Mobile Platform for Determining Particulate Flow Velocity

A Major Qualifying Project

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ABSTRACT

The Mobile Measurement Platform project develops a methodology to measure velocities in particulate flows. Its sensor package consists of two light obscuration sensors, each including a laser and photodiode spaced a distance *x* apart. Using two monochromatic laser beams as sensors connected to a computer via an A/D converter, custom analysis software incorporates a unique adaptation of a discrete cross correlation algorithm to calculate the time taken for the particulates to traverse the distance. The known sensor spacing divided by the software-derived time offset resulted in the flow velocity. To verify the system accuracy, the MMP was tested against a vane anemometer in four generated flows. The MMP values were repeatable and precise, but had an accuracy error of 22.2%.

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

The goal of this project was to create a device that measures the velocity of a particle-dense flow. The fire protection industry already employs a variety of systems to measure such velocities; however they have inherent disadvantages including interaction with the flow, resulting in inaccurate readings, and a lack of mobility. It was these disadvantages this project sought to avoid through the development of a new velocity-measurement concept. The core of this concept relied on the fact that moving smoke possesses inherent density patterns. While these patterns change over time, it was assumed that over short enough distances these features remain largely unchanged. This approach took advantage of this property by using two light obscuration sensors to track the particle concentration patterns across a small distance. Denser particle concentrations block more light, thus causing the sensors' voltage output to drop. As dense smoke features passed the sensors, these voltage drops of varying magnitude would cause the signals to drop accordingly.

The existing systems each measure a different physical quality in their attempt to determine a velocity reading. These qualities include pressure differentials, temperature change of a surface, Doppler shift of laser light, the light reflection off particulate smoke, and simple flow-driven fans. As previously stated, most of these systems suffer at least from one of two main disadvantages.

The Mobile Measurement Platform comprises of two components, hardware and software. The hardware design is a simple construction, consisting of a vertical steel tube enclosing two pairs of laser/photodiode sensors. Two pairs of sensors were used to create two mirrored signals, offset by a certain distance. This distance would be representative of the time it took for one smoke density feature to travel from the first to the second sensor. The distance between the two lasers divided by the found time offset would indicate the velocity of that particular smoke flow. A circuit assembly provides power via 9v battery to the emitting diodes, while the receiving diodes output a voltage to an analog/digital converter connected to the computer processing the data. This setup provides a simple yet

effective assembly, which is small enough to be mobile without sacrificing instabilities that would have a negative impact on the results.

The software design of this project consisted of a program designed to calculate the time offset of the smoke flow by using a method called Cross Correlation Velocimetry. The time differential was calculated by first reading the photodiode voltage signals into a custom computer program via a Data Acquisition Unit (abbreviated as "DAQ"). This hardware component was essentially an Analog-to-Digital converter that converted the voltage inputs it received from the photodiodes into a digital value two thousand times per second. Once the analog values were digitized and sent to the software, the time differences were measured via an algorithm known as Discrete Cross Correlation. In this algorithm, a known signal pattern is compared to another signal at various offsets by summing the cross-products of all parallel data points to create a Cross Correlation Value, or CCV. This value represented the likelihood that the target signal is present in the search space at the current comparison location, with higher CCVs meaning a higher likelihood. This process was repeated several times per second. Because the Cross Correlation has a margin of error, all resultant prospective offsets discovered within that second were averaged into one value before calculating a comprehensive value for the smoke flow velocity during that second.

The finished prototype was named the Mobile Measurement Platform (MMP). In order to test it, a variable-speed blower and fan created a controllable flow velocity while smoke candles acted as a smoke tracer. The device was mounted in the midst of the resultant flow in order to observe its behavior as it traveled past the sensors. For each blower velocity setting, a vane anemometer was used to obtain reference readings in order to later analyze the accuracy of the MMP in relation to a known value. These reference readings consisted of both a velocity profile and the velocities present immediately below and above the vertical enclosure of the MMP. Testing was completed on four blower-induced flow velocities, and one velocity where the only source of flow was the ambient flow originating from the smoke candle. Each of the mechanical flows was repeated three times, in order to obtain and analyze measurement consistency.

The MMP had been designed with an enclosing vertical tube to contain the target flow to avoid cross-directional interferences while the smoke was traveling past the two sensors and to prevent ambient light interference. However, during testing the velocity entering the tube was faster than the velocity after exiting the tube, suggesting that the tube caused the flow rate to decay. To compensate for this when comparing the known vane anemometer readings with those obtained from the MMP, the average of the entrance and exit velocities of the flow was used. This was done because the light obscuration sensors were located at the midpoint of the tube, and theoretically, assuming a linear decay, the flow would have completed half of its noted decay by the time it passed the sensors.

The percent error of the MMP in relation to the vane anemometer value was determined to be 22.2% on average for blower-induced velocities. A 50% error was seen for the test that measured the natural flow generated by the smoke candle, but it was discovered after testing that this ambient flow was below the anemometer's measurable limit, and thus the comparison cannot be considered accurate. In general, the MMP readings were consistently lower than the averaged anemometer readings. This could partially be due to the fact that it was impossible to determine the exact velocity degradation gradient within the tube during tests, which could have introduced error into the calculations. In addition, signal samples possessing repeating shapes or lacking enough significant features could have been incorrectly correlated by the software, resulting in an inaccurate time offset and thus an inaccurate velocity value. A third source of possible error was the vane anemometer itself, as it was rated for an accuracy of +/- 0.2 m/s, and therefore could not detect subtle flow changes.

The MMP prototype's readings were observed to be within a reasonable, correctable error; they were precise but not accurate, indicating consistent measurements that are offset by a specific value. The Cross Correlation algorithm was proven to work in real time which allowed for immediate viewing and analysis of readings by the end user. Through analysis some potential areas of future improvements were identified to be the removal of the vertical enclosure, a third sensor pair to increase accuracy and enable measurement of flow decay, and continued adaptations of the Cross Correlation software to this specific application. In conclusion, the concept of light obscuration across staggered sensors to measure velocity was concluded to be a viable approach, but requires further refinement to create a truly accurate device.

1. INTRODUCTION

The goal of this project is to design a method that can measure a flow velocity typically seen in smoky, fire induced flows. The Mobile Measurement Platform (MMP) is a hand-held device designed to record and analyze flow velocity using a measurement of light obscuration. Although there are numerous systems on the market that measure flow velocity, the MMP is unique in that it utilizes a different concept for flow velocity measurement and it is a small mobile device rather than a stationary, bulky unit.

Currently, few devices exist that do not disturb the flow during readings, and those units are generally too large to be easily used in real-life situations outside the laboratory. The MMP is designed with the goal of being both accurate and light enough to be used as a mobile device. These qualities would enable measurements to be taken at remote sites such as coal mines, smoke stacks and fueling stations. The electronic component of the device is mounted on a stable, light weight support structure in order to maintain user mobility and durability. The intended application for the MMP is to provide basic and rapid analysis of the flow velocity in both field and laboratory settings.

The methodology proposed for determining flow velocity in the MMP was based on the measurement of a change in voltage, known as a voltage drop. Employing two laser light emitting diodes each directed at a paired photodiode, two voltage signals would be generated, one from each photodiode/laser pair. When particulate smoke flows past a laser beam, it obscures a particular amount of light which ultimately causes a voltage drop. The amount interference varies based on the unique particulate density pattern inherent to the flow. The sensor pairs record similar but offset signals, which were used to calculate the velocity by identifying density features passing between the sensors. A unique adaptation of a Digital Signal Processing (DSP) principle called discrete cross correlation was employed in analysis of the signals in order to dynamically determine the time difference. Knowing this time and the static distance between the two light obscuration sensors, the flow velocity could then be computed.

The concept inherent within this device has many applications in the fire protection industry. As it was an untested concept, a considerable amount of research, design, testing, and calibration work went into the production of a prototype. Based on our results and analysis, the concept shows promise for future viability of the project's core ideas, despite requiring further refinement to improve accuracy of the physical device.

2. Background

2.1. Existing Systems

A variety of systems existed in the Fire Protection industry at the start of this project that independently measured smoke flow velocity. Different measurement methodologies were used by these systems to obtain accurate readings in assorted environments. Some systems used an object that must be directly inserted into the stream, which could possibly interrupt or change the unimpeded flow rate. Others used complicated and expensive laser components to track the speed of individual particles. However, there were few systems that utilized a light source to measure flow, and no independent system used a laser light/voltage correlation in this capacity.

The most widely used rigs for measuring flow velocity were Bi-directional Flow Sensors[1], Pitot Tubes[2], Hot Wire Anemometers[3], Laser Doppler Anemometers[4], Sonic Anemometers[5], and Optical Flow Meters[6]. The methodology used in these systems varied. It is important to understand the limits of each of these methodologies as any one system cannot accurately measure smoke flow velocity in all environments. The advantages and disadvantages of these rigs are detailed in this section.

2.1.1. Bi-directional Flow Sensor

One of the more rugged and useful flow meters, a Bi-directional Flow Sensor, uses two differential pressure sensors joined with a flow restriction, offset a certain distance from one another, placed into the flow. The flow restriction member is configured to produce a pressure drop when placed in line with the fluid flow. The sensors produce a differential pressure signal that is indicative of the pressure drop. This produces a flow rate signal that correlates with the direction and flow rate of the fluid flow [1].

The positives of this system include angular insensitivity of ±50°, which allows a more accurate assessment of velocity where flow angles are difficult to predict. It is as rugged as a stainless steel pitot tube, and responds to flow in either direction without additional calibration. However, the system includes possibly large pressure sensors/probes, which can cause greater flow disruption (based on the manufacturer), calibration problems (at a low Reynolds number, there is a nonlinear effect within the fluid), and the bidirectional probes become inaccurate at flows less than 0.4 m/s. Thus it is not useful for small or slow flows.

2.1.2. Pitot Tube

The Pitot tube is a relatively inexpensive pressure instrument named after a French engineer, Henri Pitot who first described the methodology in 1700. The Pitot static tube system is a device that uses a differential pressure gauge to measure airspeed. Pitot tubes are typically mounted on aircraft or boats, as they are simple and generally effective. The Pitot tube system uses the principle of an air pressure gradient. This measures the difference in air pressure between a static sensor not in the air stream and a sensor (the Pitot tube) in the air stream [2].

These systems utilize a well-understood principle, and are cheaper to produce than other airspeed indicators. However, they do have limitations which are amplified when the tube is exposed to a flow that contains a particulate. The Pitot tube usually possesses small pressure tap holes, which can easily become clogged with soot, nullifying any further pressure changes. They also have difficulty dealing with sudden changes in flow direction, and therefore would not be useful in an area where flow can reverse its course multiple times without warning.

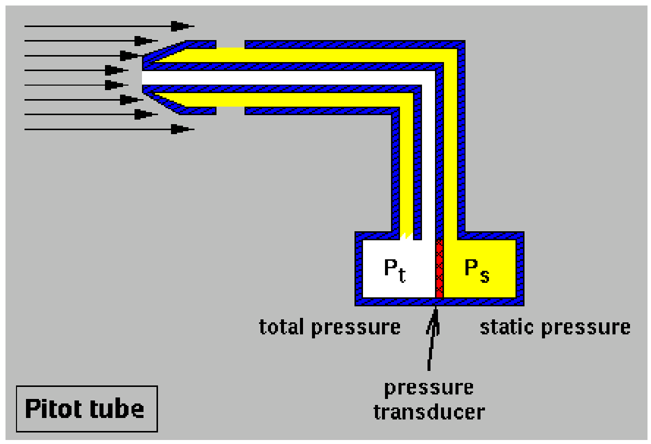

FIGURE 1: PITOT TUBE

2.1.3. Hot Wire Anemometers

Hot wire anemometers use a very fine wire, electrically heated up to a temperature above ambient. Air flowing past the wire has a cooling effect on the wire. Since the electrical resistance of most metals is dependent upon the temperature of the metal, a relationship can be obtained between the resistance of the wire and the flow velocity [3]. Hot wire anemometers have an extremely high frequency response and a final spatial resolution as compared to other measurement methods.

Hot wire anemometers are very useful in both laminar and turbulent flows. However, although they are fairly accurate, they possess a set of problems that prevent them from being utilized effectively in non-laboratory conditions. They have a limited range, and unknown spacing can cause unexpected calibration problems during set up and use. They are also extremely fragile in a smoky atmosphere, which could accordingly cause high equipment failure rates in those conditions. Additionally, they respond to temperature fluctuations more readily than velocity fluctuations, so if the temperature of the flow changed independently of the velocity, the hot wire anemometer will be unable to detect that change.

2.1.4. Laser Doppler Anemometer

A laser Doppler anemometer is similar to the proposed light system in that it utilizes a laser light projected into a particle stream. However, that is where the similarities end. A laser Doppler anemometer shines a beam of light into a flowing particle stream and measures the light backscatter when the beam intersects a particle. When the particles are in motion and impacted by the light, they produce a Doppler shift that reflects back to a sensor. This sensor is able to record the Doppler shift of multiple particles, calculate the speed of the particles, and therefore the speed of the flow [4].

The advantages of this system are that it uses a laser to measure flow, which causes no flow disruptions. However, this system is very costly, has large power requirements and is generally non-portable.

2.1.5. Sonic Anemometer

A sonic anemometer, shown in Figure 3, uses sound to measure wind speed. It sends a sound signal from a fixed transmitter to a fixed receiver, and by measuring the time it takes for the sound to arrive, can compute the speed of sound. Wind speed will increase or decrease the speed of sound depending on whether it is a tail wind or a head wind. By measuring the speed of sound in both directions, the wind speed along that axis can be calculated from the difference of the two measurements [5].

There are many advantages to this system. Since it uses sonic pulses, the measuring method itself does not interfere with flow, as there is no physical object in the flow path. Furthermore, if the system is set up with enough transducers in a certain arrangement, it can measure one, two, or three dimensional flows. It can take fine temporal measurements (20Hz or better), and is therefore good for turbulent flow. Finally, there are no moving external parts, so equipment failure is at a minimum.

However, there are disadvantages to using a sonic anemometer. The tower/rig needed to support the transducers usually distorts the flow around and after it is measured. Theoretically, this could interfere with the non-disturbing sonic measurements. This device is also not optimal for field work, because it needs frequent specific wind-tunnel calibration to correct for flow disruptions. It also requires specialized equipment, making it difficult to employ.

FIGURE 2: SONIC ANEMOMETER

2.1.6. OPTICAL FLOW METER

The closest device to the Mobile Measurement Platform (MMP) is an optical flow meter. This device uses visible light (usually from light emitting diodes), which is directed into a particle-dense flow. The photodiodes are used to detect and record the light scattered by the particles in the fluid flow (backscatter). While this is a very similar system to the MMP, the optical flow meter is also a very large, ungainly structure that is difficult to move and employ in non-laboratory conditions. This method is a progression from the laser Doppler theory, as it measures the light backscatter from the particle flow. This meter has positive aspects. It does not impinge upon the flow and it is a fairly accurate/precise device with a wide measurement range that varies from 0.1 m/s to above 100 m/s [6].

However, in addition to the lack of mobility disadvantage mentioned above, there are additional limitations to this method. The light does not pass through the flow, measuring only a few particles on the outside of the flow, depending on calibration. This means if there is a column of smoke moving faster in the center, or on one side, this system will only measure the part of the flow that was oriented towards the light emitters and photodiodes. As it does not penetrate the flow, it cannot take into account possible turbulence or difference in flow speeds. It also cannot account for the density of the smoke. Hence there are no calculations or recordings on how much light is lost or passes through overall; because only the light reflected directly back is measured.

2.1.7. MMP Advantages

The Mobile Measurement Platform utilizes a simple 5 mW, 650 nm laser light passing through a particle medium, impacting on a photodetector-type receiver which outputs a voltage based on the amount of laser light that hits the receptor. This light opens an electronic "gate", allowing a limited current to flow based upon the quantity of light that reaches the receiver. This is a unique system because the measurement is simply based on the remaining laser light that was not scattered by the particle field; it does not require any specialized/expensive sensors or lasers; and calculates the flow rate using cross correlation velocimetry versus backscatter Doppler shift. As the system uses lasers instead of LED's, the engineer does not need to consider light being broadcast outside the plume, as 99% of the transmitted coherent light would impact the plume. The system measures the flow using cross correlation velocimetry of the resultant voltages, allowing for an accurate assessment of the flow speed.

2.2. Software/Hardware Interactions

As smoke passes through the light obscuration sensors, it outputs a voltage based on how much light is transmitted through the particulate. Given these voltage outputs, a system component was required that would transfer these voltages into the accompanying software. Once read into the computer program, the voltages could then be interpreted into the measurement desired (in this case flow rate) based upon custom calculations derived through calibration and testing. There were a number of similar ways that voltages could have been transformed into data inside a program, all having to do with a hardware interface that performed an Analog to Digital (A/D) conversion. An Analog to Digital conversion is one in which a physical attribute (such as voltage level) is transformed into a digital signal that represents the value or intensity of the physical attribute[7]. The main difference among available approaches involved the relation of the A/D hardware to the computer running the interpreting program.

2.2.1. Handheld Unit

The initial concept for this project envisioned a small, hand-held computing device attached to the handle end of the sensor apparatus. This computer would ideally have had the A/D hardware built in to simplify connections and minimize costs. It would also have had to run an operating system that provided facilities for writing and running a data calculation and display program, and possess the hardware to interact with the program.

Unfortunately, during the search for such a device, it was discovered early that a device with the required attributes would not only be prohibitively expensive but also hard to find. Table 1 is a chart showing two devices found and their attributes. As shown in the chart, there were other limiting factors besides cost and availability such as low screen resolution and non-programmability. The limitations of this type of all-in-one platform led to the search for an alternative approach that separated the unit responsible for acquisition of data from the computer running the analysis program.

TABLE 1: TABLE OF HANDHELDS CONSIDERED

	A/D Resolution	Max Sample Rate	Input range (V)	Input Accuracy	# Inputs	Screen Type	Programmable?	Size (WxHxD)
DaqPRO 5300	16-bit	1/sec	0-10	+/- 0.5%	8	Monochrome, small	No	7.17x3.94x1.10"
Mosaic Handheld	8-bit	100k/sec	0-5	?	8	Monochrome, 128x128	Yes	4.6x10.3x2.5"

2.2.2. DATA LOGGER

The next idea was to use a hardware device called a data logger (see Table 2) that would run on battery power and periodically store readings locally. This device could then have been disconnected from the sensor apparatus to be connected to a computer to upload and analyze the data it contained[8]. This would enable the sensors to be remotely located and unattended, which could have proven useful in field applications. Furthermore, data loggers were much less expensive than the all-in-one handhelds previously investigated.

TABLE 2: DATA LOGGERS CONSIDERED

Unit	Cost	Analog Inputs	Input Range	Input Resolution	A/D Resolution	Max Sample Rate	Size (mm)	Operating Temps
EL-USB-3	$75.25	1	0-30V	+/-1% (overall)	14-bit	1/sec	?	-25*C to 80*C
HOBO U12	$105	4	0-2.5V	+/- 2.5%	12-bit	1/sec	58x74x22	-20*C to 70*C
Avatel DS-VS	$299	4	0-2.5	+/- 1%	12-bit	1/sec	?	?
Pico ADC-16	$229.35	8	+/- 2.5V	+/- 0.2%	17-bit	1.5/sec	?	?

However, data loggers had their own set of limiting attributes. The biggest negative was that sampling rates for data loggers tended to be very low (approximately one sample a second, max rate). Due to the MMPs approach to detecting smoke flow rate, this was much too slow. The other major detrimental factor was that data loggers did not allow readings to be viewed in real time, something that would be useful in many applications, which will be discussed later in Section 3.1.2 Software Design.

2.2.3. DATA ACQUISITION UNIT

Continuing the search for an option that offered the best collection of attributes and abilities, the Data Acquisition Unit (DAQ) was considered next. A DAQ typically is connected between the analog data source and the computer. The analog data, which in this case was voltage, was read into the DAQ through various inputs. From there the A/D conversion was completed, and then the digital value was automatically passed on to the computer or held until the computer requested it. DAQs are typically tethered to the computer via a USB cable, although more expensive units are capable of wireless connections[9].

FIGURE 3: DATA ACQUISITION UNIT

The DAQs investigated varied in their construction and features, but in general using a DAQ with a common laptop computer provided most of the advantages and functionality originally envisioned, at a reasonable price.

TABLE 3: TABLE OF DAQS CONSIDERED

Unit	Cost	Analog Inputs	Input Range	Input Resolution	A/D Resolution	Max Sample Rate	Size (mm)	Analog Outputs	Output (V)	Output (µA)	Operating Temps
DATAQ DI-148U	$50	8	+/- 10v	+/- 19.5mV	10-bit	14.4k/sec	66x66x28	N/A	N/A	N/A	0-70*C
DATAQ DI-158U	$99	4x2	+/- 10v	+/- 4.88mV	12-bit	14.4k/sec	66x66x28	2	0-1.25	+/-300	0-70*C
DATA DI-158UP	$99	4x2	+/- 64v	+/- 31.3mV	12-bit	14.4k/sec	66x66x28	2	0-1.25	+/-300	0-70*C
LabJack U3-LV	$108	16	0-3.6v	?	12-bit	50k/sec @ 12-bits	75x115x30	2	0-5	?	-40*C to 85*C
LabJack U3-HV	$114	16	-10/+20v	?	12-bit	50k/sec @ 12-bits	75x115x30	2	0-5	?	-40*C to 85*C

As can be seen in Table 3, DAQs generally offer very high sampling rates, which facilitate accurate tracking of the sensor's data. In a configuration where the DAQ automatically read values as often as possible and funneled them into the program on the laptop, data is theoretically processed and viewed in real time. By using a laptop the screen area available to draw graphs and calculations in the GUI was also increased, which allows for a more comprehensive and usable program where more data was readily visible. The only notable disadvantage of a DAQ in this application is that the sensor array had to be tethered to the computer by a USB cable, in order to keep costs down.

From the DAQs listed in Table 3, the one that was used in this project has been highlighted in the yellow row. After comparing it with the others, it had the best combination of features for our application. It has a high resolution of 12 bits, can automatically calculate the voltage differential between paired inputs, has analog outputs, and is compact in size while still having fast and accurate sampling.

2.2.3.1. Program Features

The application of the sensor array in a variety of areas ranging from laboratory use in experiments to field use in remote locations created a need for an easy to use data analysis program. The data analysis program selected also had to possess a set of features that make it widely useful. By carefully considering the possible applications of this instrumentation package and what each component entailed, it became possible to form a list of core features that would maximize usability of this software package. The two major elements are discussed in the following sections.

2.2.3.2. Real-Time Graphing

To facilitate using this device in a setting where immediate analysis of readings is important, there was a need for a graph of all data that was updated in real time. Such settings could include a laboratory situation where an experiment being run was intended to alter smoke type or flow, and a correlation between time and the change of these properties was desired. The reason behind plotting a graph rather than building a table was that a graph is easier to understand and interpret than the plain table of the information it represents, especially for large data sets like those produced by this sensor. Ideally, the user would be able to pan and zoom on the graph, to examine large amounts of data. While it was possible to purchase a commercial graphing framework to employ in the software, the high average cost of such packages warranted opting for a free or self-developed option. There were a few approaches that could have been taken in this case, which are discussed individually below.

2.2.3.2.1. Freely Available Packages

Graphing frameworks that were free online had the obvious advantage of adding no cost to the overall development of the sensor package. However, there existed a lack of quality options in this realm. Most free packages lacked some features that were desired for this application, such as the ability to update in real time instead of drawing a completely new graph.

2.2.3.2.2. Linking with Microsoft Excel

A more viable approach could have been to leverage the existing power of a fairly common program such as Microsoft Excel, which specializes in calculations on sets of data. Excel has built in features such as tables and graphing utilities that could form the basis of a complete solution. Use of Excel could have been completed via two avenues: Writing a separate program which inserts data into an Excel spreadsheet via a link called a Dynamic Data Exchange, or to write the program as an add-in to Excel in the form of an XLL (an Excel Linked Library).

A Dynamic Data Exchange is a link within the Windows operating system that facilitates inter-program communication of data or commands [10]. In this application, the link would have been formed between Excel spreadsheet cells and/or charts and an external program responsible for retrieving readings from the DAQ. Those readings would have been sent into Excel, where the tables/charts automatically updated. While sound in theory, this approach required two separate programs running to accomplish a single task. Also, a DDE link may not have been able to operate quickly enough for this application, where there was the potential to have several thousand readings entering the system from the sensors each second.

By writing an XLL (essentially a Dynamic Linked Library, or DLL, specific to Excel), the functionality of reading and processing the sensor data could have been integrated directly into the menu and/or GUI of Excel [11]. This would have only required Excel to be open during the collection of readings and all calculation would be self-contained within the GUI and menu systems.

2.2.3.2.3. Custom Development

The last approach considered was development of a custom graphing suite. With this approach, it became possible to tailor it specifically to the needs of this application. A custom graphing setup eliminated a "middle-man" program such as Excel between data acquisition and computation. One beneficial result of this design was the speed with which incoming readings from the DAQ could be displayed on the graph. Moreover, a graph created with this strategy could be integrated into a simple, clean GUI providing all needed data and controls in an easy to understand format. The one main disadvantage to choosing to build a custom graph unit was that it required significantly more time for implementation and debugging, for a project where development time was at a premium.

2.2.3.3. Save/Read Data To/From Files

Raw data read into the program was not automatically persistent; it regularly would be lost when exiting the application. While this might have been acceptable for simple field readings where the instrumentation was used to take spot readings and write down single values, it may not have been acceptable in other situations. For example, during the execution of a research experiment, the program could have created a large amount of data that required in depth analysis at a later time, or shared among colleagues.

By providing the user with the ability to save the current session's data to a file, large sets of data could then be accumulated and stored for future reference and analysis. Additionally, this facilitated easy sharing of data. The program also needed the capability to open a data file and display a graph of the data in a format that enables detailed data analysis.

2.3. MMP Material

The Mobile Measurement Platform consisted of various electronic and mechanical components. However, without the proper structure supporting the lasers and electrical systems, the components would have been ineffective at best and unusable at worst.

The physical MMP structure (henceforth referred to as the rig) needed to be constructed from a noncombustible material that was easily crafted and shaped. Therefore materials such as wood or plastic-based products were unusable because they could either deform under heat or char. Price was also a factor since the electronics were so costly; the rig itself could not be prohibitively expensive as sufficient funds needed to be allocated to the components of the circuit. The selected material also needed to be readily available, and easy to purchase.

Another consideration was the ability of the material to be constructed. It needed to have the capability to be assembled in various positions without readily available specialized tools. The ease of welding was part of the consideration in selecting the material for the MMP.

Finally, the material could not be too heavy nor conduct excessive heat. The weight was a factor in determining mobility of the rig, so the material chosen had to be minimally detrimental to the portability and transportability of the device. The structure also could not absorb and transmit too much heat, both for the protection of the temperature-sensitive electronics and the user holding the device.

A rough preliminary engineering analysis was performed, based on the experience of the designers. Initially four different metals were selected as useful for rig construction. However, a more detailed, in-depth analysis was required to compare their various properties. Those four metals include unmodified steel, stainless steel, aluminum, and titanium.

Table 4 compares the materials and their various properties[12, 13, 14].

TABLE 4: COMPARISON OF MATERIALS

	Steel	Stainless Steel	Aluminum	Titanium
Cost Per Lb	$1.70	$7.65	$6.00	Thousands
Weight/Mass (lb/ft2)	490	490	165	280
Density (1000 kg/m3)	7.85	7.75-8.1	2.6-2.8	Unknown
Thermal Expansion (10^-6/K)	11-16.6	9.0-20.7	20.4-25	Unknown
Melting Point	1380+	1375+	660	Unknown
Heat Conductivity (W/m-k)	24.3-65.2	11.2-36.7	235	Unknown
Tensile Strength (MPa)	276-1882	515-827	230-570	Unknown
Availability	Extremely High	High	High	Very Low
Joining Ability	Good, especially Low Carbon Steel	Moderate	Low to High, dependant on Purity	Unknown

After reviewing this information, it was concluded that low carbon steel was the best choice to build the structure. Stainless steel was discarded since it was much more expensive and possessed a lower joining ability, while aluminum (although being very light) has a prohibitively high thermal conductivity and relatively low melting point. Titanium is incredibly expensive. Note: tool steel was not considered, due to its extreme resistance to deformation, and therefore cutting.

Low carbon steel possesses a high ability to be joined using traditional welding methods (no specialized equipment) and it can withstand both high temperature and rough treatment. It is three times heavier than aluminum, but given that the rig uses rectangular steel, the total weight of the steel used was less than eight pounds, without sacrificing strength.

The MMP is required to measure a flow that does not have enough density or light altering properties to be measured by the laser diodes. In this case, the best solution is to produce the smoke in such a way that it does not affect the original flow, but it still is measurable by the laser diode beams. As with all components, cost, availability and size were taken into account when deciding the best method and product for the platform. Along with these restraints, there are other vital criteria that needed to be considered.

A key consideration in picking a smoke source is smoke composition which includes density and smoke by-products. The production of the smoke has to have enough density to be detected by the laser diodes. It also has to be a 'clean' smoke, so that it does not coat the rest of the platform with any film or dust. Any precipitates from the smoke could cause the laser diodes to be obstructed or encourage corrosion of the platform. Excessive and/or highly specialized cleaning and inspection requirements could lead to an increased potential for errors in the system due to inaccuracies in measurement along with long-term damage to the metal and electrical equipment.

Health concerns regarding the composition of the smoke were also considered. Inhalation of any smoke is generally harmful and is strongly ill-advised. Although safety precautions regarding smoke inhalation should be observed, it is always possible that small quantities of smoke could be inhaled. Therefore any smoke produced should be harmless.

Along with the smoke composition, the ease with which the smoke source can be replaced was also considered. The source of the smoke should be readily available and should fit easily onto the platform.

The reliability and consistency of the method of the smoke production is a major factor, since a more constant smoke flow is easier to measure. To fully be effective the smoke stream has to be continuous without impeding the original flow. If the stream of smoke is not continuous, the accuracy of the readings from the laser diodes may be adversely affected. Other issues with respect to smoke producing component include the way the smoke will be ignited/turned on, how long the stream of smoke will continue and the method used to halt the flow once sufficient measurements have been taken. The emission and arresting of the smoke stream should be easy and safe for the user. Furthermore the smoke generator needs to be mounted in such that the flow will be unaffected, yet the orientation allows the smoke to cross both laser diodes at the same speed as the original flow. Otherwise, the velocity of the induced smoke flow will have to be taken into consideration during calculation.

The project team reviewed several choices for the best smoke generator for the MMP. The simplest design was that of a small crucible with a removable cover. This crucible could be as small as a quarter, ensuring that it would not unduly affect the initial flow of the fluid. It would be connected to the rest of the platform via a metal bar, just under the initial diode. The bar ensures the crucible is kept relatively stiff in relation to the laser diodes. The material inside would be lit manually with a match or lighter. To halt the stream of smoke, the cover would be placed on top of the crucible, cutting off the supply of oxygen and smothering the flame.

Two materials considered for the crucible system were wood or candles, but they were quickly ruled out for several reasons. These sources did not offer consistent and controllable smoke production. Consistency is essential when taking measurements of flow rates. Use of these products would require the same type and size of wood or candle to be used every time. This is both impractical and difficult to obtain and verify. This requires research to determine which sources is most beneficial for the production of smoke, identification of exactly which type of wood or candle is best suited, a cost analysis, and availability of the source. This option was not pursued due to more viable options being available.

Another smoke source considered was linseed oil soaked in fabric. Linseed oil has several advantages. It produces a significant amount of white smoke. Linseed oil is easy to ignite, not overly toxic and the smoke generated is sufficient for the laser diodes to function properly. The largest concern with using linseed oil is its extreme combustibility and possibility of an oil coating post-ignition. Linseed oil takes very little heat, as little as a hot day in the sun, to ignite. This is not only dangerous to the user but requires careful storage. Oils also tend to leave unwanted by-products from their smoke which is to be avoided.

Once the crucible idea was determined to be unsatisfactory, the possibility of obtaining and using an already constructed smoke generator was introduced. Toy trains and boats have smoke stacks, that when connected to a power source, produce steam. Steam leaves no by-products, is non-toxic, and still obscures enough of the laser diodes to allow for measurements. A smoke stack would also allow for an easy ignition and halting of the steam and could be done remotely with a switch. This removes the need for the user to carry ignition material. The only concern regarding the smoke stack is that it may produce its own flow. However, with proper orientation of the smoke stack, this can be easily remedied. The cost of such smoke stacks is affordable, replacement sources are readily available and the power source required is a 9V battery. This was by far the most efficient and satisfactory solution to the issue of smoke generation.

FIGURE 4: SMOKE GENERATOR & DISTILLATE

2.4. LASERS VS. PHOTODIODES

Lasers are one of the key components of the platform. Using the interference incurred by the smoke when passing through the laser, the flow velocity can be determined through voltage change. To do this, the laser has to meet certain criteria. The laser chosen has to be affordable, easily replaced, small enough to fit on the platform, have a required power source of no more than 9V, have a wavelength that would produce the best results when smoke flow occurred, and have an output easily read by the DAQ.

The first requirement dealt with was the wavelength of the laser. This was only an issue in the sense that a laser should not have a wavelength in the infrared range. Areas that will be measured and analyzed could have a heat signature that would interfere with infrared range lasers and give inaccurate readings.

Lasers with smaller wavelengths, such as those in the "green" colored range were briefly researched but quickly dismissed for a number of reasons. The biggest issue with the green wavelength lasers is they are too large to fit onto the platform. It is not practical to have them fitted onto the platform due to the extent of redesign of the rig required to accommodate them. These lasers are also often more expensive and require a larger power source than is realistic.

The final decision was to select a wavelength within the 450 – 800nm range. This outputs a red color, easily visible to the eye, while staying out of the infrared range. This is important because the operator will be able to determine that the laser is on even when not receiving any readings. Lasers in this range are quite common, have varying price ranges and come in a variety of sizes.

The next issue to be considered was the output of the laser. The easiest way to feed information to the DAQ is by using a voltage. Based on the amount of light that would penetrate the smoke, the laser outputs a voltage, thereby creating the peaks and troughs required to calculate the velocity. This proved to be a critical issue as lasers that output a voltage are quite rare and difficult to find. Although there are lasers available that satisfy this requirement, they proved to be inadequate for other reasons, such as cost, size and availability. They were generally too bulky to fit on the platform and even if that constraint was satisfied, they were too expensive and difficult to obtain.

Light Emitting Diodes and photodiodes were briefly considered, but after a quick examination of available LED/photodiode combinations this idea was discarded. Most, if not all, LED/photodiode pairs are built to broadcast infrared light. This is due to the fact that most LED/photodiode pairs are built to be used in video recorders or other devices that only recognize the infrared spectrum. Although these combinations are extremely cheap, they were eventually abandoned. It was reasoned that a hot flow could shadow or cover up signals from the LED, rendering the mobile measurement platform useless in warm rooms or streams.

A button laser (shown in Figure 6) was eventually located, which satisfied the design requirements. This laser was an evolution of a light emitting diode (LED), with the difference that it emitted a stream of coherent (one-direction) light, versus an LED's incoherent (random broadcasting) light. This laser is compact enough to fit on a printed circuit board without having to be disassembled first, is the correct wavelength (650 nm), requires a minimum input current and voltage, and is cheap enough to easily justify the cost and its implementation into the design. A major benefit of the button laser is that the three-prong design allows the laser to function as both a sender and receiver. Thus, no additional photodiode calibration is needed. This laser, in theory, appears to be a good fit for use in a simple non-inverting circuit, with the addition of an op amp if the voltage needed increasing. The negatives of the button laser are few. Due to its minute size, it needs to be oriented perfectly, while the three prong design would need additional testing to determine correct voltage. Initially the laser was extremely difficult to locate, although a reliable supplier was secured once the specific model of laser was determined.

FIGURE 5: BUTTON DIODE LASER

2.5. Directional Flow

Bi-directional flow is an issue that can occur in places such as coal mines, where the air ‘breathes’, or fluctuates in and out of a certain orifice in a controlled fashion. This phenomenon is important when designing a mobile measurement platform. Although the device could measure flow in both directions, it initially would only recognize a magnitude of flow, but not indicate the direction of travel. This could be problematic when flows slow down, stop, and then change course. There would be no way to differentiate flow as the same reduction and then increase of flow would register regardless of the flow direction. The simplest solution is to have a device that detects the direction of the flow and sends a signal based on that direction. Three solutions were investigated; an air-sock, a flap and a fan.

2.5.1. Air-Sock

Use of an air-sock requires a piece of lightweight material to be attached to the device where it would not interfere with the laser diodes, but still be affected by the flow moving between them. This is a straightforward approach to the problem that requires very little effort to apply or maintain. The issue with this technique is that it only works as a visual aide to the user and would be difficult to connect to a system that would record the direction.

2.5.2. Flap

Constructing a flap to attach to the platform was the second possibility. The basis of this concept is very simple. The flap would be made of a lightweight, highly flexible material (such as paper or thin laminate) with one end securely mounted to the apparatus while the other end floated free. Each side of the flap has a small amount of electrically conductive material, such as aluminum foil. When the flow is moving upwards, the flap bends up, and the conductive contact on the upper side completes a circuit releasing a positive voltage. When the flow is downwards, the flap bends down, and the opposite contact completes a separate circuit that releases a negative voltage.

The flap approach guarantees the simple sign-check calculation of flow direction mentioned in the description of the fan concept. In addition, it would be much more sensitive to low flow rates as not much flow is required to bend a piece of paper. Lastly, the flap would almost immediately reverse direction in the case of a flow direction change, which eliminates the inertia the fan would encounter while changing speed. This method is only slightly more complicated than the air-sock design and has more benefits.

Despite these advantages, there are two distinct shortcomings to this scheme which eliminates it from consideration:

- Particulate smoke would build up over time on the electrical contacts on the flap and eventually cause a loss of functionality without meticulous cleaning.
- The flap material requires the lightness and flexibility of paper, but paper is not a durable material. It is combustible (a potential issue in high-temperature flows), decomposes over time, can crease or crinkle and be eaten by insects. A more durable substitute with the required properties could not be found.

2.5.3. Fan

The final solution considered was utilizing a mini-fan to detect the change in direction. This works on the same principle as the air-sock and flap except instead of the entire mechanism changing directions, only the blades of the fan would move in a different direction. This concept revolves around mounting an electric fan on the sensor head, which spins in the direction of the particle flow. By being spun by the air/particle flow, the electric fan generates a voltage which can be read into the software package via the DAQ. This is possible because the electric motor at the heart of the fan, as with all electric motors, can function as a generator when it is manually rotated [15]. The presence of the fan also serves as a second check on the flow rate measurement from the main sensor.

No decision was made at this time as to what method for direction detection was going to be used. The primary goal was to obtain reliable readings in a single direction, thus the multiple flow concept and measurement devices were considered secondary in importance.

3. Methodology

3.1. Design

3.1.1. Hardware

This section covers the thorough design of the Mobile Measurement Platform. The major concern was the optimal distances the lasers were to be set from each other (vertically) and from their respective receptors (horizontally) was unknown when the project began. Thus, the ability to adjust the dimensions of the laser's operating space became a key requirement of the test rig. The plan was to construct multiple test rigs, each possessing an incrementally larger fixed width between the lasers and the receptors. Each rig had a vertical "peg-board" of holes such that the distance between laser/receptor pairs could be adjusted in small, fixed increments. Following all the known requirements, the rig took a fork-like design with two L-shaped prongs (see Figure 7). The laser diodes were designed to be mounted on one prong, facing their respective light receptors located in the opposing prong.

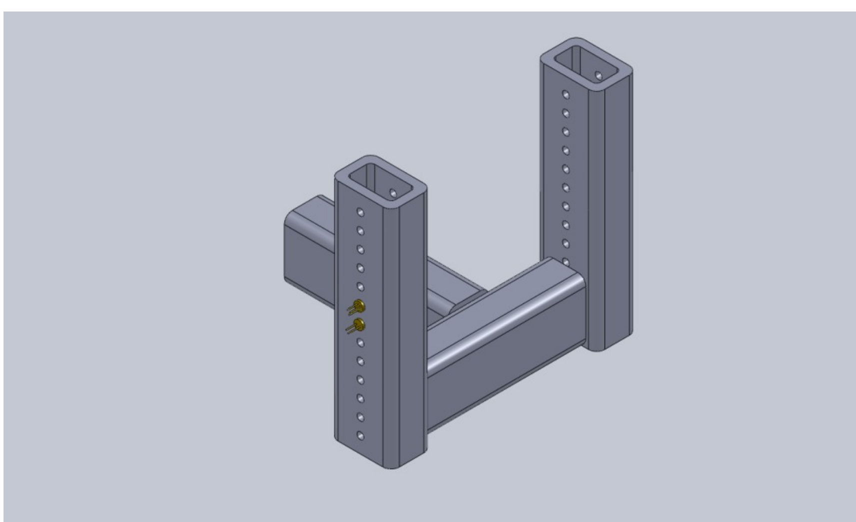

FIGURE 6: INITIAL RIG DESIGN

3.1.1.1. LASERS

The laser selected for installation within the MMP was a Lumex Opto Diode Laser. The laser emitted a coherent light pattern within the visible range of the spectrum - 390-750 nm[17] – as this prevented residual heat from either the smoke or the operating environment affecting the measurements. The lasers were small enough to reasonably fit within a portable device while being in close proximity to one another. Lastly, simplifying parts ordering and construction, the lasers could perform as both an emitter and a receiver/photodiode depending on how they were connected to the circuit. The lasers had three prongs extruding from the base instead of the usual two. Thus, a single diode functions either as an emitter or receiver depending on the pin connections to the circuit.

3.1.2. SOFTWARE

The first step of the software development process investigated the Application Programming Interface (API) and code examples for the DAQ in order to determine the structure of interactions that occurred between the DAQ and the software. The code examples provided by the manufacturer demonstrated that, due to the existence of an ActiveX control (a standard component that can be easily incorporated into third-party applications) provided by the company to handle I/O with the DAQ, the interactions were relatively simple. The ActiveX Control defined the main interactions with the DAQ first by creating hardware connection parameters and then issuing commands to either start or stop reading data. In addition, the control required the definition and identification of a function that it executed each time a new batch of data points was ready to be processed.

The function was the entry point of new data into the program, and thus it was the origin of all data processing.

The next key point in the design phase was determining the functional requirements of the software. A list of required features included:

1) The ability to connect to and read data from the DAQ
2) Large, constantly updating graph of all received data to facilitate the observation of readings in real time.
    a. Must draw incoming signals, time lags discovered, the speed readings derived from those time lags, and any other potentially important information.
3) The ability to discover the inherent time lag between the signals received from each of the two sensors.
    a. A technique for converting these time lags into values denoting the speed of the smoke passing the sensors.
4) A mechanism to save a session of data to a file for later opening and examination.
5) The ability to smooth the incoming data to eliminate some of the incoming signal noise. This makes discovery of time lags more reliable.
6) A Graphical User Interface (GUI) that was easy to understand and use, which also conveyed as much information and controls as possible without being cluttered or cramped.

After becoming familiar with the DAQ's interface and compiling the required features, a basic design for the software's internal structure was laid out. Since the user interface needed to graph sensor data in real time, and the data had to be stored for at least the length of the program's run time, the Model-View-Controller design pattern was employed. In this pattern the program is split into three logical units:

1.) Model – Stores and processes all the data.
2.) View – Manages displaying the data to the user.
3.) Controller – Directs the actions of these units, as well as processing the incoming data. This data can come from the user in the form of UI interactions or from the DAQ.

Since various components of the program needed a common copy of the model data, it was decided that the Model component should exhibit the Singleton design pattern[18]. Under this pattern, only one instance of a given class object can ever be instantiated, and all subsequent attempts to reference this object type return references to the same object.

3.2. IMPLEMENTATION

3.2.1. HARDWARE CONSTRUCTION

The final design of the Mobile Measurement Platform hardware component is that of a compact portable device. All component details can be found in the "Budget" section. The components necessary to build the rig are:

1. 1 x 9" hollow rectangular steel tubing, divided into two sections, 5.5" and 4" respectively.
    a. Dimensions: 1.5 x 1.0" {A} x 0.760" ID {B} x .120" Wall {C}
2. 4 x 0.125" thick maple planks
    a. 2 x (1.5" W x 5.5" L)
    b. 2 x (2" W x 4" L)
3. 1 x Prototyping Circuit Board

4. 4 x Diode laser, 650 nm
5. 1 x 170 ohm resistor*
6. 2 x 22 ohm resistors
7. 1 x 9 volt battery
8. 1 x 9v battery harness
9. 1 x mechanical switch
10. 2 x (1" W x 3" L) Velcro strips (or another form of reusable adhesive product)
11. 1 x DATAQ Instruments DI-158U Data Acquisition Unit, 2 input channels minimum
12. Various: Assorted wire lengths, epoxy, drill.

* Note: This resistor can be replaced by any combination of resistors in series that, combined, equals a value between 164 and 170 ohms. It can also be replaced by a potentiometer, for scalable resistance.

3.2.1.1. ASSEMBLY

This section provides the assembly method for the MMP. It details how to create the physical platform that was used in this project.

1. Join the two steel components into an L-shape; with the 5.5" segment forming the upright (see Figure 8).

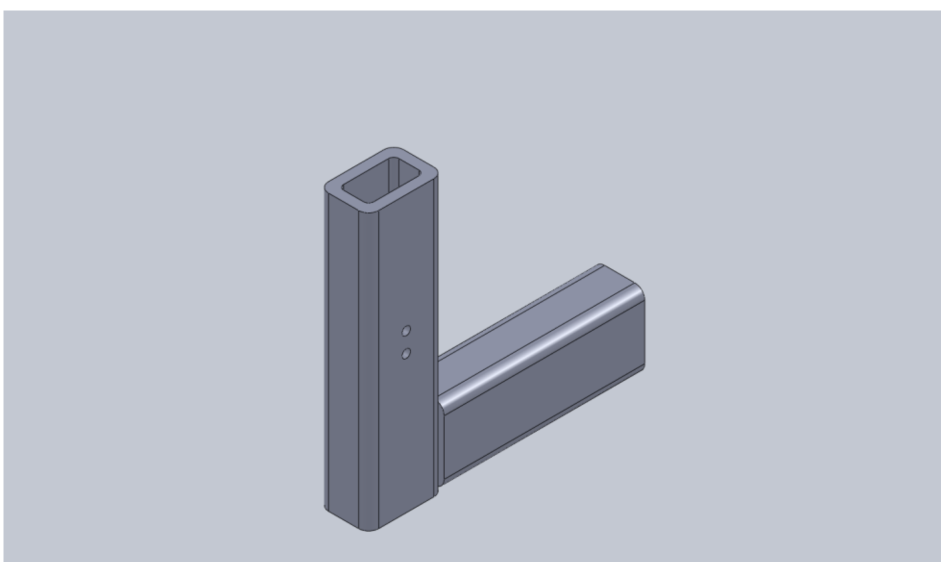

FIGURE 7: INITIAL BRACKET

2. Epoxy the maple slats onto the rig as shown in Figure 9. The 1.5" x 5.5" length should be affixed on the vertical bracket, and the 2" x 4" length on the horizontal

bracket. On the horizontal segment, mount so that the longer edges are flush with the top of the metal.

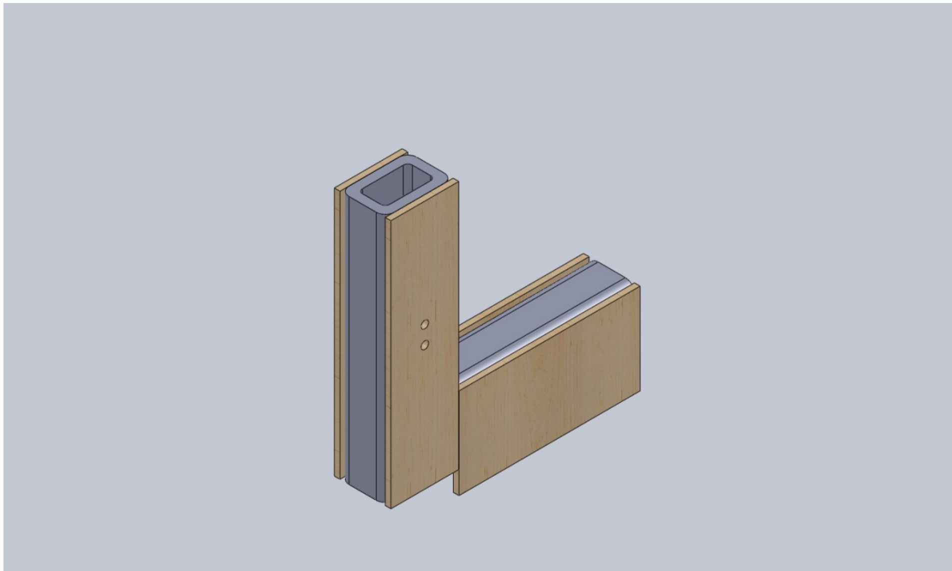

FIGURE 8: MAPLE PLANK ADDITIONS

3. If not previously created, drill 2 x 9/64" holes horizontally through the vertical brackets (both maple & steel). The bottom hole should be 2.75" from the bottom of the vertical upright. The second hole should be 10 mm (0.39") apart from the first on the vertical plane, and directly in line (see Figure 10).

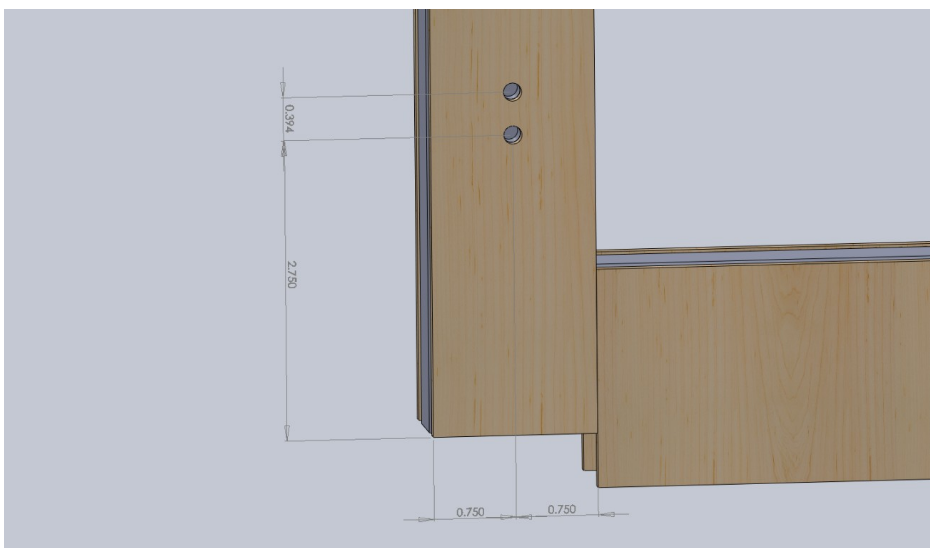

FIGURE 9: HOLE CREATION

4. Apply the Velcro strips onto the middle region of both the right horizontal wood slat and the top of the 4" steel member (see Figure 11). The joining Velcro ends should be applied to the back of the DAQ and Protoboard.

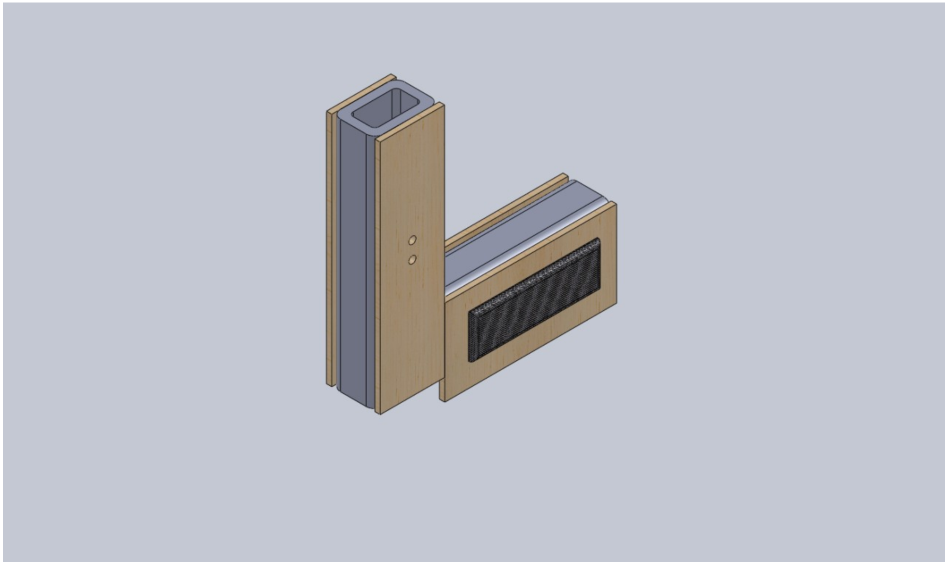

FIGURE 10: VELCRO ADDITION

5. The circuitry will be assembled in this step according to the diagram in Figure 12.
    a. The power input to the lasers should be constructed so that the 170 ohm resistor is in series with 2 x 22 ohm resistors assembled in parallel, one output to each laser.
    b. The two outputs should be connected to one laser each, and the negative terminal (see laser specification sheet) connected back to the protoboard.
    c. Both the battery and the switch should be assembled so they directly power and control the circuit/laser activation.

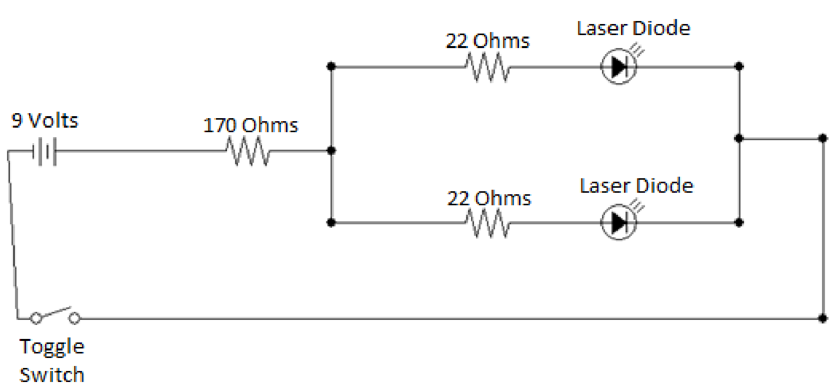

FIGURE 11: CIRCUIT DIAGRAM

    d. To attach the emitting diodes, the positive and negative wires need to be connected to the respective pins shown in Figure 13:

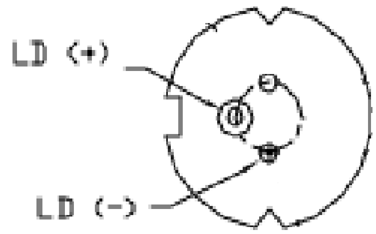

FIGURE 12: PIN SELECTION FOR EMITTER CIRCUIT

6. Attach the protoboard to the right side of the bracket, and plug the two lasers into the previously drilled holes (see Figure 14).

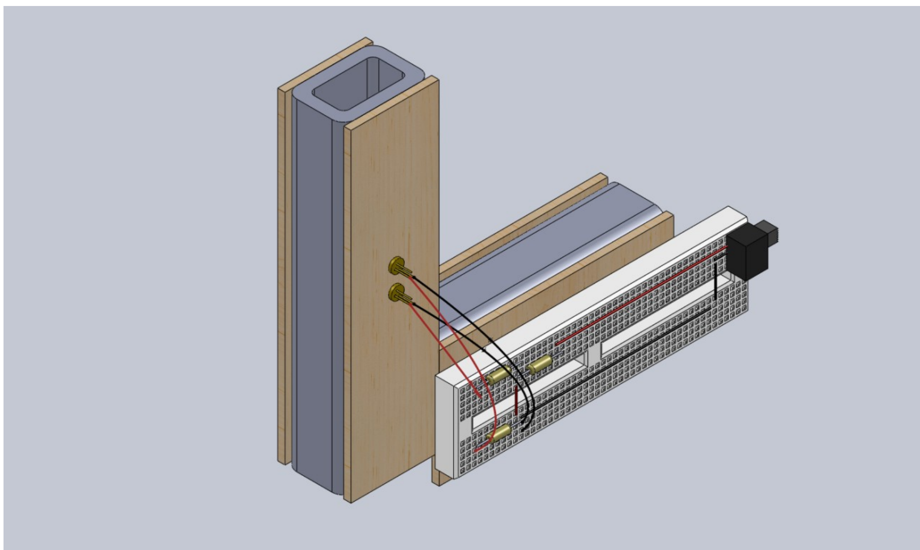

FIGURE 13: COMPLETE WIRING FOR EMITTER CIRCUIT

7. Wire the two remaining lasers into channels 1 and 3 of the DAQ, and attach the DAQ to the left side of the bracket (see Figure 16).
    a. To attach the receiving diodes, the positive and negative wires need to be connected to the respective pins as shown in Figure 15:

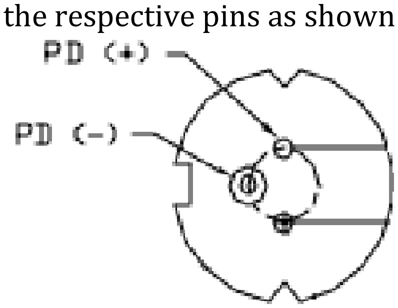

FIGURE 14: PIN SELECTION FOR RECEIVER CIRCUIT

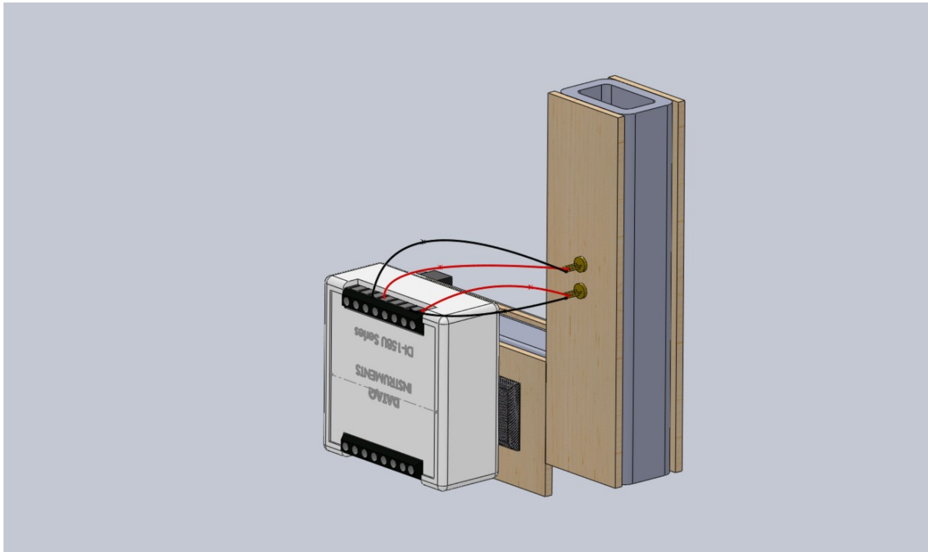

FIGURE 15: COMPLETE WIRING FOR RECEIVER CIRCUIT

8. Insert the battery into the end of the horizontal tube. Wrap with electrical tape as needed for a pressure fit

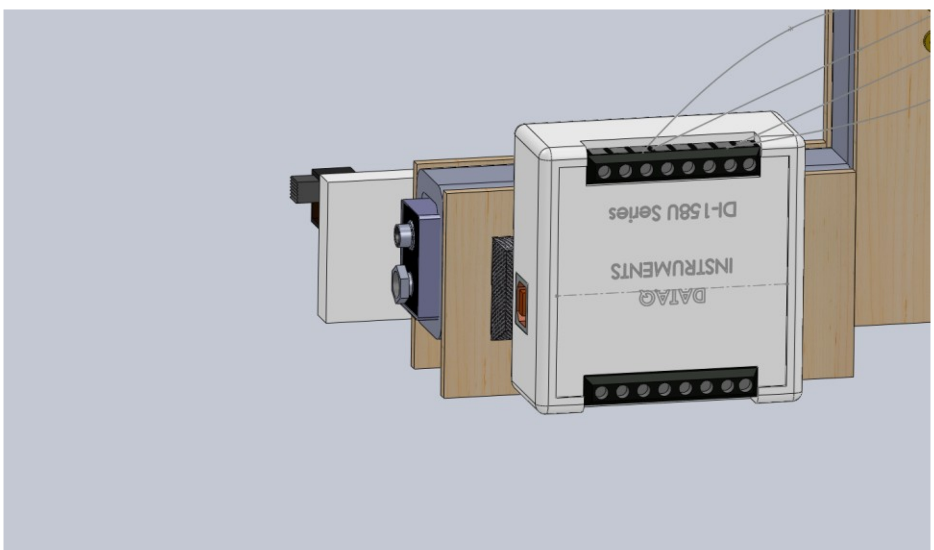

FIGURE 16: BATTERY INSERTION

9. Attach the 9v connector to the battery. Plug the ends of the harness into the space indicated, making sure to complete the circuit.

10. Connect a length of wire from the “AGnd” port on DAQ to any metal point on the rig. Figure 17 shows the rig after battery insertion

3.2.2. Software Construction

3.2.2.1. Cross-Correlation:

The first approach attempted was to ascertain time lags by manual detection and matching of significant graph features. A subroutine was written that found and marked all points in the graph that were lower than an adjustable *n*-number of adjacent points to both sides of the chosen value. Low points were desirable because they would mark locations where the densest smoke features had obscured a large amount of laser light, making for ideal features to match across signals. A subroutine was written to match marked low points of similar magnitude, following the theory that a similar order of magnitudes of marked points would be observed on both signals and therefore allowing a time alignment. However, before this approach was tested, a better technique was discovered and adopted.

This approach was found through continual research on the concepts behind Digital Signal Processing (DSP), which yielded the more efficient and accurate algorithm commonly called "matched filtering" or discrete cross-correlation[20]. In the execution of this method, a known waveform is translated in relation to another parallel signal, and the two are compared after each translation. At each time/translation step, the products of each value in the known waveform and their parallel in the other data stream are summed to create a value denoting the cross-correlation of the two signals, with higher cross-correlated values indicating a higher likelihood of being a match.

This process is explained in conjunction with Figure 18, which gives a visual explanation of the relationship between the known waveform t[n], the parallel signal x[n], and their cross-correlation signal y[n]. Each value in y[n] is a single cross-correlation value (CCV) representing how similar the known waveform t[n] is to the parallel signal x[n] at that time translation point. The dotted box is moved left or right in a manner such that its output points to the sample in y[n]   currently being computed. At the top of the dotted box the samples are multiplied with their parallels, and at the bottom they are summed into one output point which becomes an element in y[n]. In this example, y[n] can be viewed as a new signal representing the complete cross-correlation of the two signals in the given time frame [19].

Equation 1 provides a more formal representation of the cross-correlation calculation as a common formula for the discrete cross-correlation of two real signal sequences. Signal names have been matched to Equation 1. Here "m" represents the lag being computed, and the infinities represent the ends of the signal; if the signal(s) are finite (as they are in the MMP implementation), they are replaced with appropriate endpoint values [20].

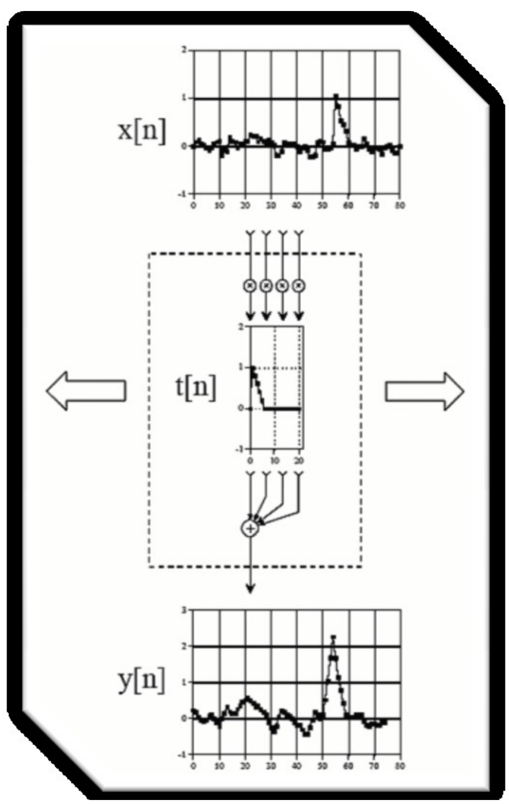

FIGURE 17: WAVEFORM RELATIONSHIP [19]

EQUATION 1: WAVEFORM[20]

$$\begin{aligned} R_{tx}(n, n-m) &= R_{tx}(m) \\ &= \sum_{n=-\infty}^{\infty} (t[n]\, x[n-m]) \end{aligned}$$

3.2.3. Cross-Correlation as Applied in MMP Software

This algorithm needed little initial adaptation for the needs of the data analysis program that was written in this project. In the following sections, the process of implementing and then improving the algorithm are documented. The first section describes the initial implementation in the software, and the following section discusses the application-unique modifications made later in development to make the calculations more accurate for the purposes of this sensor package.

3.2.3.1. First Code Iteration

In the first iteration of Cross-Correlation Value (CCV) code, the calculation described above was run each time a new sample of data was received from the DAQ. At that time, channel 1 of the DAQ was connected to the uppermost laser/photodiode pair and channel 3 was connected to the lower pair. Each time the program received a new block of data for both channels from the DAQ (which arrived simultaneously due to inner workings of the DAQ's API), the newest block of data for channel one was used as the known waveform (t[n] in Figure 19), and the entire history of channel 3 including the newest data was used as the opposing signal.

The CCV was calculated for each time offset up to a maximum value (which was adjustable), where a time offset of 1 meant that the known waveform (channel 1) was offset backwards against the opposing signal by one data point. Calculations translated the waveform backwards when the smoke flowed upwards because the physical orientation of the laser/receptor pairs caused channel 1, the top sensor, to continually lag behind channel 3 (smoke features passed the lower sensor first). The correlation value at each lag position was compared to a variable that stored the highest known CCV encountered during the current run. If it was greater, the just-calculated CCV became the new maximum value. The time lag value of the CCV at that moment was also stored. For a pseudo-code version of the algorithm, see attached code.

Following the calculations, two variables tracking the highest known value from the current run and its location were set to the value and lag from the greatest correlation between the two distinct values found between the current samples. This data revealed the most likely offset from channel 3's signal to channel 1's signal, measured in the number of samples between matching features of one channel to the other. Due to the speed of these calculations and the amount of data being received per second, the program typically was able to compute multiple maximum CCV's per second. This redundancy provided the opportunity to average the CCV's from a given second to get one comprehensive reading per second. The averaging of multiple CCV's helped to eliminate some of the low-scale "noise" or inaccuracies the CCV calculations produced. This one comprehensive cross-correlation lag found per second was then used in calculating the average speed of the flow during this second.

As the software polled the DAQ at a set rate of approximately 2500 Hz (2500 data samples per second), utilizing the sample lag allowed conversion of the data to display the fraction of a second the two signals are offset via dividing the CCV-derived lag by the known sampling rate. The calculated flow speed in meters per second was then derived by dividing the known vertical distance (in fractions of a meter) between the sensor pairs by the found time value.

3.2.3.2. IMPROVEMENTS TO CCV/SPEED CALCULATIONS

Following the initial implementation of the CCV algorithm, the next step was to make it as accurate as possible to minimize the range of error for the resulting speed calculations. The four techniques used to hone the accuracy of the cross correlation process are signal smoothing, pattern filtering, improving time interval accuracy, and isolating analysis to discernable features.

The first approach to improving the CCV was signal smoothing. Smoothing of the received data was partially required in order to eliminate some of the raw signal's noise. The method of smoothing called "Hanning Smoothing" was implemented. In this approach, the magnitude of any point in the signal is re-assigned to the weighted sum of its own magnitude with the adjacent points' magnitudes via the formula [21]:

$$i^1 = (0.25 * [i - 1]) + (0.5 * i) + (0.25 + [i + 1])$$

This technique does not converge any points, but rather performs a smoothing operation on them in-place so that there is no loss in number of total points.

The second method was pattern filtering. The behavior of smoke could produce both a waveform and an opposing signal that not only had many similar features within them, but these features could differ in their width from one signal to the other, creating a false positive. The observed problem was that the most significant features of the waveform were sporadically matching with greatest confidence against similar, but not as significant, features in the opposing signal. As a result, it became important to isolate the most significant features of the waveform from the similar-magnitude "noise".

This was achieved by writing a subroutine that took the known and produced a "data filter" from it in which the most significant data points were kept and the rest were set to a magnitude of zero. This effectively removed the impact of any non-significant data on the CCV. Significant points were defined as those where the observed voltage was lowest, and therefore the smoke density was highest. In the creation of the filter, the program would find an *n*-number of significant points and keep each of those points as well as a certain number of points adjacent to it on either side. The resulting mask highlighted important data points while eliminating extraneous data that could throw off the CCV.

CCV Lag to Speed Conversion

A third approach to improving the CCV was improving the time interval accuracy. In the first implementation, the average lag was always divided by the known sampling rate of 2500 Hz. However, this value did not always reflect the true number of points gathered in a given second, which varied within an error range for each experimental run. Due to the fact that there might be more or less than 2500 points actually received during a second, this had the potential to not only skew the readings for a given second but also the results of all subsequent readings.

In order to minimize the error in this calculation, it was decided that a timer should run on a separate thread from the rest of the program. This caused the speed to be calculated every time an exact, real-time second had passed as measured by the system process, with the divisor used reflective of the independent timer. This gave the most accurate result possible since the time-lag was derived more exactly from the average sample-lag value calculated by CCV requirement.

The final method used isolating the CCV analysis to discernable features. Since the lag value used in speed calculations represented the average of all the lag values found in a given second, the speed calculation could easily be thrown off by "bad" CCVs within that second. To identify and prevent the inclusion of such values, two separate but complementary methods were employed.

The first adjustment was to allow the user to manually define a range of magnitudes on the graph panel within which a waveform must possess at least a few data points before the CCV was calculated. The aim was to eliminate the CCVs from intervals where either nearly all or nearly zero light reached the sensor. Keeping these intervals in the calculation produced rather random and meaningless CCV values; therefore removing them narrowed the scope of the calculations to only those useful values.

3.2.4. File Saving Mechanism

In order for the program to save a data session to a file that could later be opened and examined, a standard file output technique offered by C# called "serialization" was used. A Serialization object encodes the contents of an object into a string that is written to a file. Each object saved had to be given a "handle", or a string that labeled the object. To retrieve the saved values, a matching De-Serializer uses the handle to retrieve the file, and it re-creates the original object by decoding the handle.

In the case of the MMP software, all data was stored in the singleton data model object[18]. This data represented the internal state of all readings from a given session, and needed to be saved for reference in the future. However, the model object also contained certain run-time values, variables, and flags that were not required to be saved. To save memory and maintain a degree of simplicity, the crucial data was extracted and a new object was created to hold only that data. It was this object which was then serialized into the output file.

3.2.5. Graph

The graph was another crucial element to the success of the MMP software as it had to provide an easily understandable visual representation of the resultant data. A Data Graph class was defined which was a subclass of the C# "Panel" entity. In C#, a Panel object is essentially a canvas on which controls can be placed or arbitrary drawing operations can take place. A graph was implemented as a subclass of the Panel as the graph required specialized functionality to handle operations such as redrawing the graph whenever it was invalidated by a program thread.

Additional functionality added to the graph included the ability to automatically grow and scroll to keep the newest data points in view. This allowed the entire history of the data session to be available, but also allowed the user to observe the incoming data in real-time while using the MMP. A baseline and a grid were also drawn to provide a frame of reference for the user while examining the session recording.

Later in testing, during the calibration phase, it was discovered that our speed reference was providing readings in MPH while the MMP software was originally set up to provide readings in meters per second. This necessitated a change in the MMP software to provide readings in either unit to simplify testing and let the end user choose their preferred unit. Additionally, testing showed that due to large amounts of data being graphed, speed values drawn on the graph were pushed out of view by new data before they could easily be read.

This issue prompted the addition of the ability to either view the full graph of all data and calculations, or a simplified graph that only showed a line graph representing the velocity readings over time. Since only one speed reading was produced per second, this simplified graph grew more slowly and thus produced a more usable view of the velocity readings and changes. An additional line representing the average velocity over an n-number of consecutive reading was added as a graph option to the control panel. This allows the user to display a more realistic result, since the averaging process helps smooth out varied velocity readings.

3.2.6. VIEW OF FINALIZED SOFTWARE

This section details the appearance and functionality of the final software product.

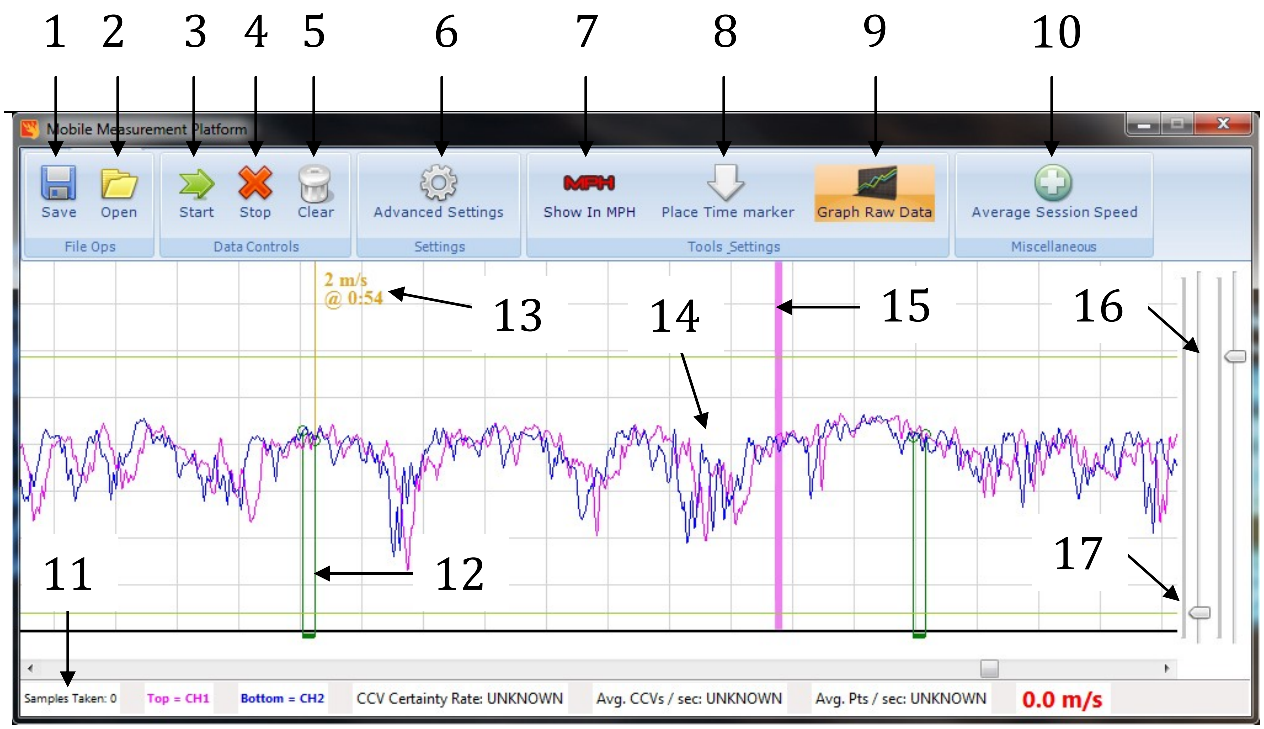

FIGURE 18: RAW DATA VIEW

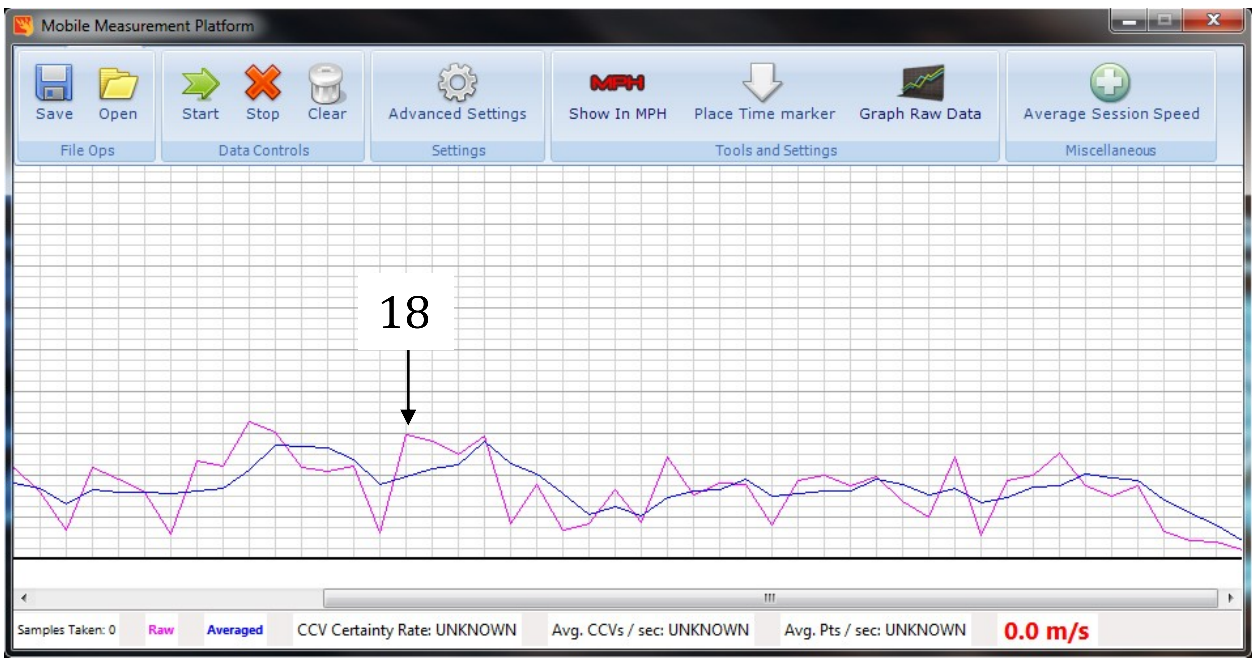

FIGURE 19: VELOCITY VIEW

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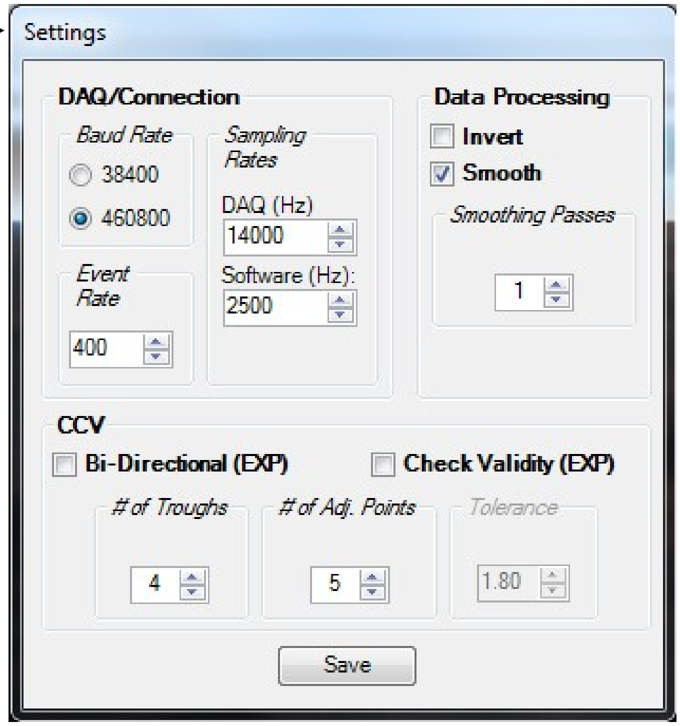

FIGURE 20: PROGRAM SETTINGS

1. **Save** – Save the current data session as an *.mmp file.
2. **Open** – Opens an *.mmp file and replaces the active session with the file's session.
3. **Start** – Begins collection of data from MMP hardware and calculation of velocities from that data.
4. **Stop** – Terminates data collection and calculation.
5. **Clear** – Completely resets the session. All unsaved data will be lost.
6. **Advanced Settings** – Access advanced program options. See item 19 for description of available options.
7. **Show in MPH** – Shows the velocity readings in MPH rather than m/s.
8. **Place Time Marker** – Allows user to place a marker on the raw data graph for later reference.
9. **Graph Raw Data** – Toggles data view mode from the raw data view to the velocity view.

10. **Average Session Speed** – Averages all significant velocity readings computed in the current session.
11. **Status Bar** – Displays miscellaneous information to the user. Described below left-to-right.
    a. **Samples Taken –** Number of data points gathered in the current session
    b. **Key –** Shows user a simple map of data color to its source/meaning.
    c. **CCV Certainty Rate –** Used by an experimental feature which attempts to determine which CCV values are invalid and thus can be thrown out. Displays the percentage of "good" CCV results.
    d. **Avg. CCVs / sec –** Displays how many CCV calculations are completed per second on average.
    e. **Avg. Pts / sec –** Displays how many data points are gathered per second on average.
    f. **Last Velocity –** Provides user with an easy location to monitor the last velocity computed.
12. **CCV Marker** – Visually represents the estimated time lag between the two signals at the marked time.
13. **Second/Velocity Marker** – Marks the end of each second of data, as well as the velocity observed during that second and which second in the session it represents.
14. **Raw Data Signals** – Graph of all data streamed in from the MMP hardware, as converted to a line graph. Each horizontal pixel is a separate data point.
15. **User-Placed Marker** – A marker placed by the user via clicking the button labeled #8. Used for reference.
16. **Upper Limit Adjustment** – Slider sets the upper limit of the range that the majority of data must be contained within to be considered for a CCV calculation. Green-yellow line visually represents this limit on the graph.

17. **Lower Limit Adjustment** – Same as #16, except sets the lower limit.
18. **Velocity Graph** – Simple view that only shows the MMP-calculated velocities. Displays actual readings (magenta) and readings as averaged with prior 3 velocities (blue).
19. **Advanced Settings Menu** – Allows the user to modify how the program operates and calculates values.
    a. **DAQ/Connection**
        i. *Baud Rate* – Controls the communication speed between the computer and the DAQ on the MMP hardware. Higher is faster. Should only be changed to slower option if communication issues are experienced.
        ii. *Sampling Rates*
            1. *DAQ (Hz)* – The rate at which the DAQ hardware samples the voltage channels.
            2. *Software (Hz)* – The rate at which the DAQ send data points to the software. If lower than DAQ setting, extra points are averaged to create each of these data points. For example, at default of DAQ = 14,000Hz and Software = 2500Hz, each sample given to software is comprised of 14000/2500 = 5.6 data points averaged by the DAQ.
        iii. *Event Rate* – The number of data points the DAQ is to buffer for the software, before sending them as one consistent "block" of data.
    b. **Data Processing**
        i. *Invert* – Flips processing to treat the top photodiode's signal as the bottom photodiode's signal, and vice versa.
        ii. *Smooth* – Smoothes the incoming data via Hanning Smoothing.

iii. *Smoothing Passes* – The number of passes the Hanning Smoothing subroutine will perform. More passes theoretically outputs a smoother signal.

c. CCV

i. *Bi-Directional (EXP)* – Activates an experimental program subroutine that attempts to ascertain the direction of the flow merely by computing CCV in both directions and seeing which yields the likeliest match. {This feature was not fully tested during the project time scale.}

ii. *Check Validity (EXP)* – Activates another experimental subroutine that attempts to determine which CCV results are invalid and throws them away. {Largely untested.}

iii. *# of Troughs* – Sets the number of most significant troughs the optimized CCV algorithm will use to create the known signal "mask".

iv. *# of Adj. Points* – Sets the number of points to be retained to either side of each trough used in known signal mask creation.

v. *Tolerance* – Used in the experimental "Check Validity" function. Denotes the multiple of the CCV-calculated lag that is the maximum allowed heuristic-computed value allowed to confirm a "valid" CCV.

4. EXPERIMENTAL METHOD

4.1. TESTING & DATA

Three tests were performed to calibrate the hardware and software of the MMP. Along with multiple small tests that occurred during the term, these tests helped unify the different components of the MMP into one viable device.

4.1.1. TEST 1 – FEBRUARY 19TH, 2010

4.1.1.1. GOALS

1. Investigate whether the smoke candles were a valid option for measuring faster flows. The smoke generator used previously was too wispy and would dissipate at velocities of above 0.5 m/s. The goal is to determine if the smoke candle will provide a plume that is robust enough to handle faster velocities. This will allow an increased range of measurable velocities.
2. Ascertain the velocity profile of the smoke flow using a vane anemometer. To accomplish this, at least five measurements around the horizontal plane of the plume are required, taken at the height the rig will be during the experiments. This provides an understanding of how the smoke velocity may change over the course of the profile. If the velocity changes significantly, then it is important to take that in to account when taking measurements using a different device.
3. Experiment with a rough cross-correlation program that was recently implemented into the MMP. It is vital to check whether the programming is progressing in a satisfactory direction. If the measurements obtained are significantly different from the

results acquired from the vane anemometer, then the program needs to be changed or severely calibrated.

4. Proper recordings made of the procedures. A camcorder is set up to record all of the events. The experiment is documented so that if necessary, the recordings can be referenced to determine missing variables, or to insure proper procedure.

4.1.1.2. EQUIPMENT AND PREPARATION

Equipment Used:

1. MMP
   - Physical Rig
   - Laptop with CCV Program
   - USB 2.0 Cable
2. Camcorder
3. Vane Anemometer
4. Hood
5. Safety Glasses
6. Computer
7. Smoke Candles
8. Cardboard box
9. 2' Metal Pole w/ Stable Base
10. Clamp
11. Preparation:

Preparation:

The camcorder was set up in a position for optimum view. All components were clearly visible from the chosen angle. Although not used in the initial tests, the MMP was attached to a clamp-stand to record the smoke velocities at different heights and allowed a hand-free approach for the users, which was beneficial as it reduces human error. The cardboard box was also used later, to counter the draft in the room. The hood was set at a constant, medium-low velocity.

4.1.1.3. Procedure and Observation

1. The first two experiments were simple smoke tests. The smoke candles were placed on the floor, directly under the hood. Both types of candles (45 and 60 second burn time) were lit individually and observed. It is important to note that the 60-second candle exhibited a lot more smoke and seemed to have a higher velocity.
2. Experiment 3 and 4 were both used to determine the velocity profile. The measurements were taken at a height of 0.53 meters. In both cases, the velocity was determined to be between 0.009 – 0.179 m/s, depending on the length of burn time. Unfortunately, the results obtained seemed inaccurate due to a strong crosswind emanating from the room's sole window. This draft was strong enough to move the smoke approximately 0.5 m away from the hood centerline, therefore changing the smoke velocity. To solve this problem, a 0.28 m H x 0.30 W cardboard box wall was placed between the smoke and the window to block the flow of the crosswind.
3. The previous two experiments were repeated, but with a protective box that allowed the smoke to billow upwards and not be affected by the crosswinds. The velocity profile showed very similar velocities at all points measured. Once again the smoke flow had a range of 0.009 – 0.179 m/s that fluctuated during the course of the 60-second burn.
4. As the velocity profile had been determined, it was now time to establish the performance of the MMP under laboratory conditions. The rig was attached to a clamp stand and placed 38 centimeters above the smoke candle, parallel to the top of the

protective box. Unfortunately, the window crosswind increased, creating a slight vortex effect that pulled the smoke 0.05 m x 0.07 m off centerline, towards the upper right corner of the box. Since the MMP was placed in the middle, it recorded very few measurements.

5. To solve this problem, the MMP was placed closer to the smoke candle, this time 30 centimeters up from the candle. A 60 second smoke candle was used. The readings improved, but the smoke movement was still far too sporadic to obtain accurate results.
6. The bottom of the rig was placed 0.20 meters above the smoke candle. A smoke candle of 60 seconds was used. Real time readings were taken with the vane anemometer as well as through the MMP. Satisfactory readings were found when the smoke was flowing into the rig consistently, which happened much more often than before due to the proximity of the rig to the emitting point of the candle. The results obtained were also higher than before, 0.35 m/s – 0.48 m/s, probably due to the proximity of the smoke candle.
7. It was noticed that the smoke was still being pulled to a specific side of the protective cover. To remedy the problem, the 60 second smoke candle was placed along the side of the box that the smoke was tending towards. It was placed 0.05 meters from the back of the board and 0.076 meters from the side of the board. A velocity profile was taken with this arrangement at a height of 0.28 meters. It was found that the velocity rarely changed over the profile and stayed relatively consistent between 0.36 m/s – 0.5 m/s.
8. For the final three experiments, the same previous set-up was used, except with the MMP attached 0.20 meters above the smoke candle (meaning the first lasers was 0.28 meters above the production of smoke). Readings were very consistent, between 0.36

m/s and 0.55 m/s from both the MMP, which had a very close correlation to the real-time measurements of the vane anemometer.

4.1.1.4. CONCLUSIONS

1. It was determined that a protective cover or external enclosure is needed for accurate results as uncontrollable crosswinds cause far too much interference in the Fire Science laboratory. The size of this cover needs to be only large enough to enclose the rig and equipment producing the smoke. Any larger and the smoke flow becomes inconsistent and it defeats the purpose of the enclosure.
2. A device with multiple velocity settings, such as a fan, is needed to provide variable smoke velocities so the resolution of the MMP can be tested, as well as further testing the maximum and minimum velocities it can handle.
3. 45 second smoke candles did not produce smoke long enough or with enough consistency to be useful. Candles with a minimum of a 60 second lifetime should be used.

4.1.2. TEST 2 – MARCH 26TH, 2010

4.1.2.1. GOALS

1. Obtain velocity profiles at different induced velocities using a vane anemometer and compare these results to the readings taken from the MMP.
2. Determine whether there are minimum and maximum velocity limits that the MMP can read.

4.1.2.2. Equipment

Equipment Used:

1. MMP
    - Physical Rig
    - Laptop with CCV Program
    - USB 2.0 Cable
2. Camcorder
3. Vane Anemometer
4. Hood
5. Safety Glasses
6. Computer
7. Smoke Candles
8. Cardboard box
9. 2' Metal Pole w/ Stable Base
10. Clamp

4.1.2.3. Procedure and Results

All measurements taken by the MMP and anemometer are 0.61 m (or 18") from the source of the flow. The smoke source is situated 0.152 m (or 5") below where the measurements are taken. The hood in the fire lab is set to low – medium low. The velocity is taken at five different points (as shown in Figure 24) to ensure a uniform velocity profile. These points are situated as follows: 1) Middle, 2) Back, 3) Front, 4) Left, 5) Right.

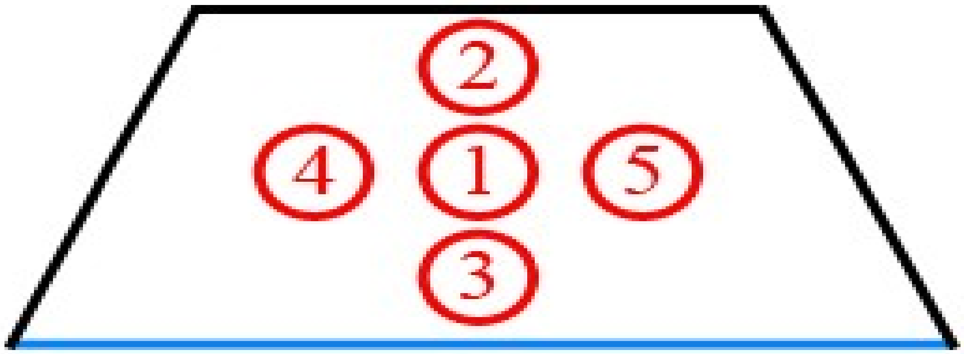

FIGURE 21: VELOCITY PROFILE DIAGRAM

TABLE 5: VELOCITY PROFILES OF TEST 2

Position	Fan/Blower & Speed (m/s)			
	Fan/Low	Fan/High	Blower/Low	Blower/High
1	1.47	1.79	2.28	4.16
2	1.52	1.88	2.37	4.33
3	1.38	1.34	2.23	4.29
4	1.38	1.56	2.10	3.98
5	0.67	1.56	2.15	4.07

4.1.2.4. OBSERVATIONS

Other than the 0.67 outlier in position five of Fan Low in Table 5, the velocity profiles were fairly uniform. Namely, as the anemometer moved away from the flow source, the velocity would decrease. The exception to this rule is when measurements are taken near a wall along which the plume flows, occasionally causing a flow velocity higher than even directly above the flow source. The measurements taken by the MMP were very similar to those read by the anemometer.

It should be noted that when the velocity is above 3.58 m/s, the MMP has difficulty reading the velocities. Further testing is required to determine the extent of this issue as well as the cause, but initial observation leads to the theory the smoke may not be thick enough to obscure the laser lights when flowing at such a higher velocity.

4.1.3. Test 3 – March 31st, 2010

4.1.3.1. Goals

1. Obtain and measure 5 different velocities
2. Recreate aforementioned velocities multiple times to check the consistency of the MMP
3. Further investigate whether the minimum and maximum velocities of the MMP.
4. Determine the temperature of the smoke candle so buoyancy velocity can be calculated

4.1.3.2. Equipment and Preparation

Equipment Used:

1. MMP
    - Physical Rig
    - Laptop with CCV Program
    - USB 2.0 Cable
2. Camcorder
3. Vane Anemometer
4. Hood
5. Safety Glasses
6. Computer
7. Smoke Candles
8. Cardboard box
9. 2' Metal Pole w/ Stable Base
10. Clamp
11. Fan (0.81 – 1.05 m/s)
12. Blower (1.184 – 2.44 m/s)

Preparation:

All measurements taken by the MMP and anemometer are 0.61 meters from the source of the flow unless otherwise stated. The smoke source is situated 0.127 meters below where the measurements are taken. The hood in the fire lab is set to low – medium low. A cardboard box was used to impede the draft in the room. The distances between the smoke, MMP and flow source were altered to allow for more accurate readings.

4.1.3.3. PROCEDURE AND RESULTS

1. The initial test was performed to verify all equipment was working properly. No formal measurements were taken but all the apparatus seemed to be in order. There was no induced flow; the smoke was allowed to rise naturally.
2. Measurements were recorded using the fan, set at low speed. The anemometer was reading at 0.89 – 1.1 m/s. The MMP had similar results, 0.789 – 1.117 m/s. It should be noted that the lasers tend to overheat after 60 seconds of exposure to both the hot smoke and continuous operation. A heat sink may be necessary for future applications.
3. The distance between the MMP and flow source was reduced to 0.45 meters. This allows for more accurate readings as there is less distance for the smoke to dissipate.
4. The temperature of the smoke candle was measured to be between 300 and 315 degrees centigrade.
5. Table 6 shows the readings taken using the anemometer and MMP.

TABLE 6: ANEMOMETER VS. MMP READINGS

Fan and Setting	*Anemometer Entry (m/s)*	*Anemometer Exit (m/s)*	*MMP (m/s)*
Fan High (1)	1.5	1.2	1.05
Fan High (2)			1.02
Fan High (3)			1.03
Fan Low (1)	1.1	0.9	0.9
Fan Low (2)			0.811
Fan Low (3)			0.83
Blower High (1)	3.4	2.8	2.37
Blower High (2)			2.26
Blower High (3)			2.44
Blower Low (1)	1.7	1.6	1.27
Blower Low (2)			1.205
Blower Low (3)			1.184
Stagnant Smoke	0.40	0.20	0.45

4.1.3.4. OBSERVATIONS

TABLE 7: VELOCITY COMPARISONS FROM TEST 3

Anemometer Average Velocity	MMP (mm/s)	% Error
300	450	50.000
1000	847	-15.300
1350	1033	-23.481
1650	1220	-26.061
3100	2356	-24.000

1. The percent (or approximation) error shown in Table 7 is computed via a percent error equation. Percent error is the magnitude of the difference between the known value and the measured value, divided by the magnitude of the known value. An approximation error can occur when the measured recordings are not accurate in reference to the known data. The percent error is a representation of this inaccuracy. If the known and recorded values are equal to each other, the percent error is zero. As the average error is 22.2%, it represents that the results from the MMP are similar to but are not an exact replica of the anemometer readings.

2. The average anemometer velocity was obtained by measuring the entrance and exit flow velocities during testing. These two values were then averaged to better represent the flow measured by the MMP within the tube. It was observed that the tube affected the average flow velocity. The 50% error recorded in Table 7 for the lowest velocity was due to the fact that the flow velocity was below the measurable limit of the vane anemometer. Although readings were obtained, they cannot be considered accurate.
3. The final MMP readings were consistently lower than the recorded anemometer velocities. This is likely due to the slowing of the flow due to the pressure differences within the tube. However, this is not the only error within the system; other errors may be present in the design. One possible source of error is when signals possessing repeating shapes are compared by the cross correlation code; the software could incorrectly predict the signal alignment, resulting in an inaccurate time offset.

5. CONCLUSIONS

Through testing, it was demonstrated that the concept of optical obscuration to measure velocities is viable. The prototype MMP's readings of the flows were observed to be within a significant, yet justified error. However, they were consistently lower than the recorded anemometer velocities. They were precise but not accurate, indicating consistent measurements that are offset by a specific value. This is preferred in testing, as only accuracy errors means the results were within an acceptable range of each other, but offset by a certain value. These errors are usually the result of human or equipment problems, and not necessarily difficulties inherent in the concept itself.

In this case, the percent value of the inaccuracy is approximately 22.2%, ignoring the 50% error outlier. Each value was within a reasonable margin of error from similar readings. The 50% error recorded for the lowest velocity was due to the fact that the flow velocity was beyond the measurable limit of the vane anemometer.

The cross correlation algorithm was shown to work in real time, therefore allowing immediate viewing and analysis of readings. Enabling the end user to view readings as they are computed, means the user can observe changes in the flow without having to wait until all the data was gathered and processed. In potential future applications of the MMP, such as distributed sensors for monitoring underground coal fires, immediate feedback would be a very useful feature, especially in the case of radical flow changes that require immediate attention.

However, the MMP does require further refinement to be a truly accurate device. As observed during testing, the vertical enclosure around the MMP's sensors had a discernible impact on the velocity measurements. Provisions were made during analysis to compensate for the velocity drop by gathering vane anemometer measurements at the entrance and exit of the tube, and calculating the average velocity to use as the comparison value. Though this was an unexpected occurrence, the velocity degradation caused by the tube was not the only possible source of error. The cross correlation element in the software could theoretically still be presented with situations where it may produce incorrect matches. In addition to the averaging of entrance and exit speeds using the anemometer, the anemometer itself could have caused a certain degree of error in the analysis. This is because it is rated for an accuracy of +/- 0.2 m/s, which is a relatively significant amount in the velocity range tested.

6. Future Work

Although the work completed during the course of this project produced a working device that measures the flow rate of smoke in a single direction, there are a few areas which can benefit from further work. These areas generally focus on expanding the scope of possible device applications. The following sections detail specific areas of potential improvement.

6.1. Mounted Smoke Generator for Smokeless Flows

During the course of testing and calibrating the MMP, a remote smoke source was always used. The assumption was that the flows measured by this device would always consist of particulate smoke. However, there are applications in which the speed of a colorless, non-particulate flow needs to be ascertained.

In these situations, a smoke tracer could be introduced at the lower end of the device. This smoke tracer would have to come from a device similar to the electronic smoke generator used in testing, and it would need to be mounted to the device. One important improvement would be finding an apparatus that would output smoke of a sufficient density and volume so that it does not dissipate in high speed flows.

6.2. Detecting Bi-Directional Flow

While possible applications of this device were being discussed, the concept of bi-directional flow detection was examined. Potential velocity measurement locations, such as coal mine vents, frequently "breathe", reversing the direction of the air flow at random intervals. In order to use the MMP effectively in such situations, it would have to include a method for detecting such directional changes and calculating/displaying speed appropriately. Although a preliminary software solution was attempted, it was unable to be tested. Future efforts could refine this solution or attempt a unique answer.

6.3. Calibration of Lasers Via Potentiometers

When the rig was moved to a smaller form factor, additional resistors needed to be added to the circuit so the emitting light did not overpower the receivers. Due to the compact nature of the lasers, the photodiode can be overwhelmed by a too powerful laser if the smoke is not there to interrupt the light. Adding resistors decreased the brightness of the lasers, but also introduced concern that the lasers would not penetrate a thicker smoke due to their reduced capability. It was conjectured that if a potentiometer was added in place of the 170 Ohm resistor, it would give the circuit the capability to scale the laser brightness to cope with unpredictable smoke density and the rig would operate over a larger range of dense or tenuous smoke flows.

6.4. Addition of Multiple Lasers

A further improvement to the MMP would be to add lasers on the vertical plane. When the additional laser input is added to the system, this would theoretically allow the system to record a more accurate velocity. The additional lasers could also determine whether the flow is accelerating or decelerating over the course of the flow path.

6.5. MMP Resolution

Another improvement of the MMP would be a method to accurately determine the resolution and accuracy limits of the device. Smoke density created problems during the experiments. As the smoke density increased, the MMP was able to measure higher velocities. However, If the velocity was too high, the smoke would dissipate before it reached the lasers and produce insufficient obscuration to yield any readings. A possible solution to this issue is to increase the smoke density as the velocity increases. A variable flow thickness would be optimal, although this may inhibit the flow as the density increases. At slower velocity readings the limiting factor was the anemometer. The fan was only able to measure down to roughly 0.2 m/s. A device that can measure slower velocities would assist in determining the accuracy of the MMP at these slow velocities. This is important when reversible flows are present, since the fan would have to slow down as the flow prepares to change direction.

6.6. Removal of Tube Enclosure

It was observed that the velocities recorded by the MMP could have been slower due to pressure differentials within the tube that inhibited the flow. Originally, the tube was included to prevent outside drafts from interfering with the vertical flow readings. However, with a sufficiently large smoke source, the enclosure may be large enough to prohibit the draft from outside sources without impeding the actual flow. This enlarged enclosure would allow the user to determine whether any other errors may have caused the difference in measurements other than the tube obscuring the flow.

7. Budget

7.1. Component Prices

7.1.1. Metal

1. 2 x 36” of Tubular Steel. 1” x 1.5” Outside Diameter, 0.870” Inside Diameter, Wall thickness of .120”.
    a. Distributor: Speedymetals.com
    b. Per-3 Foot Price: $6.52
    c. Total Cost: $13.04
    d. Found at: http://www.speedymetals.com/pc-4697-8224-1-12-x-1-x-120-wall-rectangular-steel-tubing.aspx

Total, including shipping = $25.04 (shipping - approximately $14 additional)

7.1.2. Smoke Generator and Candles

1. 1 x 6V Smoke Generator
    a. Manufacturer: Graupner
    b. Per-Unit Price: $18.02
    c. Total Cost: $18.02
    d. Found at: http://www.cornwallmodelboats.co.uk/acatalog/graupner_2324.html
2. 1 x 250 ml Smoke Distillate
    a. Manufacturer: Graupner
    b. Per-Unit Price: $12.45
    c. Total Cost: $12.45
    d. Found at: http://www.cornwallmodelboats.co.uk/acatalog/model_electronics.html#aG722_2e25
3. 2 x Smoke Emitter White, 10 pack
    a. Manufacturer: Miniax
    b. Total Output: 600 ft^3 over 60-90 seconds
    c. Per-Unit Price: $17.49
    d. Total Cost: $34.98
    e. Found at: http://inspectusa.com/smoke-emitter-white-cubic-feet-s103-second-burn-pack-p-163.html?osCsid=93bab7b18e9ebbeed14687184d3ead88

Total, including shipping = $83.23

7.1.3. DAQ

1. 1 x USB Data Acquisition Unit
    a. Manufacturer: DATAQ
    b. Per-Unit Price: $99
    c. Total Cost: $99
    d. Found at: http://www.dataq.com/products/startkit/di158.htm

Total, including shipping = $106.13

7.1.4. ELECTRONICS

Item numbers refer to Digikey (www.digikey.com) inventory.

1. 4 x DIODE LASER 5MW 650NM TO-18
    a. Digikey Part number: 67-1500-ND
    b. Manufacturer: Lumex Opto/Components Inc
    c. Manufacturer Part Number: OED-LDP65001E
    d. Per-Unit Price: $5.37
    e. Total Cost: $21.48
2. 2 x TERMINAL STRIP – Solderless Breadboard
    a. Digikey Part number: 923265-ND
    b. Manufacturer: 3M
    c. Manufacturer Part Number: 923265-I
    d. Per-Unit Price: $16.50
    e. Total Cost: $33
3. 1 x JUMPER WIRE 3.0" LONG PKG OF 75
    a. Digikey Part number: 923345-30-ND
    b. Manufacturer: 3M
    c. Manufacturer Part Number: 923345-30-C
    d. Per-Unit Price: $11.52
    e. Total Cost: $11.52
4. Resistors
    a. Multiple Resistor Values
    b. Total Cost: $5.50
5. Battery Connectors
    a. Radio Shack Purchase
    b. Total Cost: $2.50
6. 16 x 9 Volt Batteries
    a. Manufacturer: Energizer Eveready
    b. Per-Unit Price: $10.48
    c. Total Cost: $20.96
    d. Found at: http://www.lowes.com/pd_296455-346-A522FP-8_0_?productId=3111469&Ntt=9%20volt&Ntk=i_products&pl=1&currentURL=/pl__0__s?newSearch=true$Ntt=9%20volt$y=0$x=0

Total, including shipping = $99.94

7.2. TOTAL COST

Total cost for all parts: $292.86

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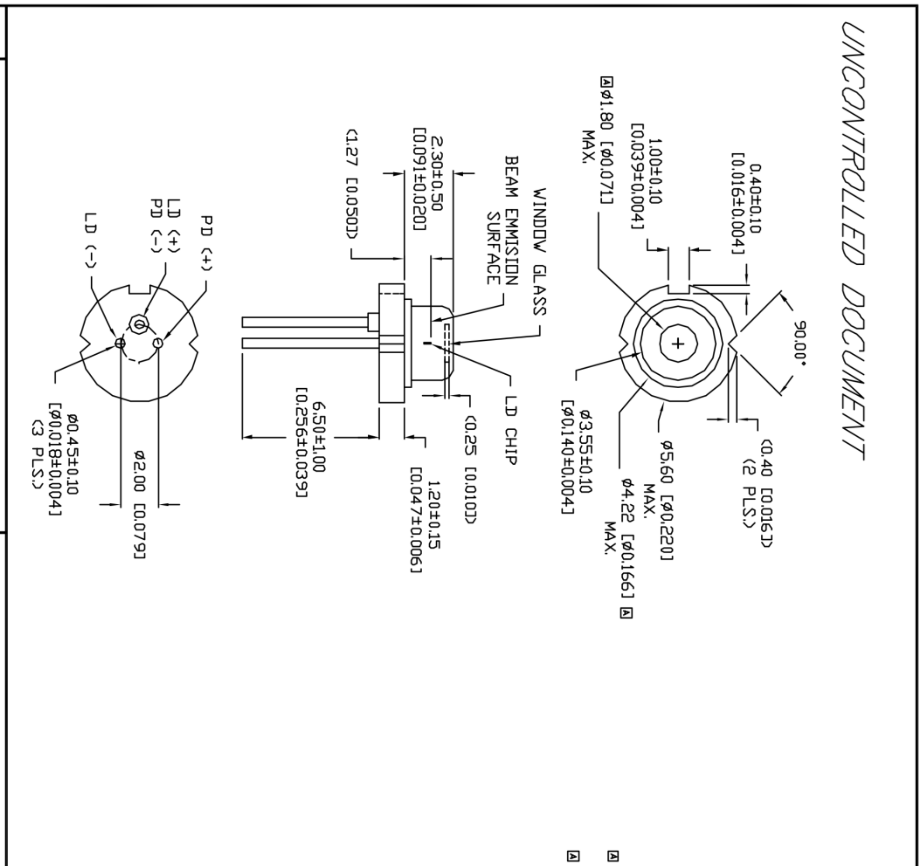
9. APPENDIX A



PART NUMBER: OED−LDP65001E REV. A

REV.	E.C.N. NUMBER AND REVISION COMMENTS	DATE
A	E.C.N. #11375.	12.13.06

ELECTRO-OPTICAL CHARACTERISTICS (Tc=25°C)

PARAMETER	SYMBOL	MIN	TYP	MAX	TEST COND	UNITS
LASING WAVELENGTH	λ		650	660	Po=5mW	nm
THRESHOLD CURRENT	Ith		20	30	CW	mA
OPERATING CURRENT	Iop		28	35	Po=5mW	mA
OPERATING VOLTAGE	Vop	2.0	2.2	2.5	Po=5mW	V
MONITORING CURRENT	Im	0.1	0.2	0.5	Po=5mW	mA
BEAM DIVERGENCE:	θ//		9		Po=5mW,	deg.
	θ⊥		35		FWHM	deg.

ABSOLUTE MAXIMUM RATINGS (Tc=25°C)

PARAMETER	SYMBOL	MAX	UNITS
OPTICAL POWER	Po	5	mW
LD REVERSE VOLTAGE	VR(LD)	2	V
PD REVERSE VOLTAGE	VR(PD)	30	V
OPERATING TEMP.	Top	−10 TO +40	°C
STORAGE TEMP.	Tstg	−40 TO +85	°C

Pb

UNCONTROLLED DOCUMENT

*UNLESS OTHERWISE SPECIFIED TOLERANCE IS ±0.25mm (±0.010")

REV. A PART NUMBER OED−LDP65001E

650nm LASER DIODE, TO−18 (Ø5.6mm) PACKAGE, 5mW OUTPUT.

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RELIABILITY NOTE
OUR MANY YEARS OF EXPERIENCE DATA ACCUMULATION INDICATE THAT SOLDER HEAT IS A MAJOR CAUSE OF EARLY AND FUTURE FAILURE. PLEASE PAY ATTENTION TO YOUR SOLDERING PROCESS.

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DRAWN BY:	CHECKED BY:	APPROVED BY:	DATE: 12.13.06
JC			PAGE: 1 OF 1
			SCALE: N/A

10. APPENDIX B – MQP POSTER