(g) = (-4.82 \times 10^{-10} g^3 + (8.024 \times 10^{-7})g^2 - 0.0006g + 0.978. \)
5.8 Conclusion

The results show that the implementation of a total internal reflection and frustrated total internal reflection force transducer is a viable technology. The technology takes advantage of the physical and optical properties of PDMS and used it as a malleable IR waveguide. The device determines the force being applied by transferring the force to the upper surface of a waveguide, causing it to deform and change the internal TIR properties of the waveguide. This change causes the IR waves’ propagating energy to change at the receiving end of the waveguide. The initial computational analysis confirmed the basis of the design of the transducer and spurred the production of an initial prototype, a proof of concept. The proof of concept was tested and demonstrated that within some constants the device is a viable solution for measuring force. The first set of data was the comparison between the deformation depth and voltage output of the phototransistor. These results supported the the computational analysis originally performed. The second set of data was the deformation depth versus force measurements from the FSR. Due to some errors with the use of the FSR, the linearity of the force was only true for the first 4 mm of deformation. This error carried into the final data set, which was the comparison of applied force to voltage output of the phototransistor. The final data set maintained the linearity between the force and voltage output for the first 700 g of force, confirming the validity of the sensor design as a whole.
CHAPTER 6
CONCLUSION

In this paper we discussed the development of a three-axis anemometer designed initially for the study of wind flow in urban areas and the wind phenomenon known as architectural wind. The need of this study was an anemometer, which could measure wind speed along all three axes. The anemometer needed to be able to be deployed with high spatial density, requiring a lower price point to purchase a larger number of sensors. The dissertation follows the journey of the sensor’s development and subsequent discoveries and innovation. These include the implementation of rapid prototyping technologies and design processes, investigation into IR sensor pairs for determining displacement, and design of an IR force transducer that uses principles of total internal reflection. The three-axis anemometer began as an alternative to the currently available anemometers currently on the market as they did not meet our needs. The original prototype was constructed from materials readily available and seen as a proof of concept. Prototype I was large and did not consist of an outer shell but rather just a proof mass located at the top of the structure. As a proof of concept, Prototype I showed the principles behind the design had merit and the design was worth pursuing. The initial results projected the sensor would be able to withstand wind speeds upward of 100 mph at a resolution of 0.2 mph. These projections would place the sensor on par with the sensors currently available on the market. The development of the anemometer continued with Prototype II, a miniaturization of Prototype I manufactured using a large scale 3D printer as a single print. The smaller design maintained the general performance of the larger prototype but issues due to the manufacturing process arose. The 3D printer used fused deposition modeling to generate the prototype, which resulted in weak points due to the resolution of the printer. These weak points were along the beams of the parallel suspension arms, which caused them to break. Due to the challenges of Prototype II, Prototype III needed to take a greater consideration for the manufacturing process. Prototype III decomposed the various axis into individually printed parts. This allowed the strands of the FDM process to be along the length of the suspensions, giving strength to the parallel-guided suspension. Prototype III was not tested because the tolerances of
the new manufacturer caused the individual prints not fit together. The final assembled prototype, Prototype IV, used a desktop 3D printer and the rapid prototyping design process. The device took several iteration to be fitted together and assembled. With Prototype IV, a new IR sensor pair was implemented to reduce the IR sensor's footprint. The small size of the IR sensors made taking measurements a challenge because the wire contacts would become disconnected after the device was enclosed.

Prior to the development of Prototype IV, we transitioned to rapid prototyping technology and design process. Rapid prototyping technology are machines that use additive methods to create a device from CAD drawings. An example of this technology is fused deposition modeling based 3D printers, such as the Thing-O-Matic and Replicator 2x. The convenience of a desktop 3D printer allows for the rapid prototyping design process to flourish. Rapid prototyping design process is differs from conventional designing because it emphasizes the quick production of multiple prototypes and very incremental changes between each version. This process is a more tactile approach to designing as the designer is able to put their hands on each iterative change to the design. In combination with a PCB CNC mill, the way that we designed our devices and testing setups evolved.

Based on the results of Prototype IV, further investigation into the performance of the IR sensors were conducted. The first of the tests examined the output profile of the IR phototransistor in relation to its displacement from the IR emitter. In this test we also studied the effects of external IR interference on the output of the sensor and possible means for mitigating any of these effects. The results of the test show that for a system where the IR sensor pair are positioned directly inline with each other the optimal range of operation is between 0 and 3 mm. This range is optimal because it offers the greatest amount of linear relation between displacement and output voltage. The greater result from the test is related to the effects of the external interference. The results showed that there is a direct relationship between the output of the phototransistor when the IR emitter is on and off, in the presence of an external IR source. This relationship allowed us to conclude that the output of the phototransistor due to the IR emitter displacement, which is not in the presence of external interference, can be derived by subtracting the voltage output when
the IR emitter is off from when it is on, when in the presence of external interference. Therefore by pulsing the IR emitter at a slower rate than the data is being collected, data processing can determine the output of the IR sensor pair with minimized effects from the external sources. Due to the favorable outcomes, further investigation was conducted to an alternative to a line of sight set up. The alternative setup, placed the two IR sensor pair components to be soldered to the same PCB adjacent to each other. The displacement would be determined by reflecting the IR light off a secondary surface back to the PCB containing the IR sensor pair. The setup produced similar results to the original setup but the change in voltage is respect to displacement occurs more gradually. This results in a larger linear region of operation, 2.5 to 6 mm of displacement.

As a method to reduce the size of the anemometer, which these sensors were being tested, PDMS based circular waveguides were tested as a means of transmitting and receiving the IR signal from a remote position. The several test and configurations for the circular waveguides resulted in negative findings and the abandonment of the approach.

Due to the failure of the circular waveguides, investigation into the development of a force transducer that used principles of total internal reflection and frustrated total internal reflection. This new transducer consists of an IR sensor pair and an optical waveguide, which can be deformed. The concept behind the design is based on TIR, when the upper surface of the waveguide is deformed due to a given force the output voltage will change. This change is proportional to the force being applied to the transducer. The initial test was a computational simulation of the theory. The results of the computational analysis was favorable to the pursuit of the new technology. Using the methods and processes of rapid prototyping, a test setup was designed and constructed to determine if the transducer would work as a practical application. The experiments tested the transducers voltage output in relation to various deformations of the upper surface. To correlate the deformations to a given force, a force sensing resistor was position between the probe and the upper surface of the device. The results of the test confirmed that the IR force transducer design is viable and the use of PDMS is well suited for the application. Also the current design has an optimal operational displacement of 0 to 4 mm, which maintained a general linearity. At the current PDMS, PDMS to curing agent ration, the upper bounds of the optimal force range is 700 grams of
force. These finding leads us to move forward with the redesign of the three-axis anemometer to incorporate the IR force transducer.

6.1 Projection of Performance of Low-cost Three-axis Anemometer

The new design will need to consist of the newly developed force transducer and abandons the parallel guided suspensions of previous designs. An initial design of the internal structure, see Figure 6.1, focuses on the two planar axes. The new design takes advantage of the IR force transducer to create the counter forces and output values for the force due to the wind. The general shape of

Figure 6.1: Initial design of a new possible internal structure of the new three-axis anemometer for two of the axes. The new design take advantage of the force transducer developed and abandons the beam structure from previous designs. The red component is responsible for measuring force along one axis. The blue component translated the force to the red component and contains the structure of the second axis. At this time the yellow component is responsible for translating energy to the second axis.

the exterior of the sensor will be a spherical shape to help reduce the objects Reynolds number. A spherical shape is favorable because any turbulence it experience as the air travels around the sensor will be evenly dispersed. The outer shell will need to be connected to the inner structure in such a way that the it reduced the amount of twisting forces on the suspensions, allowing for the best translation of energy. The size of the outer shell is projected to 10 cm in diameter, similar to the size of a fast pitch softball. At this size, the internal structure will experience forces ranging from 0 to 419.9 grams-force at 100 mph due to the drag forces, see Appendix B. This places the
forces experienced by the anemometer in the optimal range of the force transducer with room to adjust the curing ratio of the PDMS. These finding are favorable for the continued development of the three-axis anemometer.

Beyond the single use as an anemometer, the new design shows promise as a general purpose three-axis fluid flow sensors. This is due to the containment of the electronics and scale-ability of the internal pressure sensors. The implementation of the technology beyond the study of wind demonstrates the impact of the research on sensor development.
Total internal reflection is an optical phenomenon where a wave is contained within a medium as it is completely reflected back into the waveguide as it meets boundary of the waveguide [32]. The conditions for this phenomenon to occur are defined by Snell’s Law, which describes the behavior of a wave as it meets and pass through a boundary of two different medium. Snell’s Law is described by the formula,

\[ n_i \sin \theta_i = n_r \sin \theta_r, \]  

(A.1)

where \( n_i \) and \( n_r \) are the index of refraction the two medium and \( \theta_i \) and \( \theta_r \) are the angle of the wave normal to the boundary surface. Total internal reflection occurs when the refracted angle, \( \theta_r \), is greater than equal to 90 deg. For this to occur the index of refraction of the refracted medium has to be greater than the incident medium. Also the angle of incident need to be greater than the critical angle, the angle at which the angle of refraction is equal to 90 deg. The critical angle is derived from equation A.1 and results with the following equation,

\[ \theta_c = \theta_i = \arcsin \frac{n_r}{n_i}. \]  

(A.2)
This appendix provides a description of the drag forces on the outer shell of the three-axis anemometer. The drag force for our anemometer design is calculated through the following process. For the calculations the anemometer is modeled as a smooth sphere with a radius of 4.5 cm. The calculations defined the properties of air as follows: density is $1.275 \text{ kg/m}^3$ and viscosity is $1.845 \times 10^{-5} \text{ Pa*s}$. As the drag force varies based on the velocity of air relative to the object the range of wind velocity is 0 to 100 mph at 5 mph intervals; the speeds are converted to m/s during the calculation. Reynolds number is calculated using the following equations,

$$Re = \frac{u \sqrt{A}}{v}, \quad (B.1)$$

where $u$ is the velocity, $A$ is the relative area of the object ($A = \pi r^2$), $v$ is the viscosity, and $Re$ is the Reynolds number. For the best design, $Re$ should either be sufficiently large ($> 6000$) to ensure fully turbulent flow or sufficiently small ($< 100$) to ensure fully laminar flow, avoiding the transition region where oscillations due to large-scale vortex shedding can occur [33]. The Reynolds number is used to determine the drag coefficient, which is determined experimentally. According to Morrison [34], the relation between drag coefficient and Reynolds for a sphere can be expressed using the following equation up through $Re = 10^6$ but not much higher:

$$Cd = \frac{24}{Re} + \frac{2.6 \times \frac{Re}{5.0}}{1 + (\frac{Re}{5.0})^{(1.52)}} + \frac{0.411 \times (\frac{Re}{263,000})^{(-7.94)}}{1 + (\frac{Re}{263,000})^{(-8)}} + \frac{Re^{(0.8)}}{46,100}. \quad (B.2)$$

With the drag coefficient calculated the drag force and be determined with the following equation,

$$F_d = \frac{1}{2} \rho \times u^2 \times Cd \times A. \quad (B.3)$$

The calculation are presented below in a table with force presented in both Newtons and gram-force.
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Table B.1: Correlation between wind velocity to the drag force on a spherical object with a radius of 4.5 cm. The drag force is represented in both Newtons and grams force. The table also shows the Reynolds number and drag coefficient for each wind velocity.
BIBLIOGRAPHY


[33] Haniu Sakamoto and H Haniu. A study on vortex shedding from spheres in a uniform flow. 
