DEVELOPING A LOW-COST SENSOR FOR COMPARATIVE ANALYSIS OF HIGH FREQUENCY WIND SPEED FLUCTUATIONS

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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Abstract

An anemometer is an instrument used to measure the speed of the wind. There are multiple types of anemometers including cup, wind-vane, hot-wire, sonic, and pitot tube anemometers. This project uses a differential pitot pressure sensor, meaning it has both a pitot tube sensor and a static pressure sensor. The goal of this project is to design, build, and test a functioning instrument for under $100 that accurately measure atmospheric wind speed fluctuations at a high temporal resolution. This project will advance knowledge of using low-cost single-board computers in conjunction with sensors to obtain accurate environmental measurements. The hypothesis is that a Raspberry Pi computer with a pitot pressure wind sensor will be capable of measuring wind velocity to a similar accuracy as a Kestrel 5500 weather meter. In addition, it can improve on the Kestrel 5500 by providing higher frequency measurements. The observations of wind velocity by the pitot pressure sensor are found by calibrating measured voltage, which is a function of the pressure difference between the pitot and static pressures, to a known wind velocity. Both preliminary calibration tests and the final runs yield promising indications that the desired goals for accuracy and high-frequency response were achieved.

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Chapter 1

Introduction

1.1 Importance of Measuring Wind

Measuring the speed of the wind accurately has many useful and important applications, especially in the scientific field. Wind is caused by variations in atmospheric pressure. As air is pushed from high pressure areas to low pressure areas, wind is generated. The velocity of the wind is dictated by the pressure difference between the high and low pressure areas, often called the Pressure Gradient Force, as well as the density of the air. The wind that is generated is also acted upon by two other forces, (1) friction near the Earth's surface, and (2) the Coriolis force due to the Earth's rotation (Figure 1). Friction affects the velocity of the air, slowing it down at the surface while the Coriolis force creates a directional shift of the air as the Earth rotates and pulls the atmosphere along with it. Furthermore, vertical air motion is induced by thermal energy given off by the sun. The sun directs short wave ultraviolet energy towards the Earth's surface and the Earth radiates that energy back out in the form of long wave infrared energy.

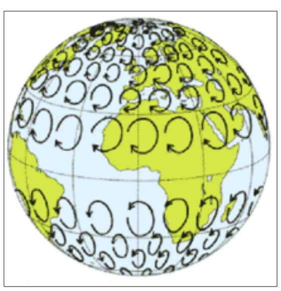


Figure 1. Coriolis Effect in the northern and southern hemispheres.

Wind governs many aspects of the natural world. These aspects include important climate functions, one being the generation of ocean currents, which influence plant and animal life. Another environmental process that is significantly influenced by wind is the erosion of the Earth's crust and the transport of airborne sediment around the globe. Unfortunately, land development by humans in both the agricultural and city environments has increased the natural rate of erosion by as much as 40 times the natural rate of soil renewal [14]. This is due to the removal of vegetation and topsoil with the simultaneous addition of nonporous concrete, which inhibits the natural drainage of precipitation [14]. Wind also allows for the critical task of facilitation of migration of plant life which is known as anemochory. Wind carries plant seeds and spores in certain directions, allowing for pollination to occur and increasing the plant's chance of survival via the possibility of long distance migration.

Wind can also play a destructive role in life on Earth, causing large amounts of damage to both plant and animal life. This can occur in the form of strong gusts of wind, storms, hurricanes, and tornadoes. These weather events carry an immense amount of force and can cause homes to be torn down if the speeds exceed a certain threshold. Severe weather events can also influence everyday human life. An example includes inhibited travel by both plane, automobile, and foot due to storms and strong wind gusts. Being able to measure the speed of the wind accurately and gaining insight into current and future weather patterns is therefore of high interest to everyone, regardless of specialization.

1.2 Instruments Used to Measure Wind Speed

Even before electricity was first used, humans created devices to measure the speed of the wind. Wind measuring instruments are called anemometers. There are two main types of anemometers, velocity anemometers and pressure anemometers. Velocity anemometers measure the direct velocity of the incoming wind. These include a number of instrument types such as the cup anemometer, vane anemometer, hot wire probe anemometer and sonic anemometer. Pressure anemometers, on the other hand, use a pressure sensor to measure pressure exerted on a diaphragm by the incoming wind. Pitot tube anemometer use this method. The following sections describe anemometers in more detail.

1.2.1 Cup Anemometer

A cup anemometer has a simple design which consists of three or four half spherical cups mounted on arms around a main rotating shaft (Figure 2). The rotational speed of the main shaft is measured and translated to a wind speed measurement [4]. The cups are oriented perpendicular to the oncoming wind direction to maintain an accurate reading. These devices are useful because they have a simple design and work regardless of the horizontal wind direction. The round shape on the back-side of the cups allows for minimal drag as it pushes through the wind and back around. The small amount of drag that is generated can be accounted for with a simple calculation. However, one large drawback to cup anemometers is the delay between the actual wind speed and the spinning of the cups as they generate or lose momentum. Therefore cup anemometers work well for long-term averages but not high frequency wind fluctuations nor extremely low or high wind speeds [4].

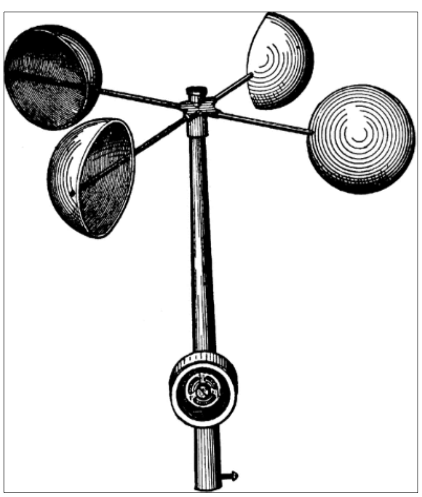


Figure 2. Robinson Cup Anemometer, named after the inventor Dr. John Robinson in 1845.

1.2.2 Wind Vane/Propeller

A second common type of wind measuring device is the vane anemometer, or propeller anemometer which measure the rotational speed of a propeller driven by the wind [6]. The two main types of vane anemometers are hand-held digital and mounted. Hand-held digital anemometers have a small wind turbine in a closed circular shell which spins and records measurements onto a microchip [6]. These are useful in many professions and environments due to being small, easily deploy, and giving accurate readings. However, the user must ensure that the device is oriented directly into the wind, as it does not have a mechanism to align itself. This is important, as misalignment with the incoming wind causes errors in the measured wind velocity. Mounted anemometers can overcome this problem.

Mounted anemometers use the same propeller type method to measure wind speed, but they include a tail and are mounted on a free spinning axis (Figure 3). This allows them to always be oriented directly into the oncoming wind, easily allowing for long term averages to be taken without supervision or manual orientation. However, vane anemometers still have the same problem as cup anemometers of gaining or losing blade momentum, but fortunately they are smaller, do not carry as much force, and are therefore able to give more accurate measurements over short periods of time [4].

Figure 3. Mounted wind vane anemometer.

An example of a hand-held anemometer is the Kestrel 5500 Weather Meter, which will be used in this study to calibrate and test the new wind sensor. The Kestrel 5500 Weather Meter is a pocket sized weather sensing device that measures 5 inches high, 1.8 inches wide and weighs 102 grams [5]. The current cost of the Kestrel 5500 is $399 and being a hand-held anemometer, the user must manually position the meter directly into the oncoming wind to gauge an accurate reading [5]. This, and other hand-held anemometers, are used in virtually every field as they offer easy portability and can store many data points (up to 10,000) [5]. The accuracy of the Kestrel 5500 is "+/- 3% of reading, least significant digit of 20 ft/min" as stated by the product manual with a resolution of 0.1 m/s, and a measurement range of wind velocity from 0.6 m/s – 40.0 m/s [5]. The battery life of the device is estimated to be up to 400 hours, as stated by the company website and the device is also waterproof [5].

Figure 4. Kestrel 5500 Weather Meter, a hand-held digital anemometer.

1.2.3 Hot Wire Probe

Hot wire anemometers are another method of measuring the wind (Figure 5). They do not use any moving components, instead utilize a very thin wire that is electronically heated to a specific temperature while air flows over it [7]. The amount of energy required to keep the wire at a constant temperature is measured and translated into wind velocity [7]. Hot wire anemometers are extremely responsive compared to cup and vane anemometers and are not reliant on perfect orientation into the wind. Because of their responsiveness, they are widely used and are simple, inexpensive, and reliable. However, many hand-held and budget hot wire anemometers are delicate and can be easily damaged by dirt or debris coming into contact with the fragile wire [7]. Hot wire anemometers are also not designed to measure wind speeds of more than ~10 m/s, although some heavy duty industrial models are able to measure winds >30 m/s [7].

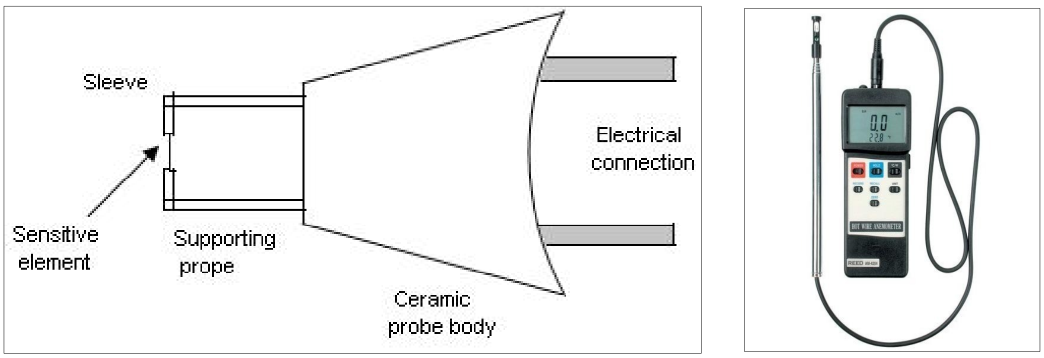


Figure 5. Diagram detailing the components of a hot wire probe (left) and an example of a hand-held hot wire probe (right).

1.2.4 Sonic Anemometer

A sonic or ultrasonic anemometer uses sound waves to measure the velocity of the wind (Figure 6). The time it takes for the sound waves to cross from one side of the device to the other is calculated and calibrated to correlate with the speed of the passing wind [8]. Some sonic anemometers measure two-dimensional flow, and others are capable of measuring three-dimensional wind fluctuations [8]. The two-dimensional models consist of three or four arms mounted to a base [8]. The three-dimensional versions have the same design but also consist of a bottom and top array, so that the vertical as well as horizontal sound waves can be analyzed [8].

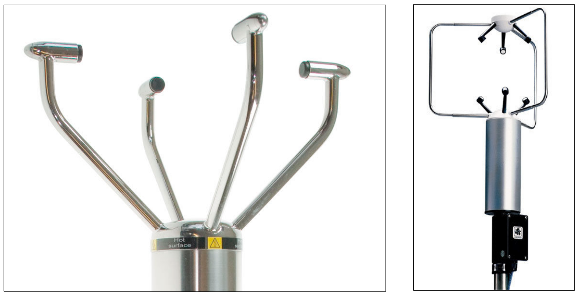


Figure 6. 2-Dimensional sonic anemometer (left) and 3-Dimensional sonic anemometer (right).

Sonic anemometers are advantageous over the previous three types of wind sensors as they have no moving parts or extremely fragile components, and can be deployed into areas with dusty or salty air [8]. However, the accuracy of the wind measurements can be affected if the air density strongly varies. Rain also impacts the measurements significantly because water is more dense than air and absorbs the sound waves [8]. These types of anemometers are also expensive, costing at least $1000 even for the budget array since they require modern sensor technology to operate.

1.2.5 Pitot Tube Anemometer

The final common anemometer type is the pitot tube anemometer (Figure 7). Pitot tube anemometers are used on all aircraft and are also the sensor type selected for use in the anemometer built for this project. Pitot tube anemometers work by measuring the pressure exerted on a sensor at the end of a thin tube into which the wind blows [11]. The measured pressure is then translated to a wind speed [11]. The pressure of the surrounding air must also be taken into account for this calculation. This can be done manually, or with the use of a pitot-static tube anemometer that measures differential pressure. Differential pressure is the pressure difference between that which is exerted by the wind and that of the ambient pressure. Pitot tube anemometers are advantageous over cup or wind vane anemometers because they are capable of taking high frequency measurements, meaning more samples can be taken in a second.

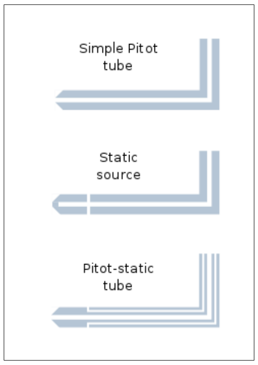


Figure 7. Three types of pitot tubes: simple pitot tube (top), static pitot tube (middle), and pitot-static tube (bottom).

Pitot-static anemometers have an inner tube which measures the direct pressure exerted by the incoming wind, and a larger outer tube separated from the inner tube [11]. This outer tube is connected with a different pressure sensor, giving an additional pressure reading for the stationary air [11]. The static port holes are typically oriented perpendicular to the pitot tube on the end to minimize the amount of interference on the static reading [11]. The two pressure measurements are used to calculate wind velocity using the following relationship [9].

$$U=sqrt((2\Delta P)/\rho)$$

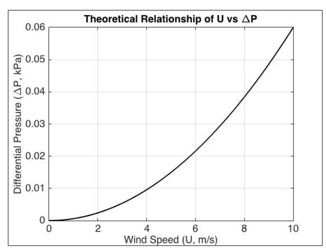


Figure 8. A modified version of Bernoulli's equation, where **U** is wind velocity, **ΔP** is the differential pressure, and **ρ** is air density (left). Theoretical relationship between differential pressure (**ΔP**) and wind speed (U) in m/s (right).

A modified version of Bernoulli's equation can be used to generate a graph of theoretical relationship between the differential pressure (**ΔP**) in kPa and wind speed (**U**) in m/s (Figure 8). This relationship can then be used to connect differential pressure with voltage, and voltage with wind speed (Figure 18).

Pitot tube anemometers can be mounted on an object or come in a portable hand-held design. The only significant downside for this type of anemometer is its requirement to be aligned perfectly into the oncoming wind. Any deviation will cause the device to underestimate the differential pressure measurement and therefore underestimate wind speed. Deviations can also cause the wind to ricochet off the walls of the pitot tube, slowing down the air, and providing an inaccurate reading [11].

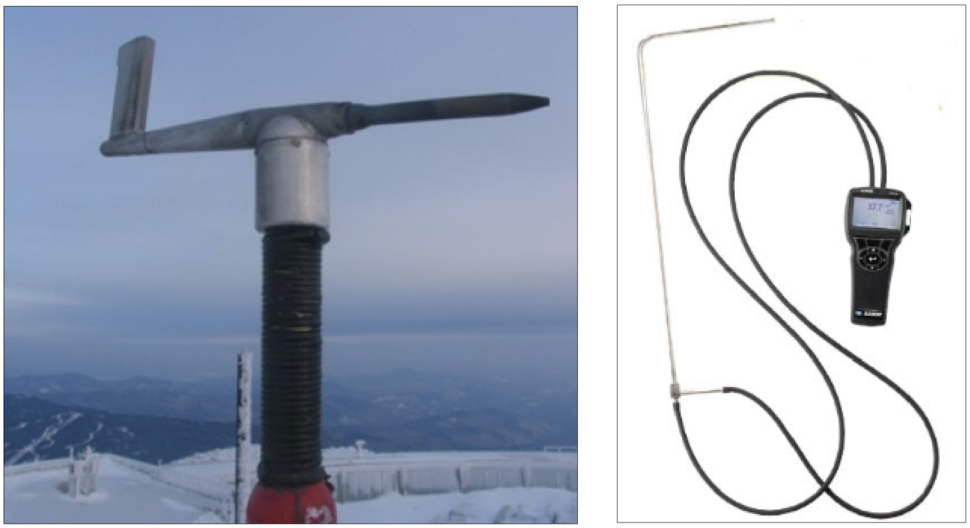


Figure 9. Mounted pitot-static tube anemometer (left) and hand-held pitot-static anemometer (right).

1.3 Advantages and Disadvantages

Each anemometer type has advantages and disadvantages, and are therefore used with different levels of success depending on the environment, field of study, and data requirements. Some anemometers offer high levels of accuracy over short intervals of time, like the pitot pressure tube, sonic and hot wire anemometers. Others are robust and easily deployed into the field without any special equipment, like the hand-held and hot wire anemometers. Some are self-orienting, like the cup, mounted wind vane, or do not require orienting like the hot wire or sonic anemometer. Yet others like the hand-held, hot wire, and pitot tube anemometers still require the user to position the device manually. These considerations were taken into account in the design of a new anemometer.

1.4 New Sensor

The new anemometer under development consists of multiple components that function together to automatically measure, log, and analyze wind speed. The new anemometer uses a Raspberry Pi Zero in conjunction with a pitot pressure wind sensor, analog to digital converter, and a 3D printed plastic housing to measure the wind. A Python 3 computing script is used to run the sensor, log the data and complete analysis.

1.4.1 Raspberry Pi

A Raspberry Pi (Figure 10) is a pocket-sized computer that is condensed onto a single circuit board [1]. Raspberry Pi computers were developed by the Raspberry Pi Foundation in the United Kingdom to encourage schools to teach basic computer skills without having to purchase expensive machines [1]. The first generation of Raspberry Pi computers (named Raspberry Pi 1 Model B) were released in early 2012 for about $35 [2]. In April of 2014 the Raspberry Pi 2 was released, which boasted 1 GB of RAM, compared to the 512MB in the Pi 1 [3]. In late 2014 the Raspberry Pi Zero was released for a mere $5, this model has an extremely small size and is powerful enough to run an operating system with a graphical user interface along with a python script. This makes the Raspberry Pi Zero an ideal choice to use in the development of a low-cost, lightweight, and small wind speed sensor. Modern versions of the Raspberry Pi and Pi Zero exist, but they are heavier, more expensive than the Pi Zero, and do not offer any additional useful features for this project.

Figure 10. All Pi generations (left), Pi 3 Model B (middle), and Pi Zero (right).

1.4.2 Pitot Tube Theory

The pitot tube used for the sensor is pitot-static, meaning it internally measures differential pressure and reads out a voltage which corresponds to wind velocity. The pitot tube used is about 4" long, has a 0.2" diameter, and is connected to a MPXV7002DP differential pressure sensor (Figure 11). The MPXV7002DP has a resolution of 1000 Hz, meaning it is able to take 1000 measurements every second. This means that this sensor is able to take high frequency measurements and collect 2000 data points in the same amount of time it takes for the Kestrel 5500 to take one. This sensor has an accuracy of +/- 2.5% as stated by the manufacturer and requires only a 5V power supply to operate. The sensitivity of the MPXV7002DP is 1V/kPa, chosen for the range of wind speeds desired. The sensor itself weighs only 2.2g and currently costs about $10 to purchase. The sensor does not require compensation for temperatures within the range of 10 – 60°C (50°F – 140°F). The response time of the sensor is 1 ms, meaning it is able to take 1000 calculations each second. However, the sensor gives a reading in analog signal and a digital signal is needed for the data to get logged into a file.

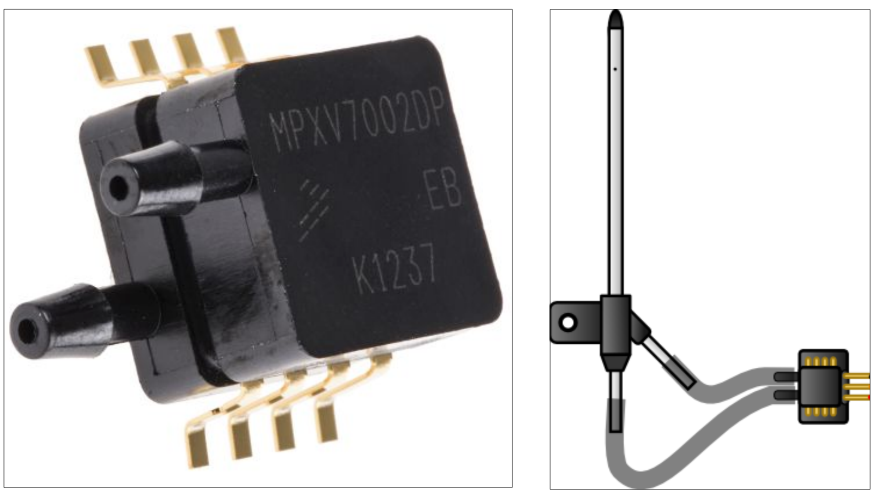


Figure 11. MPXV7002DP differential pressure sensor (left) and pitot-static tube configuration (right).

1.4.3 Analog to Digital Converter

An analog to digital converter (ADC) is used to accomplish the task of translating the analog signal into a digital signal, and for this project an Adafruit ADS1115 was chosen as the ADC (Figure 12). The ADS1115 is a 16 bit ADC that costs about $15 dollars and can take between 8 – 860 samples each second [12]. This means that the ADC is effectively a bottleneck in the system, and instead of 1000 samples per second, only 860 of the given values are able to be logged. Still, the rate is extremely high resolution and will require a running average anyway to reach a comparable accuracy to the Kestrel 5500, so the limitation is acceptable [12].

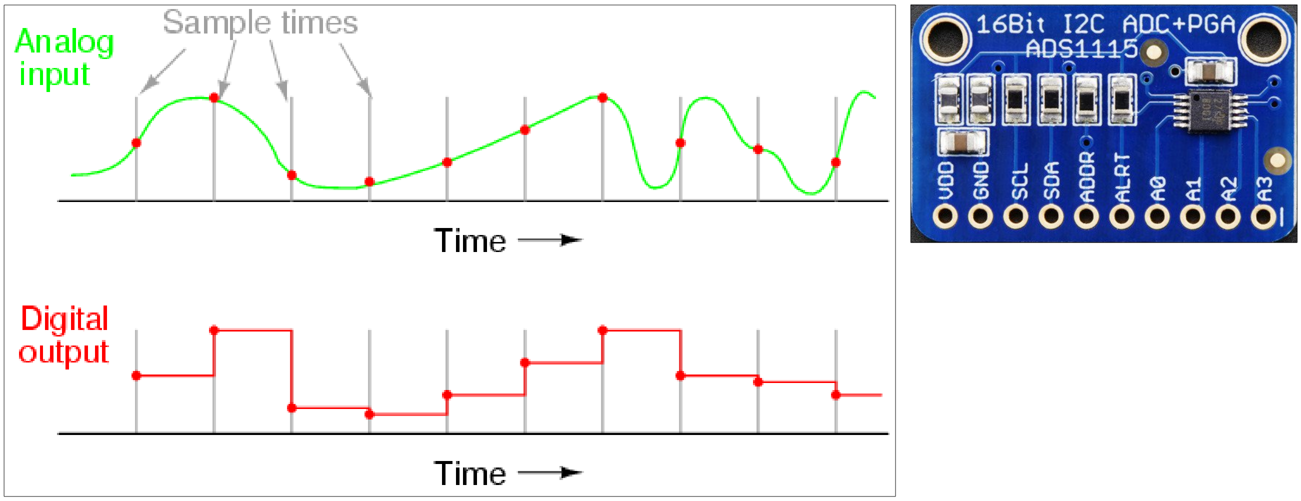


Figure 12. Analog versus digital data collection (left) and the Adafruit ADS1115 ADC (right).

1.4.4 3-D Printing and Design

The housing for the new pitot pressure anemometer is printed using a 3D printer. 3D printing is the process of using a small heated tip to print layers of plastic onto a base [10]. The printing head follows a specific path using two servo motors for each direction and one to lower the platform as the layers of the instrument housing are constructed layer-by-layer [10]. The printed plastic then cools before a subsequent layer is added and fused on the top [10]. This technology is extremely useful and has many applications, allowing a user to model anything they desire on the computer and print it cheaply and easily. While 3D printing machines themselves can be costly (several thousand dollars), they require only a spool of plastic wire to operate.

The plastic used can vary depending on the application. Some plastics are strong, cheap, light, or smooth [10]. The 3D printers also give the user the ability to fully customize the way the models print, including things like hollowing out the inside to save plastic and printing time, printing at different speeds to increase the quality, printing multiple models at once, and even using multiple heads at the same time to complete the print faster [10]. The 3D printer used in this project is the Makerbot Replicator, released in early 2012 (Figure 13). It uses fused deposition modeling and has a resolution of 100 microns with a max building size of 9.9” long, 7.8” wide, and 5.9” high 13].

Figure 13. Makerbot Replicator 3D printer.

1.4.5 Python 3

The last component of the project is the programming language Python 3 which was used to write the script that automatically logs and analyzes the data interpreted by the analog to digital converter (Figure 14). Python is a general purpose programming language that was first developed in 1991 and has been growing in popularity ever since. Python was designed to be fast, easy and efficient, offering support and modules to allow for customization. Python 2 and 3 are both free and can be used to process large arrays of data, making it an ideal choice for use in this project.

Figure 14. Python logo trademark of Python Software Foundation.

1.5 Project Purpose

The purpose of the project is to increase understanding of using anemometers for wind measurement, and to use that knowledge to develop an affordable instrument that can take accurate high-frequency measurements at wind speeds between 0 and 10 m/s. In addition to taking high-frequency measurements a tail will be included in the final design, this will allow for the device to orient itself with respect to changing wind directions. This will allow for the pitot tube to always remain pointed into the wind and reduce the angle between the wind direction and pitot tube line of measurement. Another goal for the project is to have a moving average graph generated after every run and allow for a custom window size input from the user if needed, allowing it to perform both high-frequency measurements or long term averages.

The overall price of the finished sensor is expected to be under $100, meaning that 4 of these sensors could be deployed into the field for the same cost as one Kestrel 5500 Weather Meter. The 3D printed housing for the new sensor is going to be as slim, short, and lightweight as possible to achieve the lowest cost possible. In addition to cost reduction, having a lightweight device reduces the friction between the device and a tripod as it spins to orient into the wind. The last goal for the new sensor is to have it automatically run for a desired amount of time once the script is opened, and have it automatically save the raw data and the graph with the moving average after every test.

Chapter 2

Methods

2.1 Anemometer Design

This project began with the help of the Oceanography 418 class at the University of Hawai'i at Mānoa titled "Advanced Environmental Systems", where introductory knowledge of working with Python and breadboards to create simple circuits with environmental sensors was provided. This class also introduced the concept of 3D printing. Within a few weeks after the end of the semester, a working prototype of the instrument interior was completed, as well as an early sketch of the anemometer housing (Figure 16).

The design process was done in three stages, the first was testing the sensor in the lab to ensure it was was functional and responsive to the wind speed range desired. These tests can be seen in Figure 18, however it should be noted that full length tubing was used in these two tests, which is why the voltage readings are different than the later tests conducted. The second stage was testing all the components inside the first prototype of the 3D printed housing to begin calibrating the device, these can be seen in Figures 34 – 40. The third and final stage was with a fully automated script and taking kestrel data to ensure the fan remained at a consistent wind speed for the full duration of each test. These tests can be seen in Figures 41 to 47. The following section discusses the various anemometer components and how they fit into the final product.

2.1.1 Sensor

A differential pressure sensor with a pitot tube was chosen because it offered the level of desired accuracy with respect to a higher temporal resolution (more measurements per second), with less latency than a cup or propeller, and sensitivity to both low and high wind speeds (Figure 11). Pitot pressure sensors are also cost effective with respect to accuracy, are lightweight, small, and are easily mounted onto a housing. Another advantage to using a pitot tube to measure the wind speed is less buildup of particulates on the measurement surface. This is because the surface area of the pitot tube measurement hole is significantly smaller than a cup or propeller and is therefore less prone to dust and salt particulates coming in contact with the components that have been calibrated for measurement. However, in order to get a reading and record data points from the differential pressure sensor, an analog to digital converter was needed.

2.1.2 Analog to Digital Converter

The differential pressure sensor measures the difference between the static and pitot pressures and generates a voltage that directly corresponds with the wind velocity. The Adafruit ADS1115 was chosen as the analog to digital converter as it is the same one used in the Advanced Environmental Systems class and it offered an 860 sample per second resolution, which means that it is capturing almost all the data points that the sensor is able to measure (Figure 12, right). The 140 other samples that are not able to be recorded are not of extreme importance however, as a running average is taken over many data points to increase the overall accuracy anyway. The sensor passes the voltage readings to the analog to digital converter and it is from this that the Raspberry Pi Zero logs the voltage values into a text file on an SD card.

2.1.3 Raspberry Pi Zero

In the Advanced Environmental Systems class, a Raspberry Pi 3 was originally used, which is 3.3” wide, 2.2” long, and 0.7” depth, weighing 45 g (Figure 10, middle). However, this large size and moderate amount of weight posed a challenge when designing a housing to contain all the components. Near the end of the class, a Raspberry Pi Zero was chosen instead of the Raspberry Pi 3, as the additional accessories on the Pi 3 were not needed. The Raspberry Pi Zero measures 2.5” wide, 1.1” long, 0.2” wide, and weighs only 9 g (Figure 10, right). The current price of the Pi Zero is also $10 compared to the $30 for the Pi 3. These aspects of the Pi Zero represent a significant improvement over the Raspberry Pi 3, and allowed for the design of a much smaller housing. The only additional aspect needed for using the Raspberry Pi Zero was porting over the script from the Raspberry Pi 3 and modifying it to automatically run once the script is opened.

2.1.4 Battery

The power supply chosen for this project is the Anker PowerCore 5000, which is a $15 power bank with a 5000 mAh capacity and is only 4.2” wide, 1.2” long, and 1.2” in depth. The Raspberry Pi Zero draws around 80 mA (0.4 W) while the sensor and ADC both draw a negligible about of voltage. This means that a 5000 mAh battery could run the device continuously for around 43 hrs. This power supply is actually much larger and a higher capacity than required for this project, and a smaller, lighter and cheaper power bank could easily be used in the device with only a small modification to the housing if the user needed a cheaper overall cost or lighter weight.

Figure 15. Anker PowerCore 5000 mAh portable power supply.

2.1.5 Housing

After a working prototype was completed in the lab (Figure 17), a housing design to organize and orient the components into the oncoming wind was needed. 3D printing was chosen to manufacture the housing, as it is inexpensive, lightweight, and easily allows for customization. Customization and the ability to create several prototypes was critical to the housing design process as the internal components needed to fit snugly. The effort to design the instrument housing took several prototypes. The design of each component started out as blocks, then the outside features were modeled and cut away. For the two pieces of the body, an additional step was needed to hollow out spaces for the components to fit inside snugly. The housing was created in several different parts, as there were limitations with regards to size of the printed device using the Makerbot Replicator. There are four different pieces in total: the nose, bottom of body, top of body, and tail. These components were modeled in a software program called Autodesk Fusion 360 (Section 2.5.1) and printed out with the Makerbot Replicator 3D printer (Section 3.1).

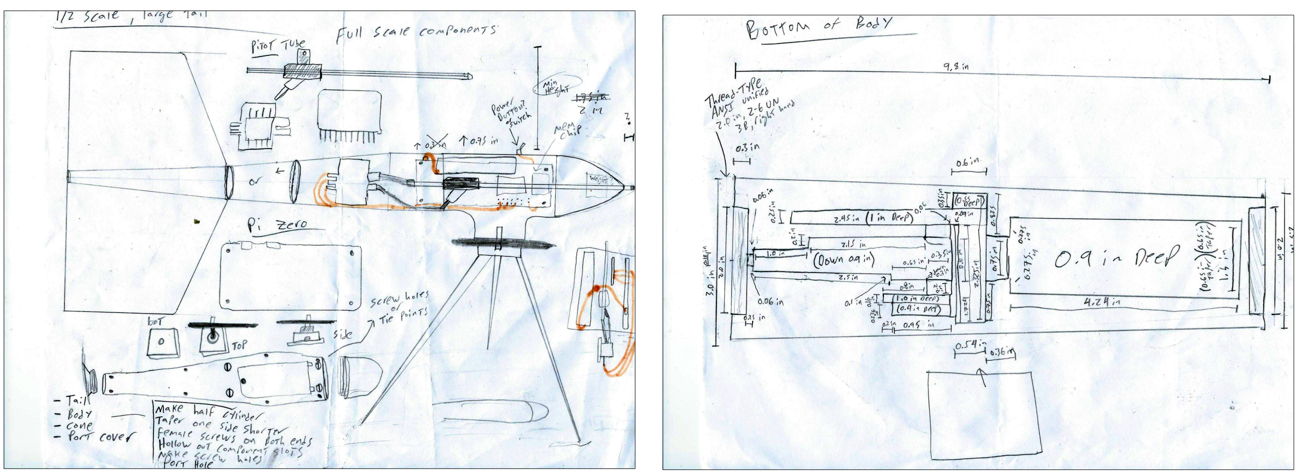


Figure 16. Early sketches of the body and housing design

2.2 Testing the Sensor

The first step after getting the sensor, ADC, and Pi Zero to function together was to write a script that would not only display the voltage values, but also log these values to a text file and average them, this allows for correlation between the voltage and wind velocity for calibration. This calibration is essential, as the sensor gives a range of values as it depresses and inflates with the wind fluctuations, meaning the voltage values need to be averaged together to generate a steady wind speed reading.

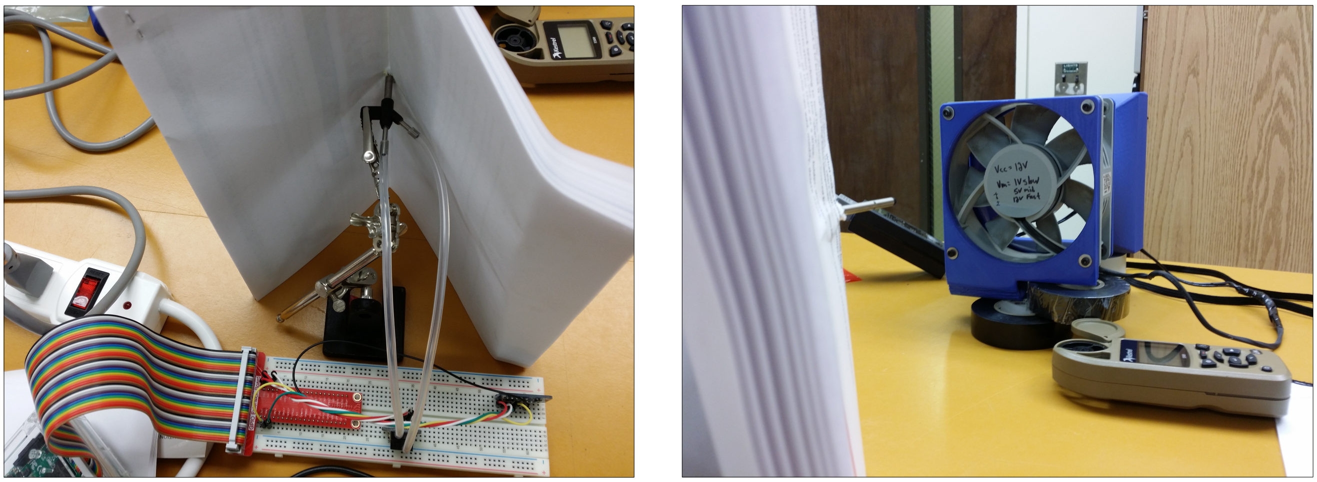


Figure 17. Early setups in the lab to verify functionality of the sensor, Pi, ADC, and scripts.

2.2.1 Analog to Digital Converter Script

A small driver script is required to run the ADC. This script is available on the Adafruit website, and from this script the parameters were set for how the ADC should read and write the voltage values given by the differential pressure sensor. This includes quantities like the sample capture rate, power draw, voltage boundaries, and internal gain. The ADS1115 uses the Inter-Integrated Circuit (I^2C) to connect with the Raspberry Pi Zero resulting in a list of readings that can be logged to a text file.

2.2.1 Sensor Script

The script to run the sensor is composed of several different sections: importing a reference of time and the ADC driver, importing modules to analyze and plot the data, defining a moving average to low pass the data set, pulling data from the ADC, logging the data to a text file, and finally applying a window size and generating a time series plot after the instrument is finished running. The objective of the final script is for it to start when the computer powers up, run for a designated amount of time, save the raw data and graph, run again, and repeat until the device is turned off.

2.2.2 Moving Average

A moving average is essential in the data analysis as it reduces the fluctuations in the wind measurement due to the pressure waves in the tube. A moving average takes a specific number of data points to the left and right side of one data point and averages them all together. This is done for each point. This generates a smoothed time series of voltages which can be calibrated to wind velocity. The number of data points on each side of each number is called the window size. Increasing this value creates a smoother line because more points are averaged together. A prompt is included in the script to allow the user to specify the window size after each sample period, and is helpful when calibrating the device as it allows the user to see the range that would give the highest level of accuracy without compromising the ability for it to take high frequency measurements. The window size selected for all the tests in this paper is 1000, meaning that with a resolution of 860 samples per second a temporal resolution of around 1 Hz is achieved.

2.2.4 Theoretical Calibration

In addition to a manual calibration with the Kestrel 5500, there is also a theoretical calculation that can be used to calculate the wind velocity from the difference in pressure. This uses Bernoulli's equation (Figure 8) as it relates pressure difference to the speed of the flow. This equation is also helpful, as each pressure (static and pitot) do not need to be known, only the difference between them, a value which the instrument provides. Furthermore, we can combine the relationship between **U** and **ΔP** with the relationship between **ΔP** and voltage to relate U directly to voltage. The theoretical relationship is as follows:

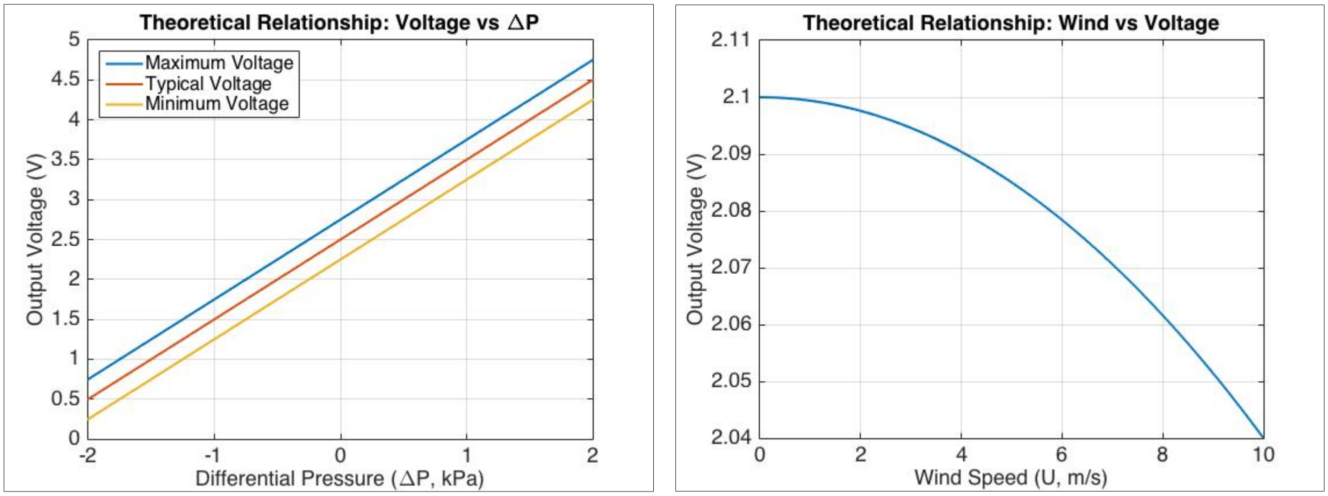
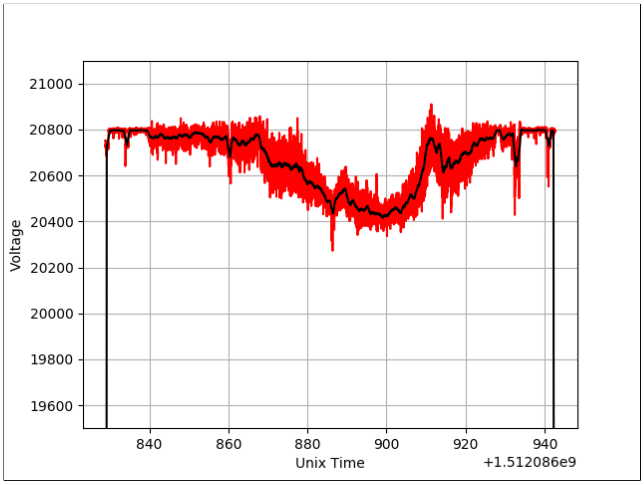


Figure 18. Theoretical relationship between voltage (**V**) and differential pressure (**ΔP**) in kPa from the sensor manual (left) and theoretical relationship between voltage (**V**) and wind speed (**U**) in m/s using Bernoulli's Equation and graph in Figure 8 (right).

2.2.5 Testing Functionality of the Sensor

Test calibrations were performed to gauge the initial performance of the sensor, ADC, Pi and pitot-static tube together (Figure 19.). The components were connected on a breadboard and run using full length tubing (Figure 17.). The wind speeds were first measured using a Kestrel 5500, with the new sensor then aligned behind it. Below we can see two graphs of these early tests. The red lines indicate the actual measurements read by the Pi from the ADC connected to the sensor, and the black line is the moving average calculation generated. The voltage values on the y-axis are in millivolts/10, as the output voltage is around 2 volts. This is intentional as it allows for more decimal points and more precise measurements to be taken than if the readings were in volts.



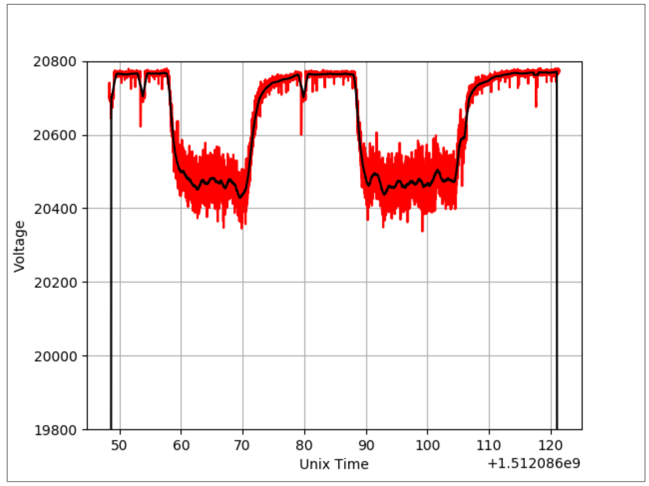


Figure 19. Wind speed slowly increasing from 0 m/s up to 9.0 m/s and back down to 0 m/s (left), and wind speed rapidly cycled between 0 m/s and 9.0 m/s (right).

2.3 First Prototype Tests

After the script was working and able to generate data points, the process of calibrating the instrument began in order to ultimately gauge its level of accuracy and responsiveness of high frequency changes in wind speed. Wind speeds were first measured with a Kestrel 5500, then the new sensor was aligned behind the Kestrel and measurements were taken. There were 5 different types of tests performed on the first prototype: sealed container, constant speed, variable constant speed, on and off, and high-frequency. These tests are explained in more detail below.

2.3.1 Sealed Container

The first test was conducted by placing the sensor in a sealed container. The objective of this test was to get a baseline of the pitot tube without any wind interference to gauge the amount of background noise that is generated. There should be no difference between the static and pitot pressures. The test was run for 5 minutes.

2.3.2 Constant Speed

The next tests conducted were at constant wind speeds of 3.0 m/s and 5.0 m/s. These tests were designed to measure stability over a long period of time at different wind speeds.

3.0 m/s

- The first test was at a speed of 0 m/s for 30 seconds, then 3.0 m/s for 10 minutes, and 0 m/s for 30 seconds.

5.0 m/s

- The second test was at a speed of 0 m/s for 30 seconds, then 5.0 m/s for 10 minutes, and 0 m/s for 30 seconds.

2.3.3 Variable Constant Speed

The next two tests were moving from low to high to low, and high to low to high wind speeds. These tests were designed to measure consistent change as wind shifts between low and high speeds.

3.0 m/s –> 5.0 m/s –> 3.0 m/s

- The first test was at a speed of 0 m/s for 30 seconds, 3.0 m/s for 5 minutes, 5.0 m/s for 5 minutes, 3.0 m/s for 5 minutes, and 0 m/s for 30 seconds

5.0 m/s –> 3.0 m/s –> 5.0 m/s

- The first test was at a speed of 0 m/s for 30 seconds, 3.0 m/s for 5 minutes, 5.0 m/s for 5 minutes, 3.0 m/s for 5 minutes, and 0 m/s for 30 seconds

2.3.4 On and Off Alternation

The next two tests were conducted by alternating between no wind speed and constant wind speeds. These tests were designed to measure the responsiveness to short periods of no wind in both low and high constant wind speeds.

3.0 m/s

- The first test was at a speed of 0 m/s for 1 minute, 3.0 m/s for 5 minutes, 0 m/s for 1 minute, 3.0 m/s for 5 minutes, and 0 m/s for 1 minute.

5.0 m/s

- The second test was at a speed of 0 m/s for 1 minute, 5.0 m/s for 5 minutes, 0 m/s for 1 minute, 5.0 m/s for 5 minutes, and 0 m/s for 1 minute.

2.3.5 High-frequency

The last test conducted was quickly alternating between no wind speed and high wind speed. This test was designed to analyze high-frequency or short term response to rapid and dramatic shifts in wind speed.

- Test was run at 0 m/s for 10 seconds, 5.0 m/s for 10 seconds, 0 m/s for 10 seconds, 5.0 m/s for 10 seconds, 0 m/s for 10 seconds, 5.0 m/s for 10 seconds, and 0 m/s for 10 seconds.

2.4 Final Prototype Tests

After the first prototype tests were performed, several final tests were conducted. These were carefully measured against the Kestrel 5500 and every test was run two times to ensure consistency between separate trials. There were 3 different types of tests performed: sealed container, constant speed, and high-frequency. These tests are explained in more detail below.

2.4.1 Sealed Container

Similar to the test in Section 2.3.1, a sealed container test was performed. This test was on the new sensor in a sealed container for 6 minutes, allowing for a baseline reading to be taken and the amount of background interference to be assessed.

2.4.2 Constant Speed

Similar to the tests in 2.3.2, wind speeds of 3.0 m/s and 5.0 m/s were measured with the Kestrel 5500 and two 6 minute trials were conducted with both the Kestrel and new sensor.

3.0 m/s

- The first pair of tests were at a speed of 3.0 m/s for 6 minutes with the Kestrel 5500.
- The second pair of tests were at a speed of 3.0 m/s for 6 minutes with the new sensor.

5.0 m/s

- The third pair of tests were at a speed of 5.0 m/s for 6 minutes with the Kestrel 5500.
- The fourth pair of tests were at a speed of 5.0 m/s for 6 minutes with the new sensor.

2.4.3 High-frequency

The last test performed was quick alternation between a wind speed of 0 m/s and 3 m/s over a 6 minute duration. These tests are similar to the ones performed in Section 2.3.4 and 2.3.5, however a device is used to block the fan between intervals, so an almost immediate change in wind speed is produced. This differs from Section 2.3, where the fan was turned on/off and took a small amount of time to lose or gain momentum.

3.0m/s

- The first pair of tests were at a speed of 3.0 m/s for 30 seconds, alternating between 0 m/s and 3.0 m/s for 5 minutes, and 3.0 m/s for 30 seconds with the Kestrel 5500.
- The second pair of tests were at a speed of 3.0 m/s for 30 seconds, alternating between 0 m/s and 3.0 m/s for 5 minutes, and 3.0 m/s for 30 seconds with the new sensor.

2.5 Pictures and Diagrams of the Design

The final design of the sensor included threads on both ends of the top and bottom of the body to allow for the nose and tail to easily screw together. The shape of the tail was chosen after looking at several different mounted wind vane anemometer tails both in person and online to determine the minimal size needed to still function as intended. A smaller size brings down the cost of the device, as less material is needed during the printing process. The distance that the pitot tube extends out of the front was designed to be as long as possible, as some space is needed between the static pressure holes on the pitot tube and the tip of the nose to prevent an inaccurate static reading. Finally, the overall circumference and length of the body was made as small as possible while still being able to comfortably house all the components. This allowed for minimal material to build the housing at the lowest weight possible.

Included below (Figure 20 – Figure 27) are pictures of the device at different stages of design and development. The images begin with models of the housing designed in Autodesk Fusion 360 (Section 2.5.1), a powerful program that is offered to students at no cost. It is with this program that several designs were created, printed, and subsequently improved upon. Next are the components placed inside the housing (Section 2.5.2). Finally, the images conclude with the housing and electronics assembled together and ready for recording measurements (Section 2.5.3).

2.5.1 Models in Autodesk Fusion 360

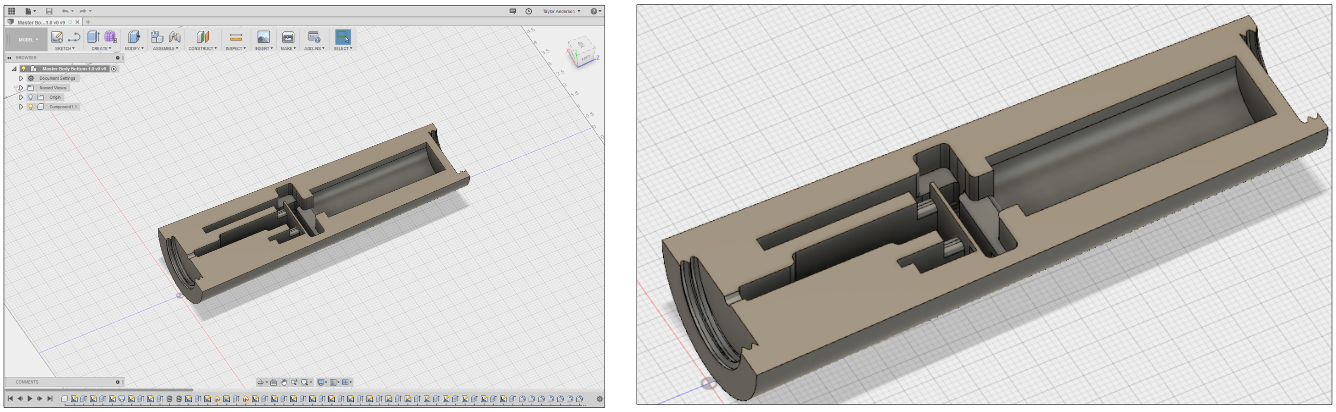


Figure 20. Bottom of body modeled in Autodesk Fusion 360 (left) and zoomed in (right).

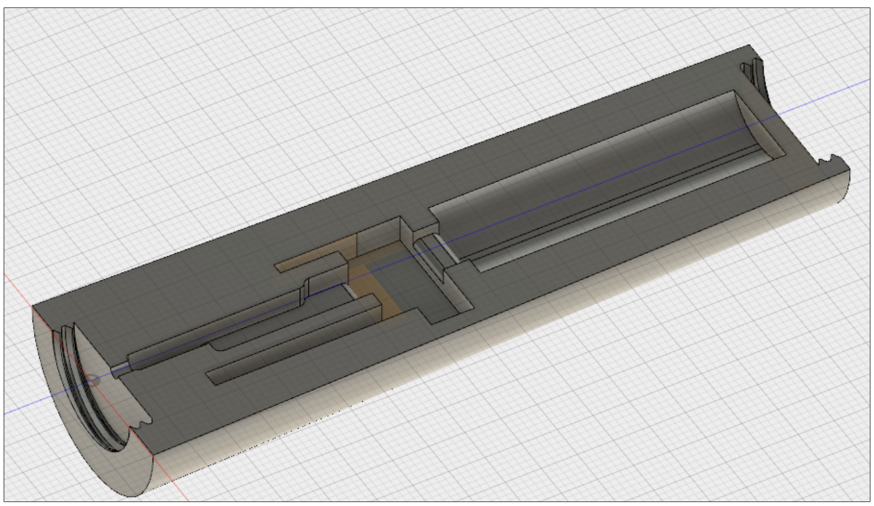


Figure 21. Top of body modeled in Autodesk Fusion 360.

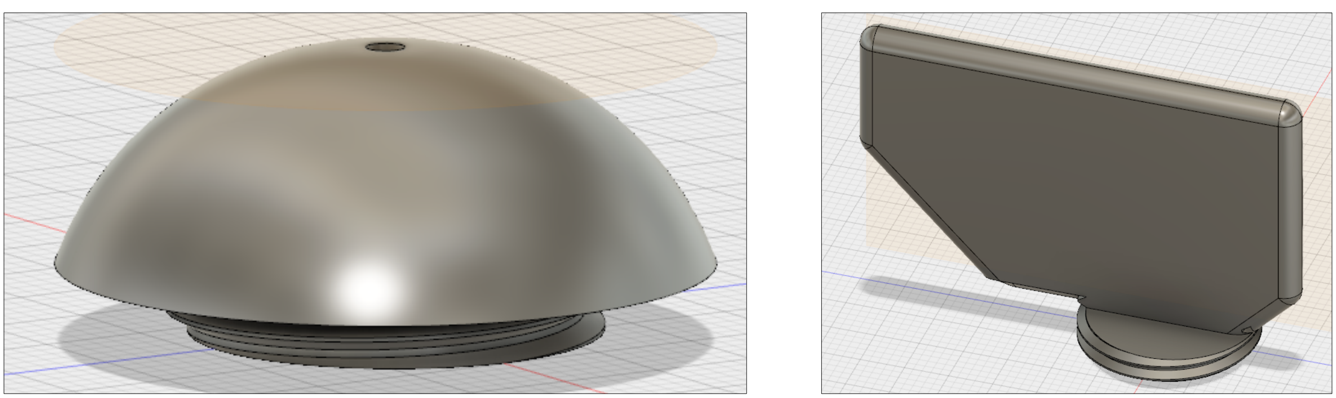


Figure 22. Nose (left) and tail (right) modeled in Autodesk Fusion 360.

2.5.2 Components in Housing

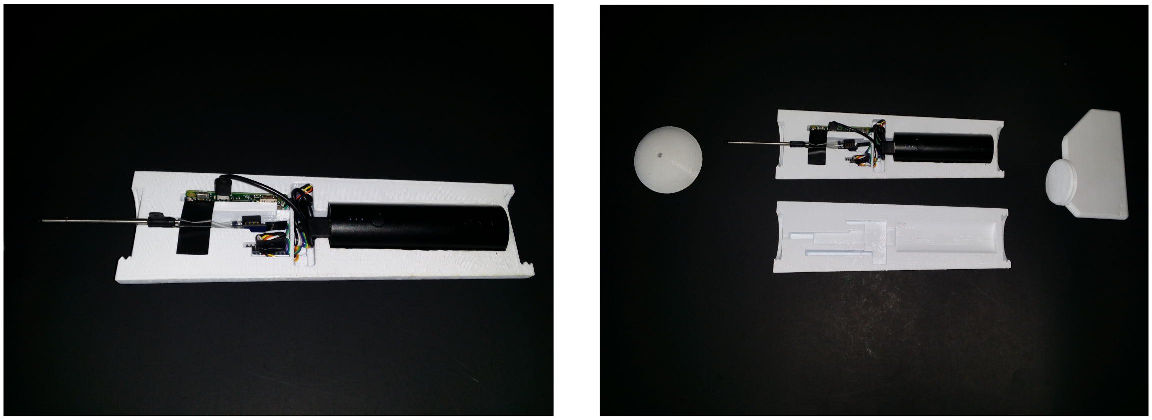


Figure 23. Components fitted inside the printed housing.

2.5.3 Assembled

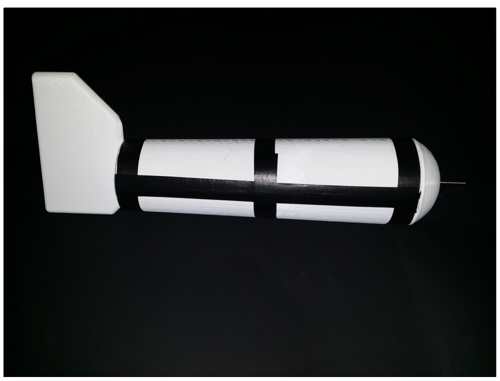


Figure 24. Body bottom, body top, nose, and tail assembled together.

Figure 25. Testing setup (top) and zoomed in (bottom).

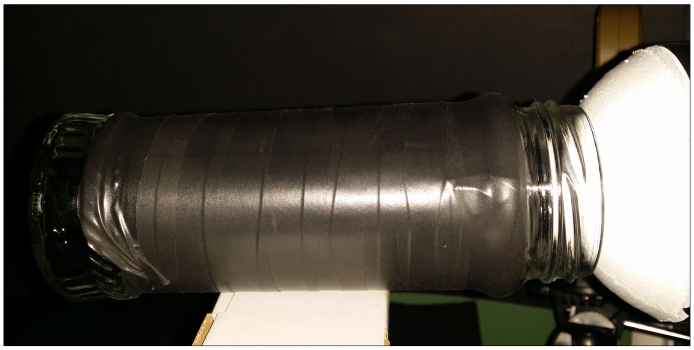


Figure 26. Sealed container test

Figure 27. Three m/s setup (left) and five m/s setup(right).

Chapter 3

Results

3.1 Instrument Housing

The first several 3D prints of the body bottom did not come out as desired. Initially there was the intention of using a 3D printer with 50 micron resolution instead of 100, however the corner of the model was printing at a slope (Figure 28.) This occurred regardless of whether a support raft was used. This posed a problem as the connecting surfaces needed to be flush in order to remain aerodynamic. The next issue encountered involved some ports (including the battery port) being too small to fit the electronic components. This occurred because the Makerbot Replicator was not printing the model as smoothly as the prior printer, and faced problems when selecting the max dimension. This issue was resolved by slightly widening all the ports and reprinting. Lastly, as a new user of 3D printing and Autodesk Fusion 360 software, there were several instances where changing small details was difficult and it was simpler to restart the drawing from scratch. Fortunately, these are the only notable difficulties encountered from the design stage to the print stage of the housing.

Figure 28. Early print of the body bottom which did not print correctly.

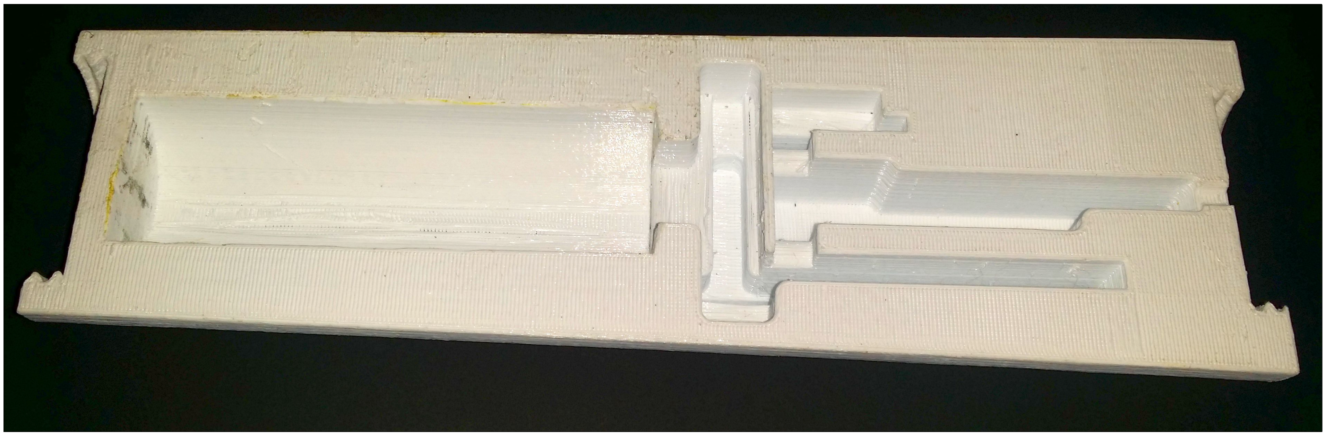


Figure 29. Bottom of body printed out with Makerbot Replicator.

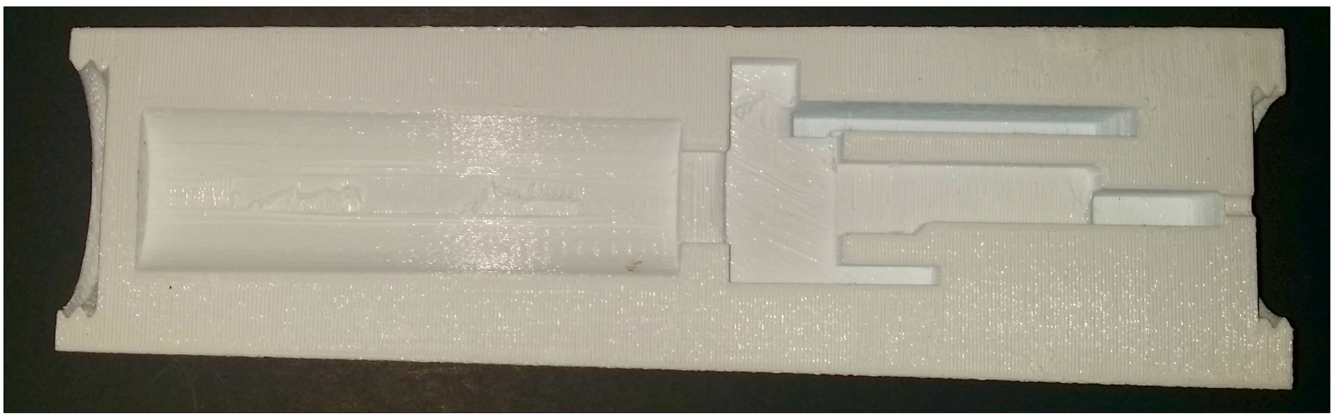


Figure 30. Top of body printed out with Makerbot Replicator.

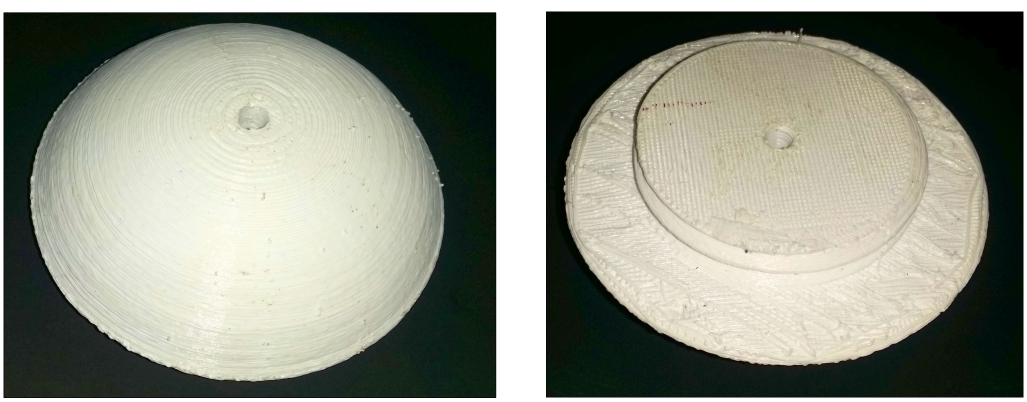


Figure 31. Top view of nose (left) and bottom view of nose (right) printed out with Makerbot Replicator 3D printer.

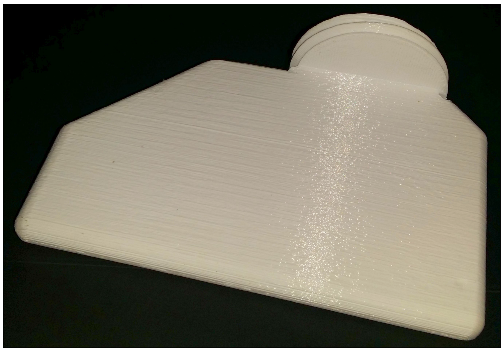


Figure 32. Tail printed out with Makerbot Replicator.

3.2 Measurements Taken

The measurements recorded were the voltage values given from the differential pressure sensor to the analog to digital converter. These values are logged into a text file after each run, with two numbers per line. The first number on each line shows the time in Unix time or UTC time and the second number on the line displays a voltage. Unix time is defined as the number of seconds that have elapsed since 00:00:00 Coordinated Universal Time (UTC), Thursday, 1 January 1970. This voltage reading corresponds to wind speed, as the difference between the pitot and static pressures are internally calculated by the sensor before the reading is passed to the analog to digital converter.

```
1512108193.34,21115
1512108193.34,21010
1512108193.35,21010
1512108193.35,21010
1512108193.35,21010
1512108193.35,21010
1512108193.35,20981
1512108193.35,20981
1512108193.36,20981
1512108193.36,20981
1512108193.36,20981
1512108193.36,20956
1512108193.36,20956
1512108193.36,20956
1512108193.37,20956
1512108193.37,20976
1512108193.37,20976
```

FORMATTED DATE_TIME	Wind Speed
YYYY-MM-DD HH:MM:SS	mps
2018-04-18 20:21:32	3
2018-04-18 20:21:34	3.1
2018-04-18 20:21:36	3.1
2018-04-18 20:21:38	2.9
2018-04-18 20:21:40	1.7
2018-04-18 20:21:42	0.8
2018-04-18 20:21:44	0.5
2018-04-18 20:21:46	0.4
2018-04-18 20:21:48	0.8
2018-04-18 20:21:50	2.2
2018-04-18 20:21:52	2.9
2018-04-18 20:21:54	2.9
2018-04-18 20:21:56	3
2018-04-18 20:21:58	2.7
2018-04-18 20:22:00	1.5

Figure 33. Sample of data generated, the left number on each line represents Unix time and the right number on each line is the voltage reading given from sensor to the ADC (left). Sample of data generated from the Kestrel 5500, with standard time on the left and m/s reading on the right (right).

3.3 Testing Functionality of the Sensor Results

While in the lab working on the first prototype, some test calibrations were performed to gauge the initial performance of the sensor, ADC, Raspberry Pi 3 and pitot-static tube together (Figure 17). The red lines indicate the actual measurements read by the Raspberry Pi 3 from the ADC connected to the sensor, and the black line is the moving average calculation generated. From looking at the high frequency measurements (red line), it can be difficult to gauge the voltage that it corresponds to. However, with the addition of a moving average (black line) it is easier to assign the wind speeds to a voltage reading. The first tests in the lab were using the full length of pitot tube hosing provided, this caused a different voltage reading to be produced than the first and final prototypes. The first prototype used a medium length hose, and the final prototype used the shortest hose length between the sensor and pitot tube possible to minimize interference of colliding pressure waves within the tube.

3.4 First Prototype Results

Below we can see the results from the trials on the first prototype. Starting with a test in a sealed container, measuring constant wind speed, variable constant, cycling the fan on and off slowly, and finally high frequency measurements where the wind speed is cycled quickly between low and high speeds.

3.4.1 Sealed Container

In this test the entire pitot-static tube was placed inside of a sealed container for 5 minutes to determine the amount of background interference. It is clear that while relatively constant, even in a no wind environment, some small fluctuations in the differential pressure (**ΔP**) are still present. The range of this background fluctuation appears to be about 1 millivolt.

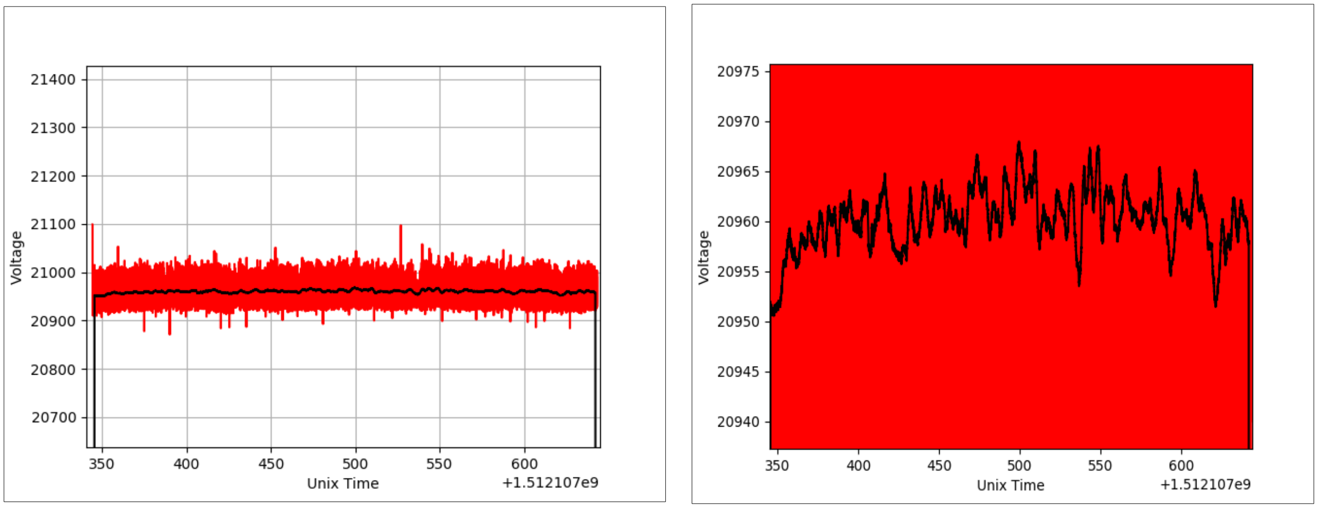


Figure 34. Sealed container test for 5 minutes.

3.4.2 Constant Speed

The constant 3.0 m/s wind speed test is shown in Figure 35. The image on the left shows the rapid decrease in voltage as the wind speed increases from 0 m/s to the steady 3.0 m/s wind speed (represented by voltage in the graph), and a rapid increase in voltage again as the wind drops back to 0 m/s at the end of the sampling period. The image on the right is a zoomed in version that shows while the wind speed is relatively steady over the 10 minute sampling period, there are again minor fluctuations most likely associated with pressure perturbations from the medium length hosing. Fluctuations are partly removed by smoothing the data-set with a large moving average window size of 1000. Below we can see the same test conducted for 5.0 m/s (Figure 36.) wind speed. The drop in voltage is largest in the 5.0 m/s case and appears to increase with larger changes in wind speed. This is what was expected, as we can see from Figure 18 that the relationship is not linear, instead the voltage changes much more rapidly for a higher wind speed (**U**).

3 m/s

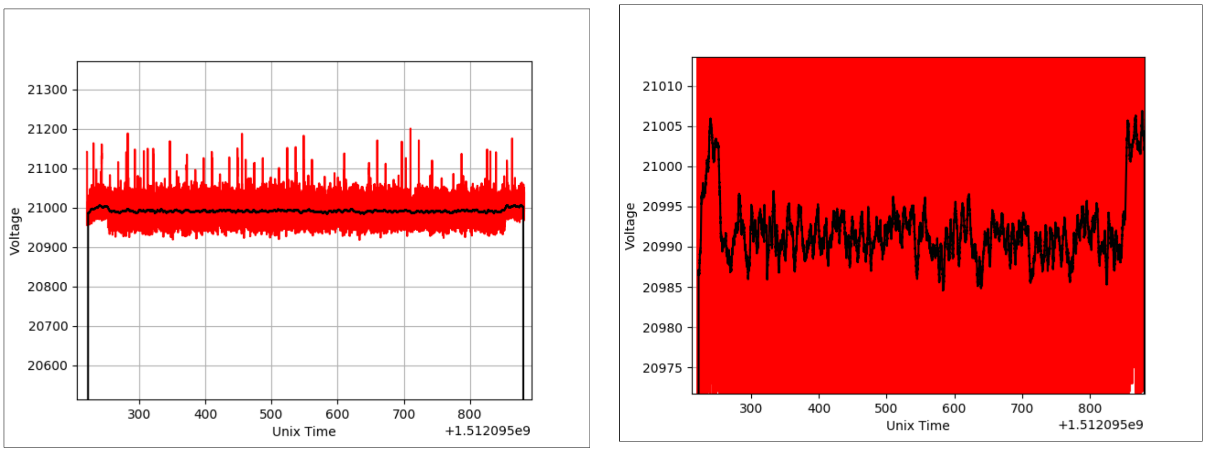


Figure 35. Zero m/s for 30 seconds, **3.0 m/s** for 10 minutes, and 0 m/s for 30 seconds.

5 m/s

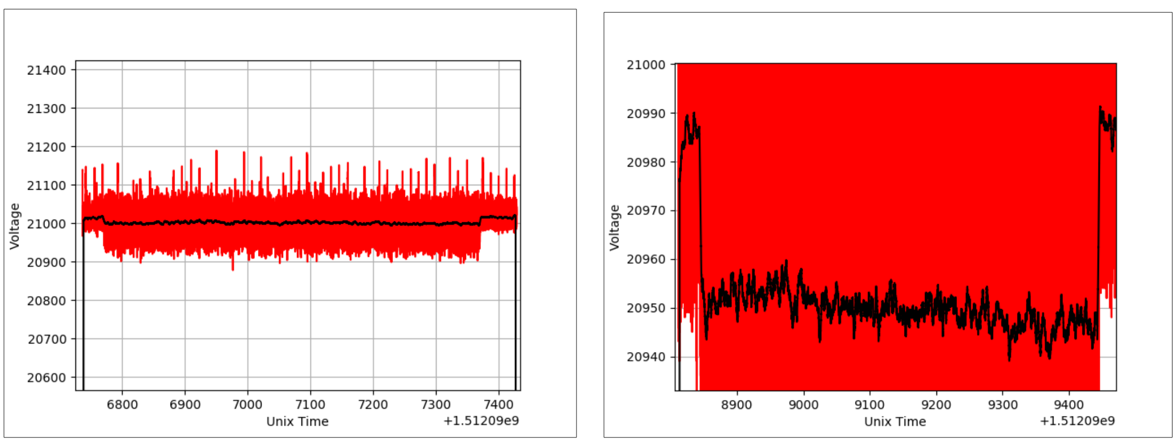


Figure 36. Zero m/s for 30 seconds, **5.0 m/s** for 10 minutes, and 0 m/s for 30 seconds.

3.4.3 Variable Constant Speed

The test from one constant wind speed to another is pictured below (Figure 37.), where the wind speed starts at zero, then at a low speed of 3.0 m/s for 5 minutes, bringing the speed up to 5.0 m/s for another 5 minutes, then back down to 3.0 m/s for 5 minutes, before ending at zero. A correlation can clearly be seen as the voltage decreases with the increasing wind speed. However, it is worth noting that when the fan was turned back down to 3.0 m/s it produced a reading lower than the first reading. This is probably due to an error while taking the measurement. Looking below at Figure 37, a wind speed of 5.0 m/s corresponds to a voltage of 2.090 volts, this is comparable to the 2.091 volts for 5.0 m/s measured in Figure 39. The latter portion of the test at 3.0 m/s is similar to to that in Figure 38, as the voltage produced at a speed of 3.0 m/s is 2.097 volts. However, it is important to note that the first 3.0 m/s portion of this test produced a voltage lower than expected, this is most likely due to human error.

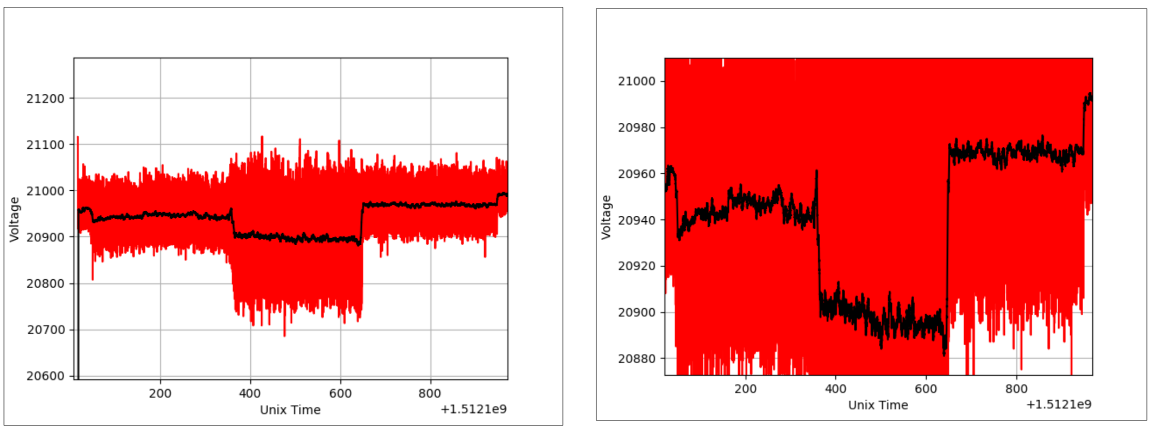


Figure 37. Zero m/s for 30 seconds, **3.0 m/s** for 5 minutes, **5.0 m/s** for 5 minutes, **3.0 m/s** for 5 minutes, and 0 m/s for 30 seconds.

3.4.4 On and Off Alternation

In Figure 38. the wind speed was held constant at 3.0 m/s, with short pauses of 0 m/s in between. The difference in voltage given between 0 and 3 m/s is difficult to estimate in the full sized graph (left), but can be seen more clearly with the graph zoomed in (right). The figure below (Figure 39.) is the same test performed at 5.0 m/s instead of 3.0 m/s. Here we can see a much more defined difference between the resting and full wind speed. The voltage reading on both graphs remains consistent after the wind speed is stopped and started again. Looking at Figures 38 and 39, a wind speed of 0 m/s corresponds to a voltage of 2.098 volts, a wind speed of 3.0 m/s corresponds to a voltage of 2.097 volts, and a wind speed of 5.0 m/s corresponds to a voltage of 2.091 volts. There appears to be a slight increasing drift in voltage in Figure 38 and no drift present in Figure 39.

3 m/s

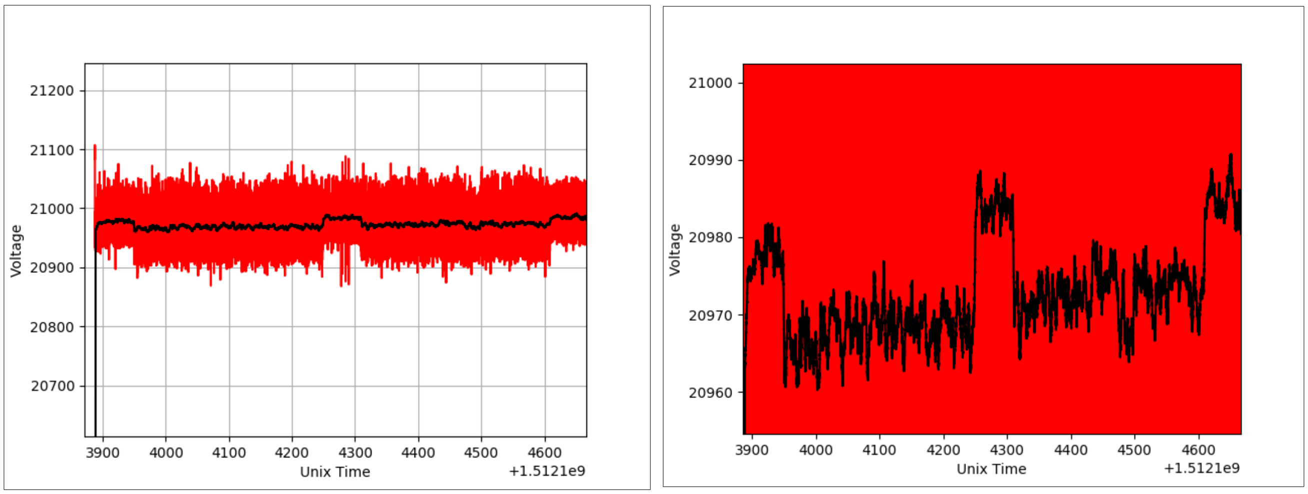


Figure 38. Zero m/s for 1 minute, **3.0 m/s** for 5 minutes, 0 m/s for 1 minute, **3.0 m/s** for 5 minutes, and 0 m/s for 1 minute.

5 m/s

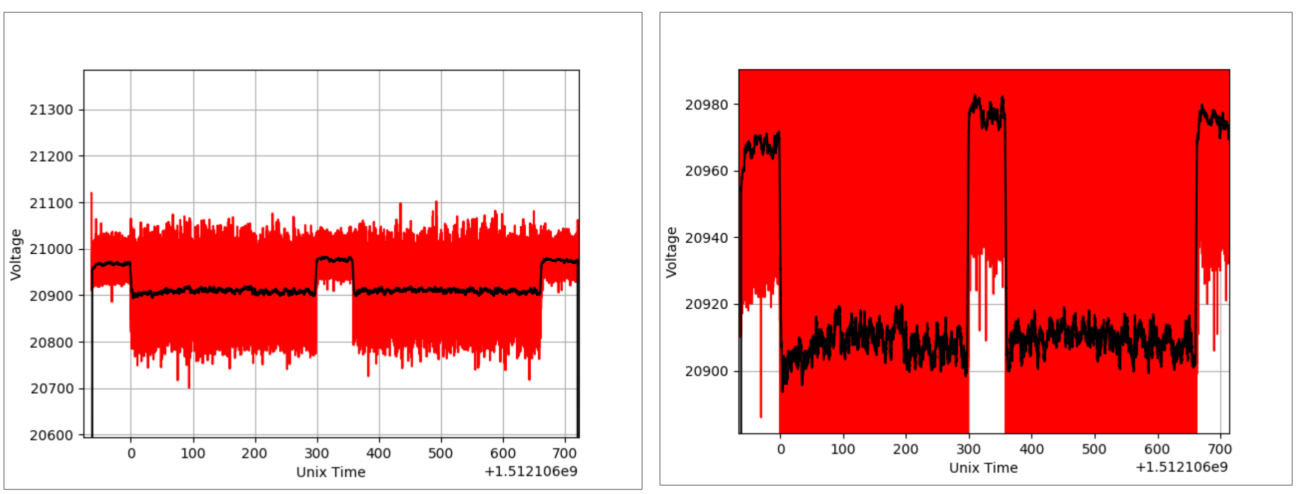


Figure 39. Zero m/s for 1 minute, **5.0 m/s** for 5 minutes, 0 m/s for 1 minute, **5.0 m/s** for 5 minutes, and 0 m/s for 1 minute.

3.4.5 High-frequency

The last test performed was to gauge the sensors responsiveness to large and quick variations in wind speed. Figure 40. details a test where the wind speed is cycled quickly between 0 m/s and 5 m/s several times. Again, same as the previous test, the similarities between the 0 and 5 m/s plateaus demonstrate that the sensor is operating as intended and taking consistent measurements. Looking at Figure 40, a wind speed of 0 m/s corresponds to a voltage of 2.098 volts and 5.0 m/s corresponds to a voltage of 2.089 volts. This is comparable to Figures 38 and 39 which had 2.098 volts for 0 m/s and 2.091 volts for 5.0 m/s.

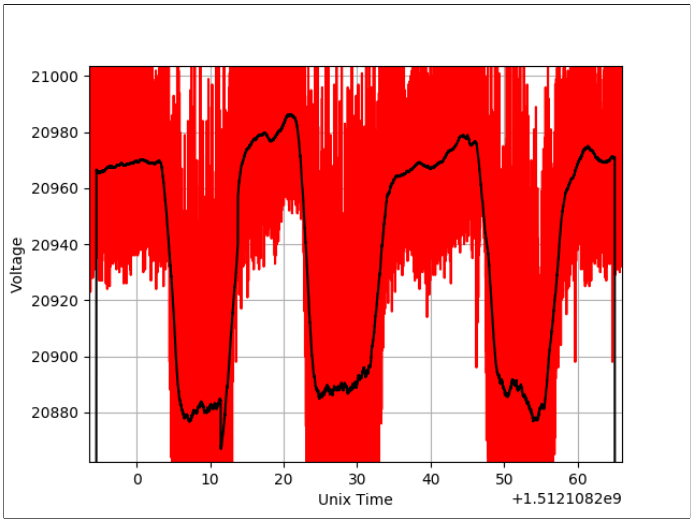


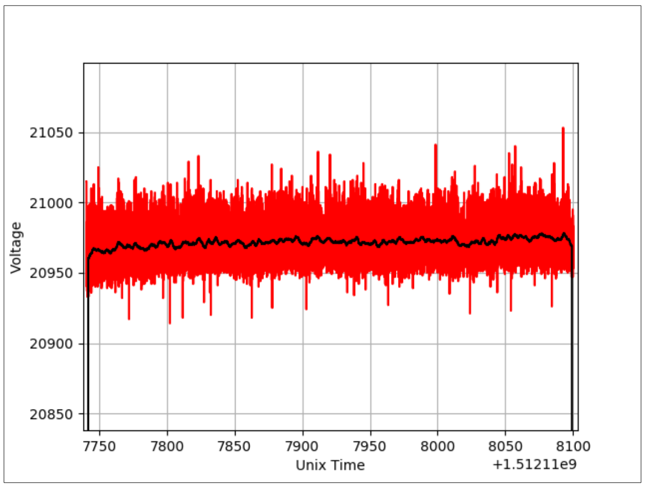
Figure 40. Zero m/s for 10 seconds, **5.0 m/s** for 10 seconds, 0 m/s for 10 seconds – repeated twice.

3.5 Final Prototype Results

After the final model, script, and component configuration were determined, a final prototype was developed, calibrated, and tested. It should again be noted that the final prototype had significantly shorter tubing between the pitot tube and sensor in addition to having a different python script, both of these factors changed the voltages generated by the sensor at different wind speeds, requiring recalibration to take place. Pictured below are the results of the tests performed: Sealed Container, Constant Speed, and High-Frequency.

3.5.1 Sealed Container

Below we can see two separate tests on the new sensor, placing it in a sealed cup to measure the amount of background noise. The variation in the moving average for the first sealed container test was about 5 millivolts, while the variation in the moving average for the seconds sealed container test was about 7.4 millivolts. While these values are higher than the 1 millivolt variation in Figure 33, 5 and 7.4 millivolts are still small changes when compared to the 100 millivolt difference between 0 m/s and 5.0 m/s as shown in Figure 40.



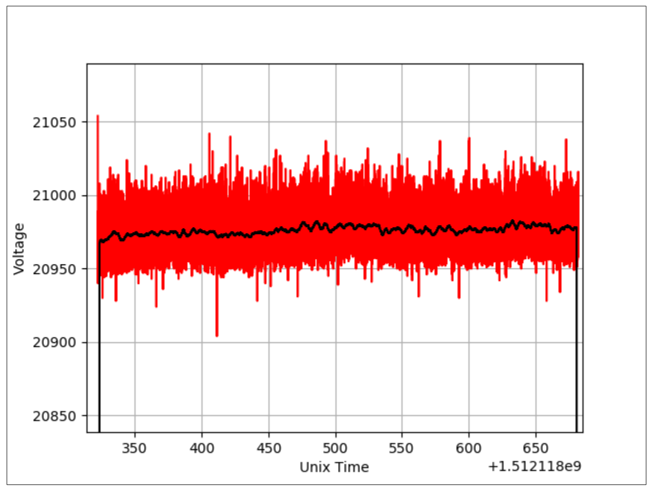


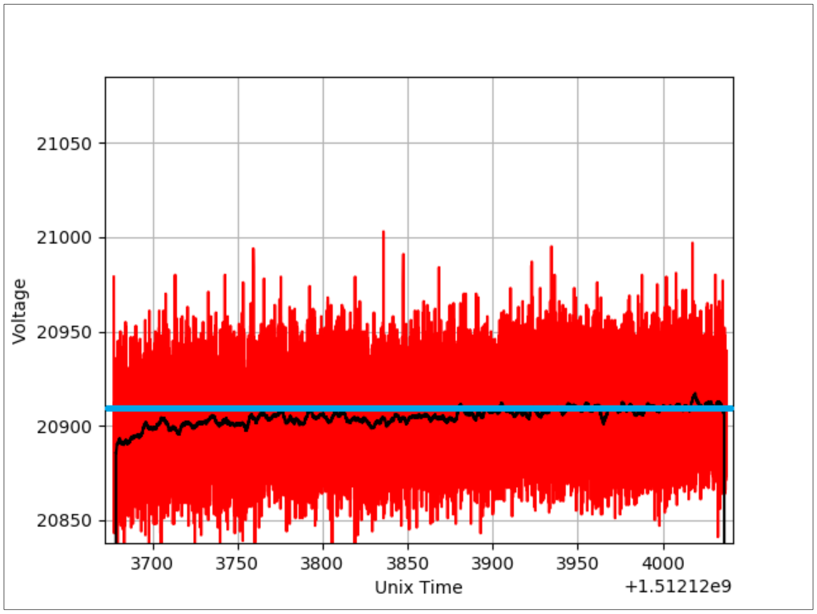
Figure 41. Sealed container test run for 6 minutes on the new sensor (left and right).

3.5.2 Constant Speed

Similar to the tests performed in Section 2.5.2, a measurement is taken of a constant wind speed over a 6 minute period. In this test, 3.0 m/s and 5.0 m/s were selected as the two speeds to measure. In figures 43 and 45 we can see the same tests performed on the Kestrel 5500, this was done to ensure that the wind speed generated by the fan remained constant over the entirety of the testing period. Looking at Figures 42 and 44, a wind speed of 3.0 m/s corresponds to a voltage of 2.090 volts and a wind speed of 5.0 m/s corresponds to a voltage of 2.084 volts. It should be noted that for all four tests (two at 3.0 m/s and 2 at 5.0 m/s) conducted on the sensor there was a small amount of drift that took place, which slowly increased the voltage reading despite the fact that the wind speed was held constant.

3 m/s

Test 1



Test 2

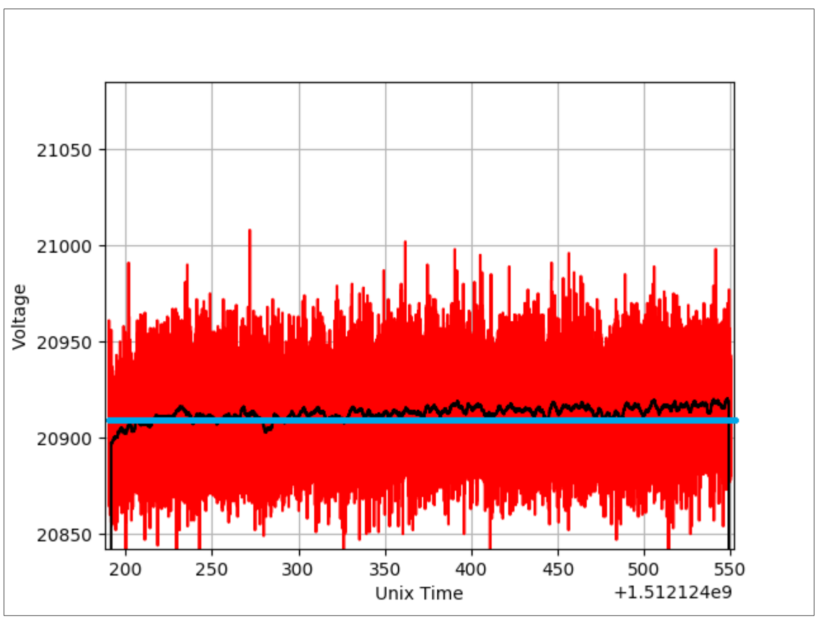
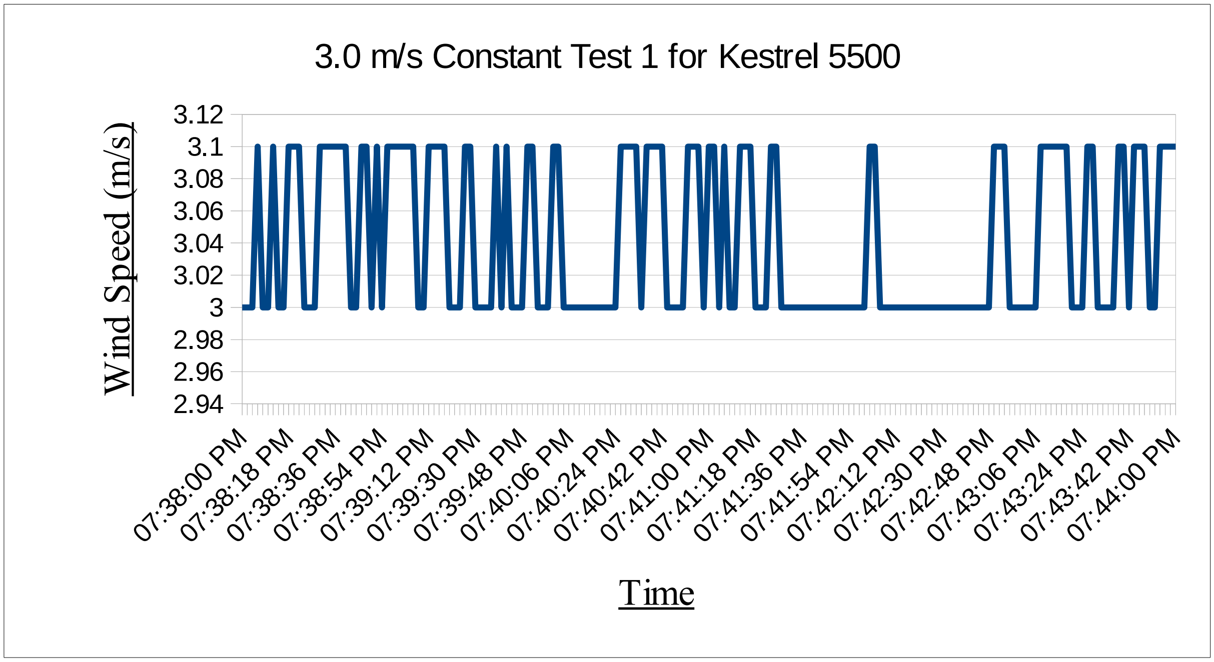


Figure 42. Two 3.0 m/s constant tests for 6 minutes using the new sensor (top and bottom).

Test 1



Test 2

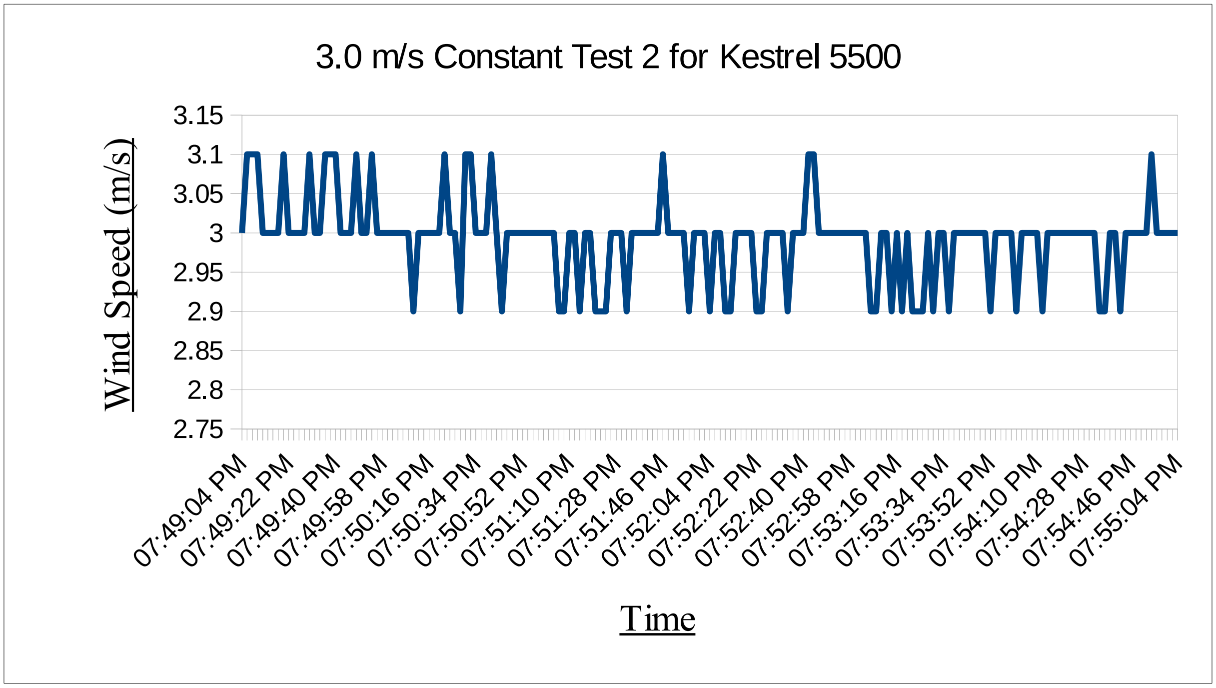
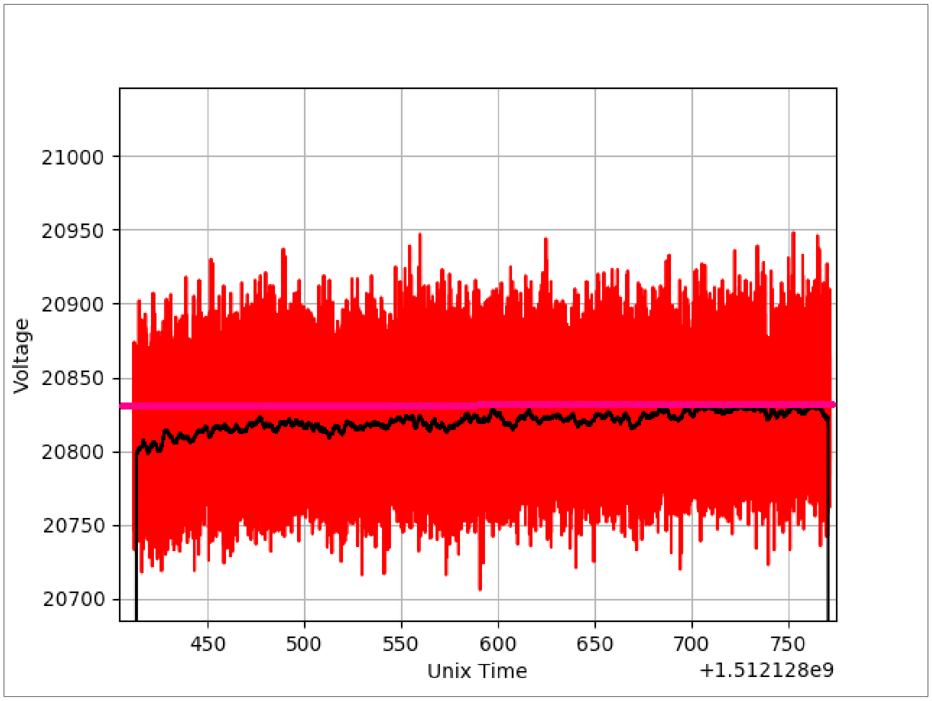


Figure 43. Two 3.0 m/s constant tests for 6 minutes using the Kestrel 5500 (top and bottom).

5 m/s

Test 1



Test 2

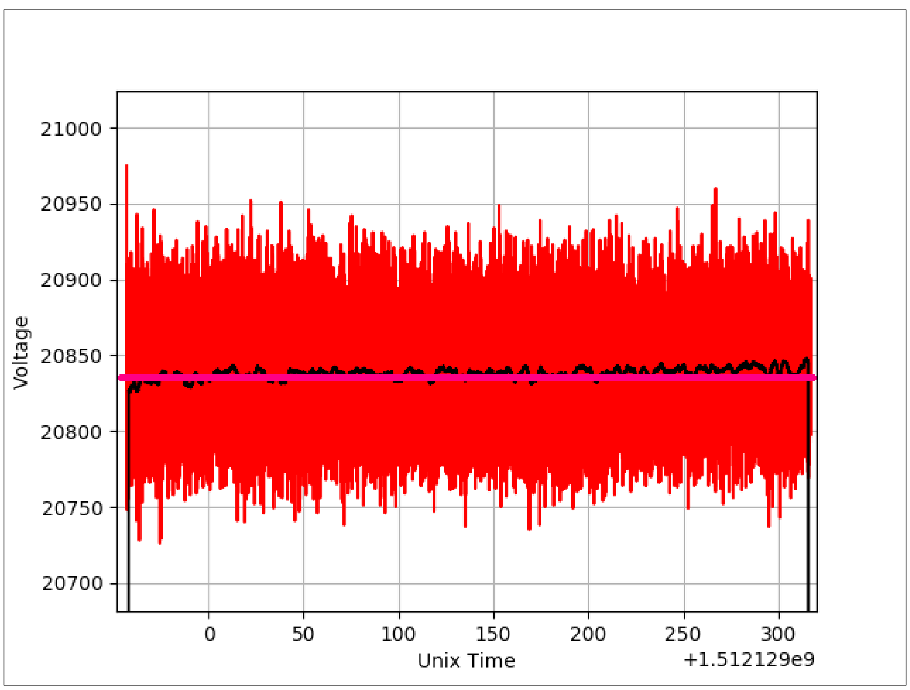
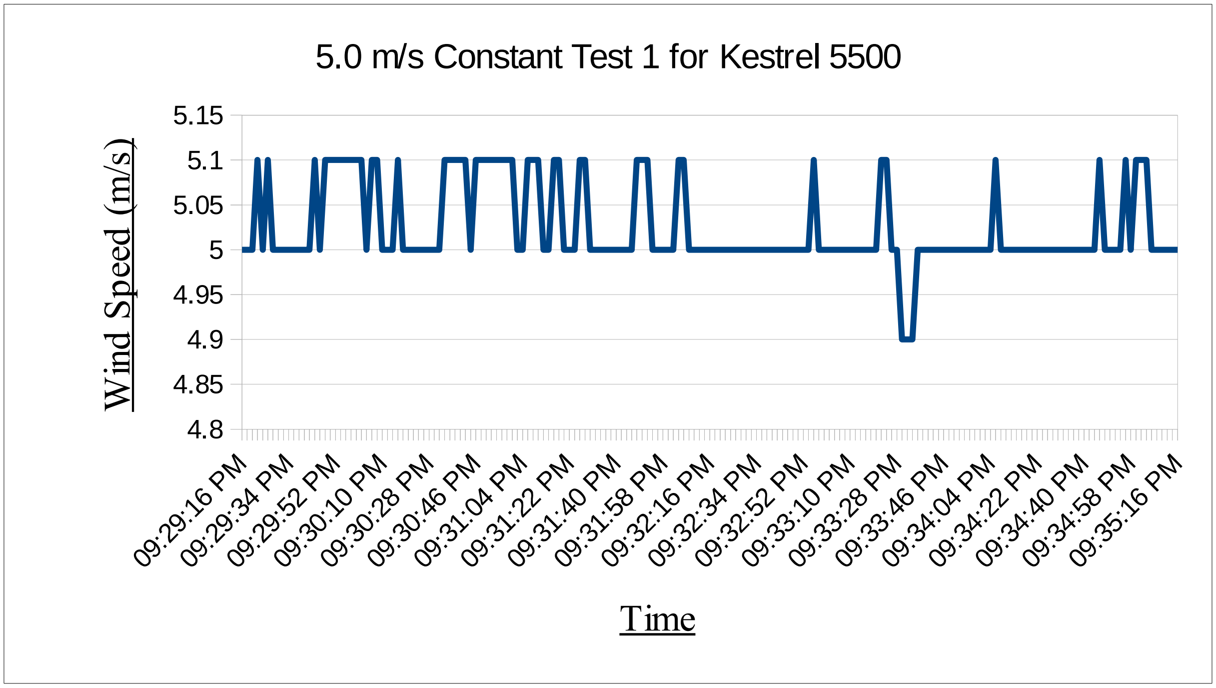


Figure 44. Two 5.0 m/s constant tests for 6 minutes using the new sensor (left and right).

Test 1



Test 2

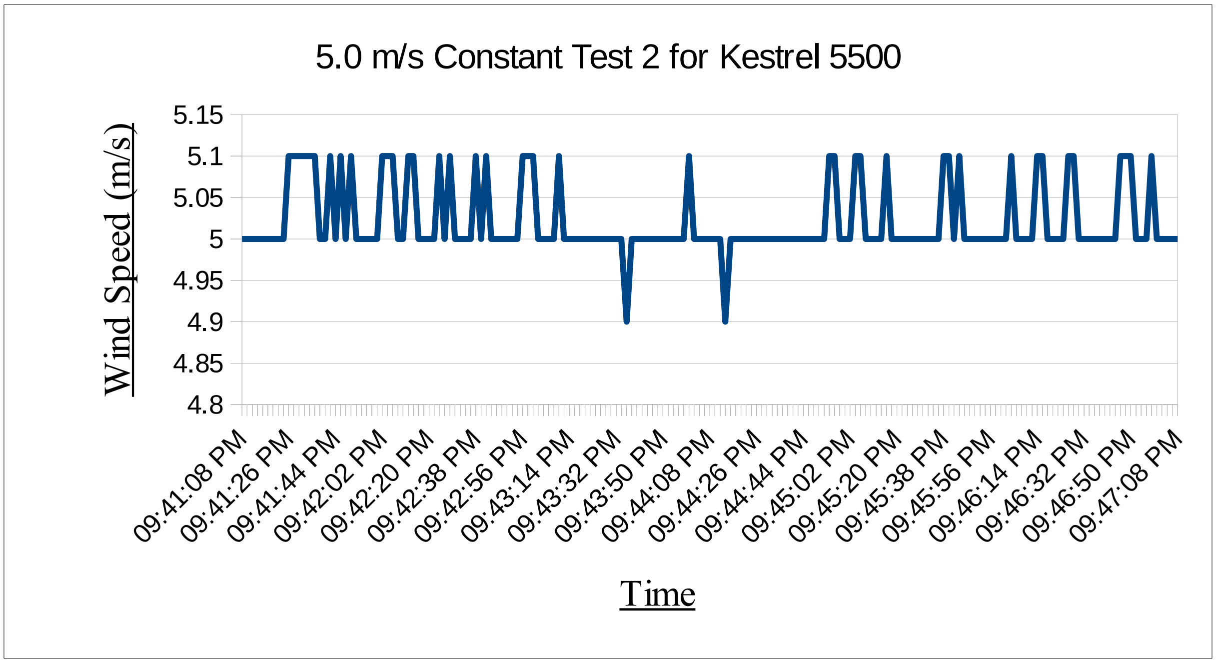
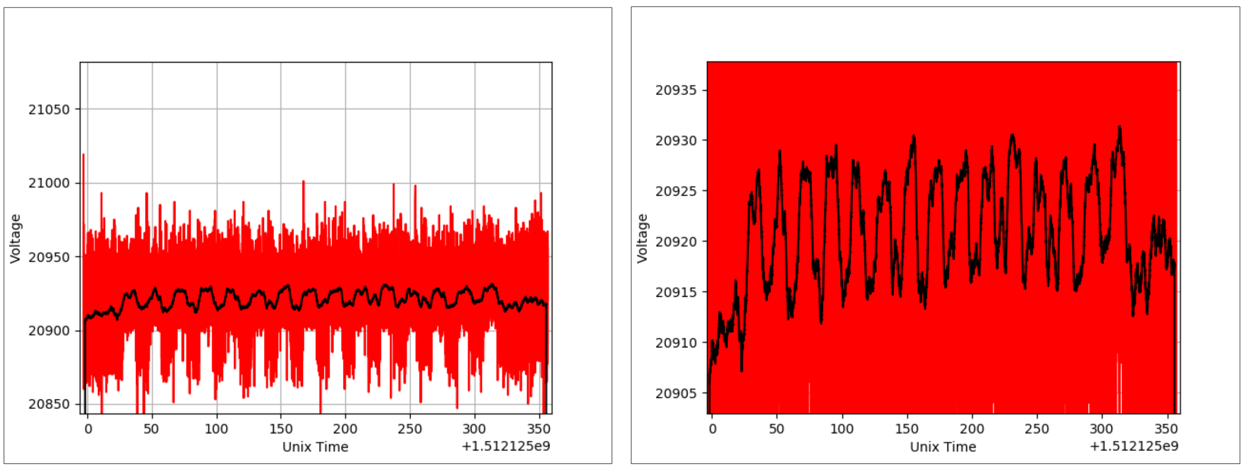


Figure 45. Two 5.0 m/s constant tests for 6 minutes using the Kestrel 5500 (top and bottom).

3.5.3 High-frequency

The last test performed was to test the sensors response to high-frequency fluctuations. This was achieved by cycling the wind speed between 0 m/s and 3.0 m/s every 10 seconds for a 5 minute run. There appears to be a difference in the voltage generated between the two tests, however the resting position of the 0 and the 3.0 m/s remains horizontally level in both tests. Below (Figure 47.) we can see the same test performed of the Kestrel 5500, however due to the Kestrel sampling the airflow once every two seconds, it is not able to observe quick shifts in wind speed. As a result, the Kestrel did not reach 0 m/s on several points when there was no wind present.

Test 1



Test 2

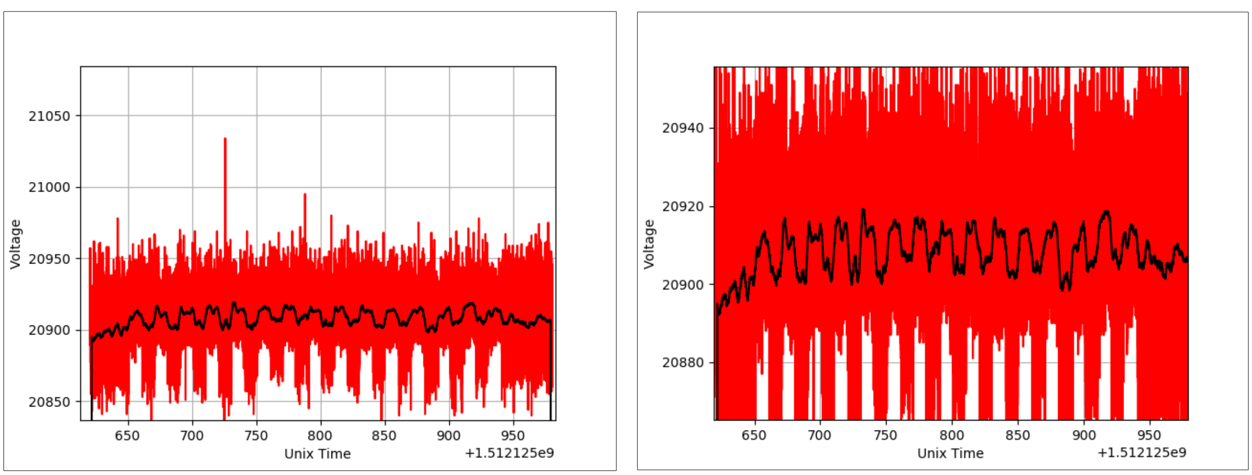
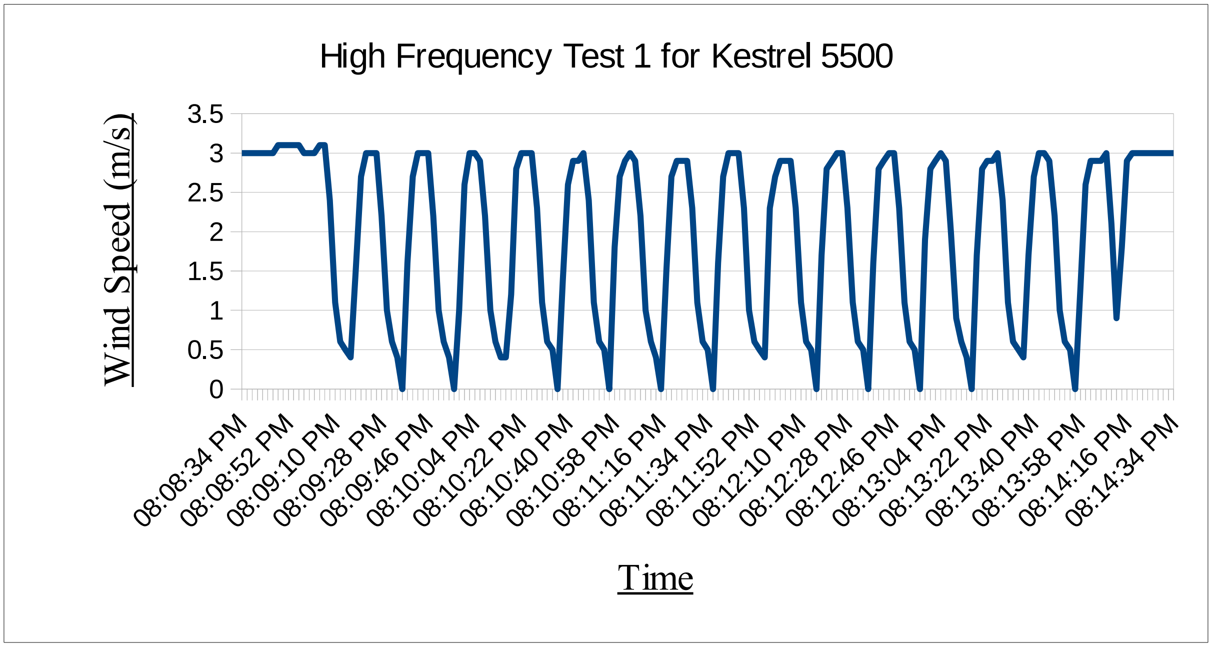


Figure 46. Two tests of 3.0 m/s for 30 seconds, then alternating between 0 m/s and 3.0 m/s every 10

seconds for 5 minutes, and ending at 3.0 m/s for 30 seconds using the new sensor (top and bottom)

Test 1



Test 2

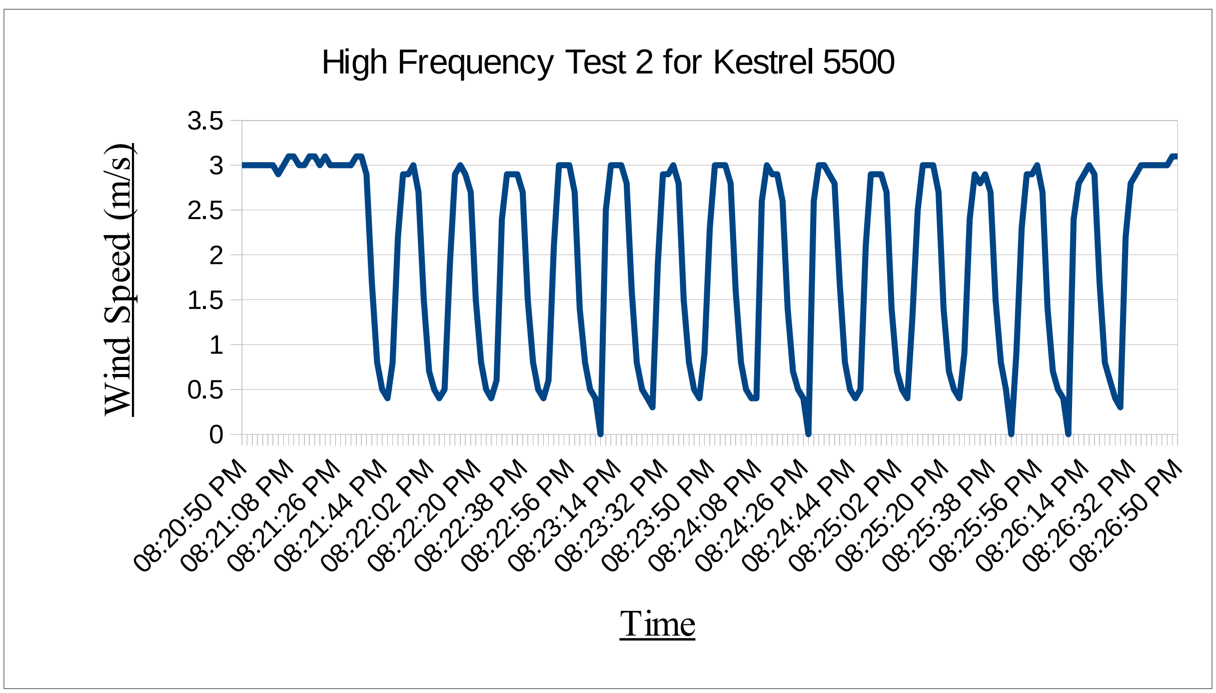


Figure 47. Two tests of 3.0 m/s for 30 seconds, then alternating between 0 m/s and 3.0 m/s every 10 seconds for 5 minutes, and ending at 3.0 m/s for 30 seconds using the Kestrel 5500 (top and bottom).

Chapter 4

Conclusion

The final cost of the newly designed pitot-tube anemometer totaled around $91, with the differential pressure sensor and pitot tube both costing about $10, the Raspberry Pi Zero costing $5, the ADC costing $15, the battery costing $15, and the 4 components of the 3D printed housing costing about $36 together. This means that the goal of fabricating this new sensor for under $100 was achieved.

The preliminary calibration results demonstrated that the new sensor appeared to be responsive to quick fluctuations with respect to the Kestrel 5500 used to calibrate it. However, while the frequency of the new sensor may be high, the Kestrel 5500 was more accurate and reliable. Figures 34 and 41 both show that even in an environment with no wind, and no difference in differential pressure between the pitot and static tubes, there were still several millivolts of background interference that was occurring. However, when compared to the voltage differences between 0 m/s, 3.0 m/s, and 5.0 m/s it was a negligible amount of interference. Figures 35 and 36 showed consistent and stable measurements over a long-term constant wind speed. These tests demonstrated the device's ability to accurately measure a continuous wind over a prolonged period of time. However, when the same tests were conducted on the final prototype with the shortened tube in Figures 42 and 44, there appeared to be a small amount of increasing drift in the voltages. This is possibly due to human error or an issue with the supply voltage when running these four tests.

Looking at Figure 39 and the second graph on Figure 44, it appears that a higher wind speed corresponds to a more stable reading. While a lower wind speed on the other hand tends to provide less consistent measurements. This is probably due to the fact that the relationship between output voltage and wind speed, as seen in Figure 18, is not linear and instead produces a more dramatic difference in voltage with a higher wind speed. However, this project is focused on high frequency measurements as opposed to long term averages at constant wind speeds. Figure 46 is an excellent example of the new sensor's ability to measure rapid changes in wind speed and remain consistent from the beginning of the tests to the end. While there was a slight amount of drift that took place when comparing the first and second tests, this is not of high importance as the voltages can be calibrated to zero to account for this. For the sake of this project we are more interested in the voltage differences between 0 m/s and 3.0 m/s, in addition to making sure they rise and fall to the same voltage values each time the wind speed is cycled.

The Kestrel 5500 was taking a stable reading while measuring different wind speeds at a constant velocity. However, there was a noteworthy and inhibitory latency when the fan speed was changed quickly. This was most apparent during the high frequency test on the final prototype (Figure 47.). The refresh rate of the Kestrel is 2Hz, meaning that it takes one measurement every 2 seconds, this is about 1700 times slower than our new sensor if we used the raw measurements. However, a window size of one would not be practical as it would be hard to determine the corresponding voltage and wind speed. While running preliminary tests on different window sizes, a window size of 100 or greater was sufficient to be able to calibrate the moving average to a voltage. This means that the new sensor would still be able to take clear and comprehensive measurements more than 17 times more frequently than the Kestrel 5500. However, I opted to use a window size of 1000 for all tests in this paper to generate the smoothest line possible while still retaining accuracy and a higher frequency of measurement than the Kestrel 5500. This means that the new sensor was averaging the measurements to give a final resolution around 1.7 times faster than the Kestrel. A window size of 1000 also significantly reduced the amount of interference present in each test. Fortunately, the script saves the raw data (red lines) from each test, so the user could easily select a window size to their preference with some manual data analysis. In addition to the high frequency fluctuations which can be smoothed with a moving average, other changes in the measured voltage can be attributed to several sources of error.

The largest sources of error in this project came from the fan in each test. If the input (wind speed generated by the fan) was not controlled very well, then the output (measured voltage) is going to have an even greater amount of uncertainly. It is difficult to differentiate if the variations are caused by the input or the sensor itself, unless a wind tunnel or similar device is used to control for the input. While the wind speed was measured for the same duration with the Kestrel 5500 before each test on the final prototype, there was still a possibility of incorrect positioning when aligning the new sensor. There was also the source of error from the fan itself, as the wind speed on each point of the fan is different, even a small shift in positioning of the new sensor with respect to the fan could have resulted in large differences in the wind speed observed and measured. This differs from a wind tunnel, where the wind speed is consistent and uniform across the entire testing area. There is also room for error that comes from possible deviations in the measurement angle, as the measured voltage changed with only small differences in the angle of measurement. Since the fan used during the final test was weaker than the one in the lab (5 m/s max versus 9 m/s max), a change of only a couple tenths of a meter per second would produce a large degree of uncertainty in the final result.

Future improvements to this project would be to test the new sensor in a wind tunnel at higher wind speeds with a more laminar and uniform wind speed to get a better relationship between wind speed, differential pressure, and output voltage. Testing the sensor in the environment to gauge its performance in the field would also be beneficial, as it would provide an opportunity to better test the sensors response to high frequency fluctuations. However it is difficult to quantify its accuracy in the environment, as there are large differences in wind speed even if the new sensor and a calibration sensor are oriented right next to one another.

Testing different models of differential pressure sensors would also be beneficial, as others might provide more consistent and accurate results for the range of wind speeds desired. Lowering the cost of the housing would also be a future improvement that could easily be accomplished simply by reducing the percentage of infill when printing the device. This would also significantly lower the weight of the device, which would be beneficial.

In conclusion, gathering reliable data on wind speed is extremely useful information. Being able to deploy five units across an environment for the same price as one Kestrel 5500 allows scientists in the field to gather not only more data, but also gather a higher degree of information about the spatial properties of the wind. One useful application for the deployment of multiple units would be in establishing a wind farm, where the spatial movement of the wind is of high importance as it dictates the most optimal position for each wind turbine. The high frequency aspect of my new sensor would also be beneficial in this field because wind turbines work best in wind that is of constant velocity. This would allow them to locate areas with the least amount of wind fluctuations over short periods of time. Ultimately this may extend the life of the wind turbine drive trains and gearboxes due to them being under less strain over time [15]. While there are certainly improvements that can be made to increase the device's accuracy and lower its cost, this is an early design. The technology to advance this project further will become cheaper and more accurate as time progresses. Differential pitot pressure sensors appear to be the most viable option for use in a low cost and high frequency wind speed sensor.

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