Abstract

TOMPKINS, MICHAEL JOHN. Automated Method for Fiber Length Measurement. (Under the direction of Jon Paul Rust.)

The price of cotton is dictated by quality and the most significant factor contributing to the fiber quality is the length distribution of the fibers contained within the population. Therefore it is of importance to accurately and repeatably measure the length of fibers within a population so that it is graded properly. Current methods are inadequate and thus prior work focused on designing a machine to directly measure individual cotton fibers using digital imaging. The current work begins with the evaluation of the effectiveness of the digital imaging machine. The machine was evaluated and sources of error identified. Modifications were implemented in an attempt to improve the error. After multiple modifications with little success an entirely new design was conceptualized. The new design aimed to eliminate all major sources of error with the existing machine while not creating new sources of error. The new design is discussed and the results are compared to those obtained by the original imaging machine. The new machine was better able to accurately measure the length of cut length fibers. The variation between fibers within a sample and entire samples of cut length fiber was significantly decreased when compared to the variation of the previous system.

AUTOMATED METHOD FOR FIBER LENGTH MEASUREMENT

by
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Biography

Michael J. Tompkins was born in Pittsburgh, Pennsylvania on March 2nd 1982 to Dennis and Paula Tompkins. He spent most of his childhood in Charlotte, NC where he lived with his parents and two brothers Johnathan and Zachary Tompkins. He played soccer through elementary, middle, and high school while also being active in the Boy Scouts where he attained the rank of Eagle Scout. In 2000 he enrolled in the Textile Engineering program at North Carolina State University. He remained active in sports playing club Rugby for much of his collegiate career. He graduated Cum Laude in 2004 with a degree in Textile Engineering. He immediately enrolled in the Masters program pursuing a co-major in Textile and Mechanical Engineering. He currently enjoys driving and maintaining his Porsche 911.

Acknowledgements

I would like to thank Dr. Jon Rust for giving me the opportunity to work on such an interesting project, and for his guidance, patience, and trust throughout the process. I would like to thank the College of Textiles and North Carolina State University for providing me with the financial support required to complete the project.

I want to thank my parents for their continued support and all of the sage words of wisdom throughout the years. I would finally like to thank my girlfriend, Heather, for her patience and understanding.

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1.0 Introduction

Previous work in the area of novel cotton fiber length measurement instrumentation at the college of textiles involved designing a machine that could continuously deliver individual fibers to a viewing area at which point they were analyzed and their length determined. Subsequent work improved the system in a number of areas including comparing the accuracy of the machine to known fiber length measurement machines. The goal of this following work is to further improve the systems ability to accurately and repeatably measure the length of cotton fibers.

In order to improve the system, errors in the existing system were characterized and their sources determined. Upon identifying the primary sources of error, modifications to the system were conceptualized, implemented and tested. The modifications consistently did not provide the desired improvement and it quickly became apparent that a new system was required.

The new system was developed with the intent to control the fibers without any form of physical contact. Five development areas were identified: the sensor, the enclosure, the light source, the camera and finally the software. Each area required individual development culminating in the integration of all components into a complete system.

The sensor would detect the presence of an individual fiber moving past it in order to trigger the camera. The sensor needed to be both fast and very sensitive in order to sense the fast moving fiber. Accurate fiber detection was critical in order to properly trigger the camera, synchronizing the time of image capture with the fibers arrival in the viewing area.

The enclosure would provide a means to control the fiber as it travels past the sensor and into the viewing area. The enclosure was designed so that it did not obstruct a portion of the fiber from the camera or cause fibers to remain in the enclosure. By carefully selecting the contour of the enclosure, the path and movement of the fiber could be accurately controlled.

A strobe light was implemented in order to freeze the motion of the fibers as they entered the viewing area. In order to provide the required contrast for image processing the light needed to be very bright, however, it also needed short strobe duration. The fiber is constantly moving and the amount the fiber moves during the time the strobe is on is shown as blur on the image. Blur significantly decreases the ability of the image processing software to accurately analyze the fiber and must be minimized.

A new camera was needed to both control the timing of the sensor, strobe, and image capture while also providing high quality images for capture. The camera selected met all criteria and was able to control the synchronization of all components while providing clear images.

The existing software was adapted to the new system by removing some code, modifying existing code, and writing new code. Many assumptions were no longer valid and therefore many algorithms needed modification accurately extract fiber length from the new images.

2.0 Technology Review

In order to design an effective machine, a thorough understanding of a variety of different components was needed. To determine what was available and what was most suitable for the future system, each area needed to be thoroughly researched. The first area of research was the camera. Second, a number of different sensing technologies needed to be investigated, including photodiodes and other light detection techniques. Third, lighting sources needed to be evaluated to determine the most suitable for the specific application. With a thorough understanding of existing technology, the design of the system can be optimized by utilizing the best components for the specific application.

2.1 Fiber Length Measurement

The length of cotton fibers is of primary importance when quantifying the quality of a cotton population. Methods currently exist to evaluate the length of cotton fibers however, they are inadequate and are known to have significant error. High Volume Instrumentation (HVI) measures fibers in bulk while the Advanced Fiber Information System (AFIS) measures fibers individually, however, in both cases, the length is measured indirectly [8]. Measuring the length indirectly introduces significant amounts of error into the measurement. Recent work has been completed to directly measure individual fibers and while a step in the right direction, it is not ready to replace the existing methods. For a more complete and detailed explanation of existing fiber length measurement technologies refer to the work of Stroupe and Byrd [29] [8].

2.2 Camera

The primary purpose of the camera is to acquire an image via a lens and a sensor and convert that image to a digital form which can be saved and processed using a computer. The secondary purpose of the camera is to provide the control over the light source through the use of output triggering. When selecting a camera, the primary purpose of image capture needs to be at the top of the selection criteria. While still considering image quality, resolution is a concern as it will affect the contrast of features within the image along with the processing time after the image is captured. For machine vision, Charge Coupled Device and Complimentary Metal Oxide Semiconductor are the two primary digital camera technologies that are to be considered.

2.2.1 Charge Coupled Device (CCD)

CCD technology has undergone a great deal of improvement and optimization since its inception in the early seventies, and thus has been the traditional choice when selecting a digital imaging technology [7]. CCD's consist of a 2D array of photodetectors (either photodiodes or photogates) arranged in a series of rows and columns on a chip. (Blanc) The photodetectors accumulate a charge related to the amount of light reaching the individual photodetector [20]. The charge from each photodetector is converted into a voltage, buffered, and transferred off the chip where the voltage is converted to a pixel value [20]. Figure 2.1 shows the flow of charge along with the accompanying circuitry.

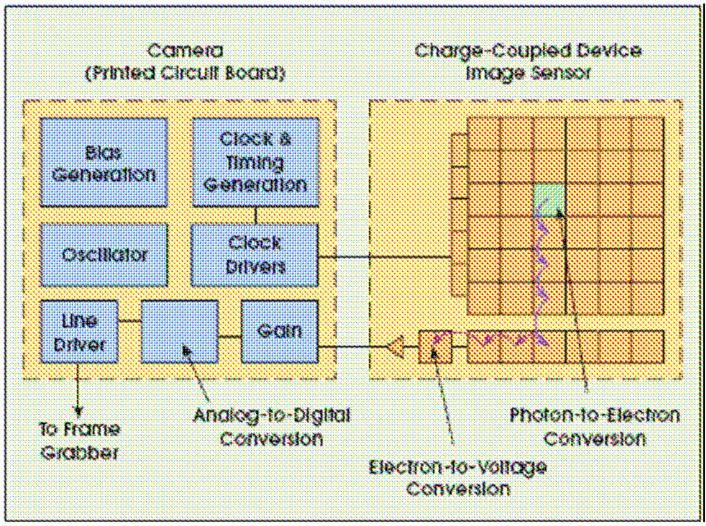

Figure 2.1 CCD Chip Diagram (Reproduced From [20])

2.2.2 Complimentary Metal Oxide Semiconductor (CMOS)

CMOS technology is a more recent technology than CCD and thus has not had as much improvement and optimization since its inception. However, recent improvements have been made that make it a viable alternative to CCD [7]. CMOS chips are similar to CCD in that they consist of a 2D array of photodetectors, usually photodiodes, that accumulate charge proportional to the amount of light present [20]. The CMOS chips differ in that they contain a charge amplifier at each photodetector site instead of a single charge amplifier for all the pixels. Converting the charge to voltage at each pixel allows each pixel to be addressed individually which allows the user to define a specific region of interest [7]. As shown in Figure 2.2, the CMOS chip contains much of the supporting circuitry simplifying production and assembly.

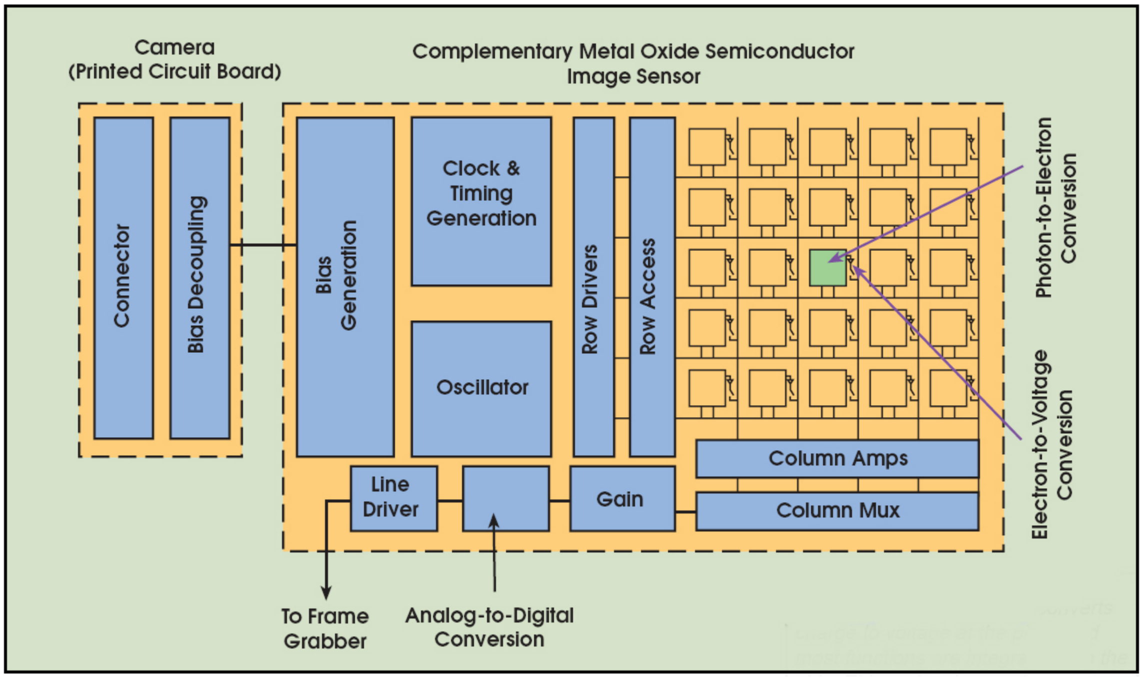

Figure 2.2 CMOS Chip Diagram (Reproduced From [20])

2.2.3 CCD vs. CMOS

There are eight attributes that determine the overall quality of the chip: Responsivity, Dynamic Range, Uniformity, Shuttering, Speed, Windowing, Anti-Blooming, and Biasing and Clocking. Responsivity refers to the amount of charge created by the photodetector per unit of light reaching the photodetector. In terms of responsivity, CMOS chips are slightly superior due to the ease at which the amplifiers can be placed. A CMOS chip allows low power, high gain amplifiers to be used whereas CCD requires higher power amplifiers [20].

Dynamic range is described as the "the ratio of a pixels saturation level to its signal threshold." CCD's generally have about twice the dynamic range of comparable CMOS sensors. CCD sensors have less on board circuitry, a higher tolerance for bus capacitance variations, and transistors which can more easily be configured to minimize noise, all of which contributes to a reduction of noise within the images [20].

The difference in pixel response across the array to the same light intensity is the uniformity of the image sensor. CCD's are generally more uniform than CMOS image sensors because of the individual amplifiers used to convert each pixel charge into a voltage. Using multiple amplifiers decreases uniformity because the charge of each pixel does not always get amplified uniformly. By implementing amplifiers using feedback, the uniformity is increased, however, it is still slightly inferior to CCD technology [20].

Shuttering is that ability of the camera to stop and start the exposure at prescribed times. CCD technology is superior when it comes to shuttering since implementing shuttering in CMOS requires a number of transistors at each pixel. The transistors take up space around the pixel increasing the physical size of each pixel. A rolling shutter can be used to decrease the number of transistors at each pixel by exposing different lines of pixels at different times, however the use of this technique results in a blurry image when there is a fast moving target [20].

CMOS is faster than CCD due to the ability to place all of the supporting circuitry on the same chip. By placing all circuitry on the same chip the distances between components, inductance, capacitance, and propagation delays are all decreased.

Windowing refers to the ability to select a region of pixels to view, and ignore all other pixels. CMOS imaging chips allow the user to select a region of interest and only output the selected pixels, while CCD's are limited in this capability [20].

Antiblooming is the ability of the sensor to drain excess charge from specific pixels that had been saturated without influencing surrounding pixels. CMOS technology is inherently superior at draining excess charge from saturated pixels, while CCD's require specific engineering to achieve the same effect [20].

CMOS also has an advantage in terms of biasing and clocking because they operate at a single bias voltage and clock level. CCD's often require higher bias voltages; however newer clocks have been simplified to run on low voltage clocks [20].

2.3 Light Sensing

There are many methods used to convert light energy into either a voltage or a change in resistance, both of which can easily be used to sense the presence of light. Photodiodes and phototransistors actually convert light energy into a small detectable voltage, while photoresitors change resistance in the presence of light. Both methods provide a means with which to detect the presence of light.

2.3.1 Photodiode

A photodiode is simply a diode in which the p-n region is exposed enabling a current to flow from the n to the p region when exposed to light. Diodes consist of two differently doped regions of semiconducting material, one region is the p region consisting of holes, and the other region is the n region consisting of electrons. [5] The diode acts as a gate allowing current to flow freely when forward biased, however, if reversed biased, current is not allowed to flow freely. To be forward biased, the positive terminal of the battery must be connected to the p region and the negative terminal to the n region. Current will not flow when forward biased until the applied voltage reaches the contact potential for silicon (.6V-.7V).

The doped silicone regions are sensitive to light allowing photons to be absorbed by the doped region resulting in a free electron and an electron hole. By using the photodiode in the forward biased configuration the freed electrons will flow, resulting in a current. The diode can similarly be used in the reverse biased configuration and act as a switch. Diodes have a significant resistance to current flow when reversed biased however when light is present the resistance is significantly decreased, and current is allowed to flow [12]. It takes a significant amount of light to create appreciable currents when forward biased, however, when reversed biased the photodiode is sensitive to much smaller quantities of light. [5]

2.3.2 Phototransistor

Transistors are similar to diodes in that they contain differently doped regions of a semiconducting material, however, transistors contain three regions and are used to either amplify current or switch current on and off. The applicable types of transistors to phototransistors are the npn and the pnp types of BJT transistors. Both transistors contain three doped regions, known as the base, collector and emitter. For simplicity's sake, the npn transistor will be the focus of the discussion, however, a pnp transistor is similar only with a different organization of doped regions. The collector is doped as a "n" region, the base is a "p" region and the emitter is a heavily doped "n" region. By applying current to the base region the current allowed to flow between the collector and emitter regions can be controlled. [5]

A phototransistor is a regular transistor where the base-collector junction is exposed to light allowing the photons of the light to serve the same purpose as the base current in the traditional transistor, allowing current to flow between the collector and emitter.

2.3.3 Photoresistor

Photoresistors differ from photodiodes and phototransistors in that instead of converting light into a voltage, or using light to switch on a current, they use light to lower their resistance. Photoresistors are made from a high resistance semiconductor able to absorb photons in the presence of light. The photons add energy to the electrons, allowing them to move to the conduction band of the semiconductor. The free electron and resulting hole will conduct electricity and effectively lower the resistance of the semiconducting material. When incorporated in a voltage divider with a resistor the change in resistance can cause a measurable change in voltage. Photoresistors have a very slow rise and decay time limiting their use to low speed applications.

2.4 Illumination

If the camera is the primary focus when designing a machine vision system, the light source would be a very close second. The proper lighting can produce a very crisp useful image, while improper lighting can produce an image that is blurry, too bright, or to dark; rendering the image useless. While there are numerous different lighting sources available, there are fewer possibilities when considering strobing light sources. Light emitting diodes or LED's are commonly used for strobing applications due to their low cost, long life, and simplicity. Another strobe light technology is the Xenon strobe which is known for its high intensity, short duration flash.

2.4.1 Light Emitting Diode

Light emitting diodes (LED's) are essentially the same as a normal diode in that they contain two semiconducting materials, one doped as a "p" region and the other doped as an "n" region. As electrons in the form of current flow from the "p" side to the “n” side the electrons come into contact with holes. As the electrons contact these holes energy is released in the form of a photon and emitted as light. The wavelength of the light is dependent on the bandgap energy of the materials used to create the p-n junction. Normal diodes are made of materials that do not release photons when the holes are filled by electrons and LED’s are made of materials that release photons in a specific wavelength to produce a desired color [12].

LED’s require low voltages to operate and are therefore much easier to work with and integrate into sensitive electronics. Because they do not draw a lot of power, LED’s are also low temperature, enabling them to be used in a number of applications where temperature would either be a safety concern, or potentially harmful to the surrounding components. LED’s do not have a filament or any moving parts and are therefore quite durable and ideally suited for use in environments with significant vibration or g-forces [12].

LED’s are small and do not produce significant amounts of light by themselves requiring many LED’s to be combined into an array for many machine vision applications. Not only is an array of LED’s brighter than a single LED, but the array is also more uniform than a single light source. By incorporating an array of LED’s with simultaneous control, an effective backlight can easily be created. LED’s are not very bright when compared to xenon strobes, and while multiple units can easily be combined, there is a limit to how many can be placed in a certain area.

High intensity LED’s available from Luxeon® produce up to 20 times more intensity per unit are when compared to traditional LED’s. These LED’s offer the same benefits of traditional LED’s while producing significantly more luminous intensity and increasing the range of applications. To ensure that the light from the Luxeon LED's is uniform the current used to drive a series of LED's needs to be controlled rather than controlling the voltage [21].

2.4.2 Xenon Strobe

Xenon strobes provide a high intensity short duration flash useful for freezing the motion of moving parts. A xenon flash lamp consists of a fused quartz tube filled with xenon gas, along with three electrodes; a positive electrode, a negative electrode, and an electrode used to apply a high voltage to the gas. In a xenon flash lamp, the xenon gas acts as a filament conducting the electricity between the two electrodes. Under normal conditions, the gas does not act as a conductor and the potential difference between the two electrodes is not enough to jump the gap. When a small transformer known as a trigger coil applies a high voltage (~4kV) to the third electrode, the gas becomes ionized and conductive. Current is now allowed to flow between the positive and negative electrode and the rapid discharge results in a flash. Energy is stored prior to discharge in a capacitor, the size of which affects the duration and intensity of the strobe. A smaller capacitor will produce a shorter, less intense flash while a larger capacitor will produce a longer more intense flash [9, 16].

Xenon strobe lights offer many advantages when compared to LED lighting systems. Xenon strobes provide an extremely high luminous intensity of 250,000 candela or more which is significantly higher than conventional LED's whose luminous intensity is on the order of 10 candela. Xenon strobes also provide the capability to obtain very short duration flashes on the order of 1 microsecond. While LED's are technically capable of flashes that short, the intensity of the flash also decreases along with the duration. Xenon flashes contain a complete spectrum of wavelengths between 150 nm all the way up to 6μm. To the human eye the light appears to be white but with the use of different types of filters any specific wavelength can be extracted to meet a specific need.

2.5 Conclusion

With a thorough understanding of the different types of components that could be integrated into the system an informed decision could be made for each component. While the specific characteristics of each component are a concern; cost, availability and ease of integration are difficult to assess when comparing general technologies. A thorough search of specific components was conducted for each area to compare specific products instead of technologies in order to select the optimal product for each application.

3.0 Previous Image Based Fiber Length Measurement System

The original machine was designed to individualize cotton fibers, control them, and introduce them into the viewing area where an image could be captured and analyzed. A modified comber roll was used to separate individual fibers from a sliver and introduce them to an electrostatic field. The electrostatic field was created between two aluminum plates designed to draw the fiber towards a urethane belt running through a slot in the center of one of the plates. The fibers would attach themselves to the belt and be transported to the imaging area at which point they would be illuminated by a strobe light and their image would be captured. Image analysis software was then used to determine the lengths of the fibers within the image. While this was an effective system there were some fundamental errors which proved very difficult to overcome.

3.1 Description of Original Design

The original design consisted of four fundamental mechanisms; the fiber individualizer, the electrostatic plates, the belt, and the imaging and analysis system. The method used to individualize the fibers consisted of a modified comber roll from a rotor spinning machine. The comber roll consists of a small rotating cylinder about 2 inches in diameter and an inch wide with small needles distributed around its surface. The needles comb the sliver, aligning the fibers, and ultimately removing individual fibers. The individual fibers are then expelled though a slot in the bottom of the comber roll and into the electrostatic field created by the plates. A DC motor drives the comber roll and allows the speed to be controlled using a motor controller. The motor was turned on and off using software via a programmable logic controller (PLC) and a relay. The sliver was fed into the comber roll using a stepper motor allowing precise control over the rate at which the fibers were introduced into the system. Controlling the number of fibers introduced to the system allowed the fiber density on the belt and thus the number of fibers per image to be controlled. Having precise control of the density of fibers allowed the number of crossovers to be minimized while ensuring that there were as many individual fibers in each frame as possible.

The comber roll removed individual fibers from a sliver and introduced them into the electrostatic field created between two plates by a high voltage power supply adjustable between 4kV and 25kV. The field induces a charge on the fibers so that one end of the fiber has a positive charge and the other end has a negative charge. This causes the fiber to be attracted to one of the plates. Upon contact with the plate, the charge on the fiber would change, either discharging or gaining charge, and thus be attracted to the opposite plate. The fiber then jumps off the plate across to the opposing plate. This behavior continues until the fibers come into contact with the nonconductive urethane belt at which point they cannot discharge and remain in contact with the belt with the free end extended toward the opposite plate. The plate with the belt was designed with a sharp point right below and above the belt causing the fibers to be attracted to this area due to a high charge concentration. The belt was continually moving and as fibers landed on the belt, they were transported to the viewing area. The belt was driven by a DC motor similar to that running the comber roll. The motor was controlled manually with a motor controller, however, it could be switched on and off using the software coupled with a PLC and a relay. The fibers in the viewing area were illuminated from behind with a strobe light while a digital camera captured images. By backlighting the fibers, the camera sees a silhouette of the fiber which is optimal for software analysis.

The strobe light was a backlight made by CCS (Reference) which consisted of an array of many small LED's behind a diffuse plate to ensure the light was uniform. The light was driven by a strobe controller which allowed the adjustment of the intensity of the light along with the duration of the strobe pulse from 10 μs to 990μs. The camera used a 1.3 megapixel CCD digital camera made by Pulnix and was connected to the computer using a framegrabber. The camera and strobe light did not need to be synchronized to effectively capture fibers within the frame. Since there was a high fiber density on the belt the camera and strobe could run continuously and consistently capture images containing fibers.

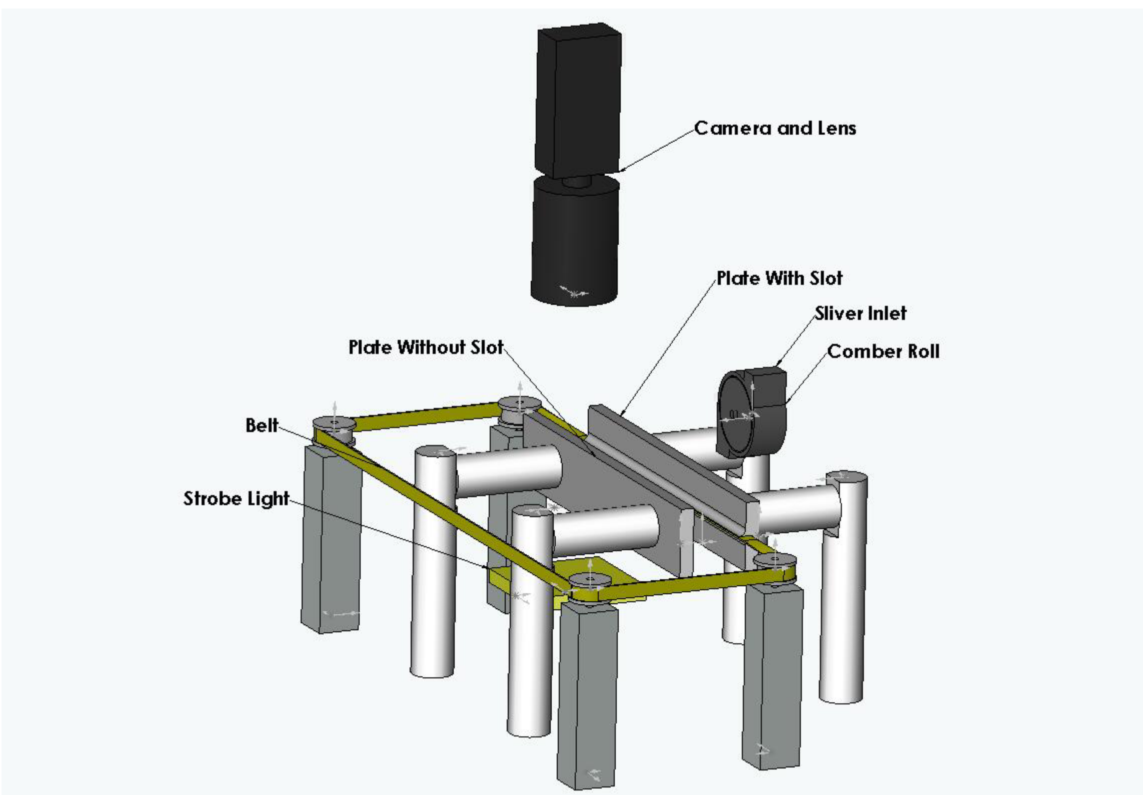

Figure 3.1 System Diagram

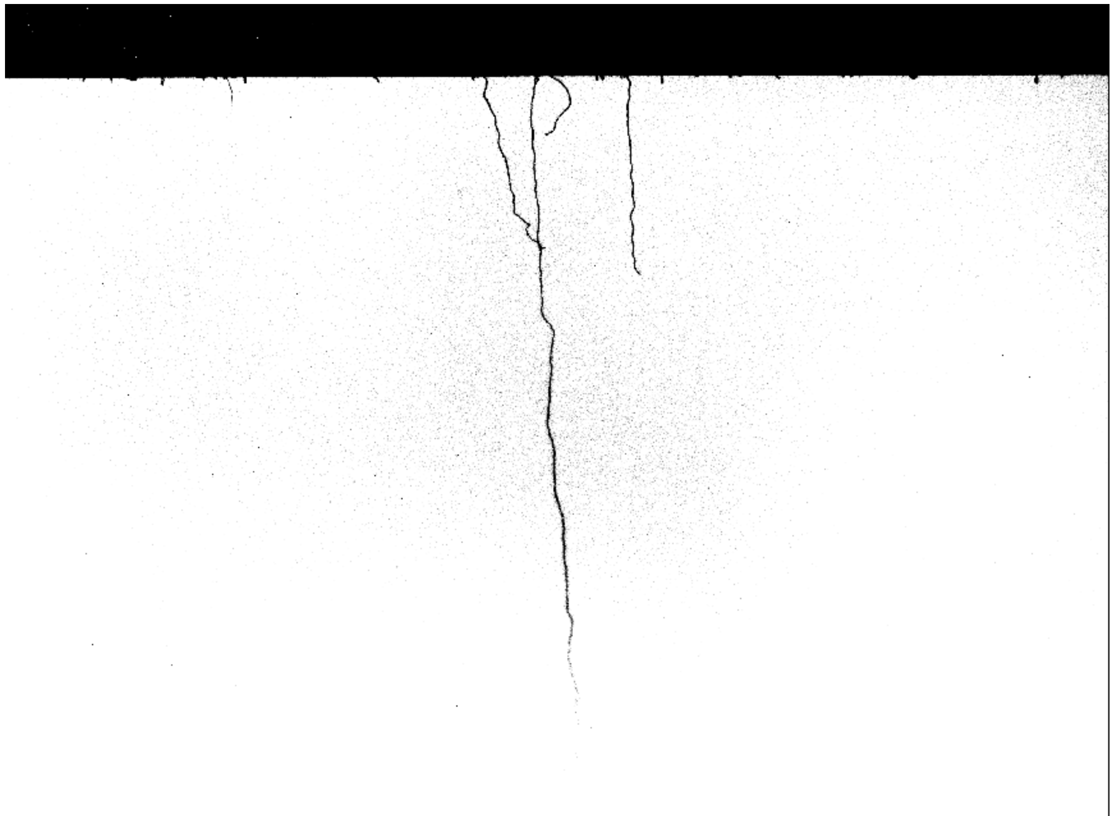

Figure 3.2 Sample Image

The images were immediately analyzed by the software before the next image was captured, yielding the number of fibers in the image and length of each fiber. The software first thresholds the image based on the average pixel value for the image by comparing each pixel to the average value of the image and turning the pixel in question black or white based on whether its value is below or above the average value. Then a thinning algorithm reduces the fibers down to one pixel wide so that the ends can be easily detected. The ends were used to check for crossovers and u-shapes and if such anomalies were found algorithms connected the u-shapes or approximated the crossovers by counting the length of the whole and dividing by ½ the number of ends. The next step was to determine the length by outlining the fiber counting each pixel as 1 for vertical or horizontal movements and 1.41 for diagonal movements to account for the difference in the diagonal direction. The length of the fiber is simply the distance calculated by the outline divided by two. The software allowed the number of fibers per sample to be selected and then displayed the length distribution of the sample along with important statistics while saving the data for future analysis.

3.2 Investigation of Possible Causes of Error

Significant effort went into determining the accuracy and precision of the machine. Because the machine is itself a measurement system it is difficult to determine the accuracy using sliver because the actual lengths of the fibers that were measured are not known. To evaluate the accuracy and precision, experiments were run using different slivers, cut length rayon, and cut length cotton.

The first experiment was designed to determine if the machine could differentiate between two different slivers. An experiment was designed with multiple runs for each sliver and randomized to eliminate error. Two slivers collected from different bales at different times were tested multiple times. The experiment was set up to allow a number of parameters to be tested. Sample size, sliver, and date were all tested to determine the individual effects on the data. The machine was thoroughly cleaned in between each run to ensure fibers from the previous run would not contaminate the sample. This experiment proved successful with the machine proving its ability to measure a statistical difference between the slivers. However the date also showed a statistical difference showing that there is significant run to run variation caused by the machine.

The next experiment used cut length samples of rayon due to low cost, and their similarity to cotton in respect to the behavior in the electrostatic field. Two different lengths of fibers, .5 and .25 inches, were used to determine if there were any biases in the system that would more favorably select one length as opposed to another. The different lengths of fibers were weighed and thoroughly mixed together so that the ratio of fibers by number was known. The fibers were then fed into the machine by hand since it proved unrealistic to form a sliver out of such short fibers. The ideal result would have been a clear transition once the fiber lengths were sorted from the longer fibers to the shorter fibers.

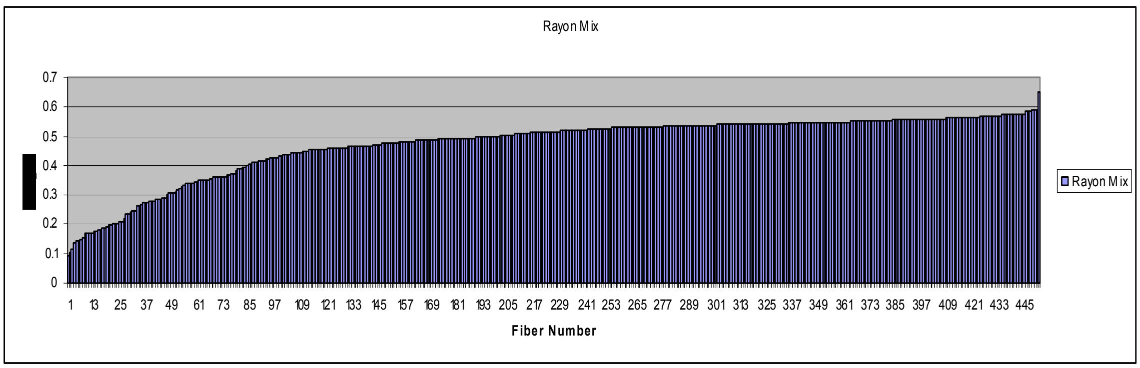

Figure 3.3 Rayon Mix

The actual result was less than ideal in that the smaller rayon fibers were not noticeable at all. There would have ideally been a significant number of fibers approximately .5 inches which are present in the graph however there would have also been a distinct drop in length to approximately .25 inches. There is a drop, however it is gradual and does not distinctly show that there were .25 inch fibers in the image. This experiment proved that there is a significant bias toward longer fibers.

The next experiment used cut length samples of cotton cut precisely to .45" and .65". Small runs of 125 measurements were made to determine the overall accuracy and precision of the machine when fibers of known length were used. Once again, the fibers were fed in by hand and the results were analyzed using Microsoft Excel because while the software does display a histogram, Excel allows all of the runs to be viewed side by side for comparison.

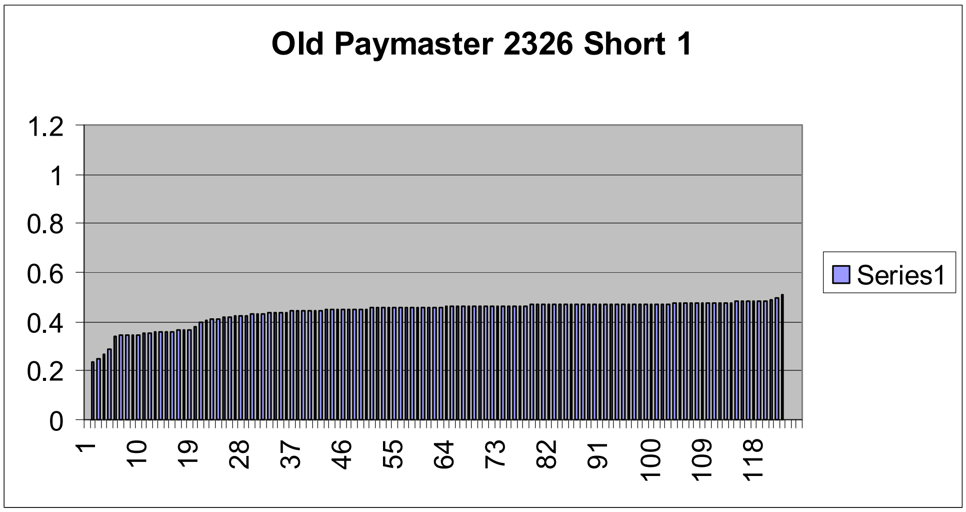

Figure 3.4 Best Run

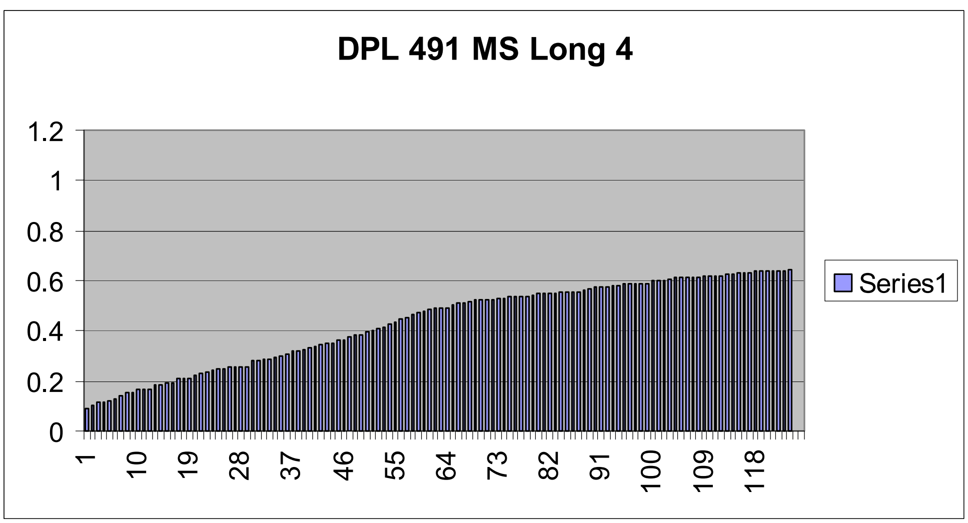

Figure 3.5 Typical Run

The first graph shows a good sample of .45in fibers with a relatively constant fiber length showing that the machine is capable of measuring with relative certainty the actual length of a fiber. However the second graph containing .65in fibers is indicative of most of the results gained from the experiment and paints a different picture all together. This sample clearly shows that while it measures a few fibers at the actual length the measured length quickly drops and a majority of the fibers are measured far less than their actual length.

3.3 Analysis of Error

The problem was known but the severity of the problem was not, prior to the test using the cut length fibers. The primary problem is that an unknown portion of the fiber overlaps the belt and therefore cannot be seen by the camera. If the fibers overlapped the belt a consistent amount it would be easy to compensate for that error however, as the graph clearly shows, an amount of fiber that overlaps the belt ranges from none to almost the entire fiber.

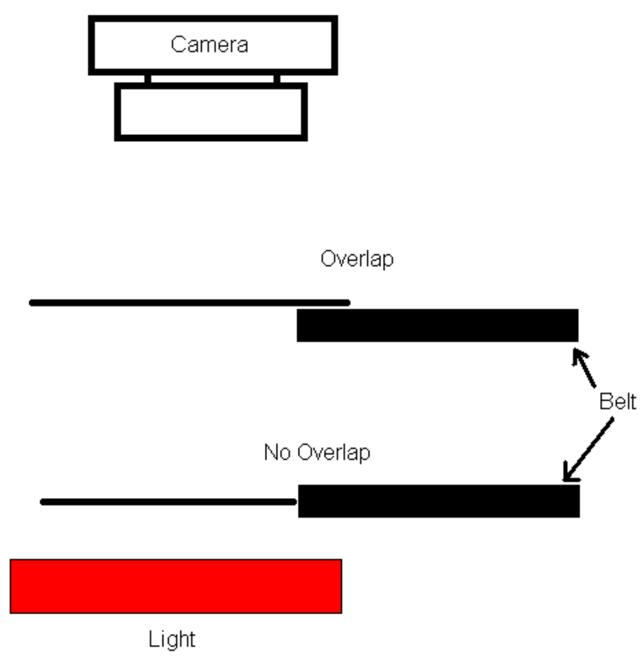

Figure 3.6 Overlap Diagram

Before the cut lengths were used, the error was assumed to be spread out over many possible sources. Breakage caused by the comber roll, selection bias, and broken skeletons were all thought to contribute equal parts to the overall error. Since all the fibers were the same length selection bias is immediately eliminated as a source of error, and while breakage is still a factor it is highly unlikely that every fiber would be broken which is the only way that such a distribution would be created. Broken skeletons are still a possibility however by individually viewing each image the effect was found to be minimal.

3.4 Research Objectives

After characterizing the error in the previous system it became evident that both the accuracy and repeatability of the system needed to be improved. A number of factors were considered when attempting to improve the accuracy and repeatability. The primary consideration was to maximize the number of fibers completely visible by the camera. A fiber is completely visible if no portion of the fiber is hidden by either a portion of the machine or the edge of the image. Secondly the contrast between the fiber and the background had to be maximized in order to achieve the highest image quality and fewest broken skeletons. The degree to which the fibers are individualized also had to be maximized to reduce crossovers. While there are algorithms that account for crossovers the presence of a crossover still introduces error into the system. Finally, any image artifacts that are not fibers need to be eliminated from the image. This may include noise, dust, or fibers trapped in the viewing area. These artifacts are analyzed and measured as if they were fibers resulting in erroneous readings. The effectiveness of each subsequent design was tested in each of the above areas.

4.0 Design Solutions to Eliminate Error

The problem with overlap was the focus on all subsequent research. The goal is to control the fibers in a matter that allows the entire fiber to be seen by the camera. The first attempts at solving the problem utilized the same machine and involved modifying the belt to try and ensure the entire fiber would be visible. To test each new design, a prototype was constructed and tested by collecting images without using the software since the software made assumptions unique to the original machine. The images were evaluated subjectively, and by analysis with modified software, simulating analysis with the actual software. Based on this analysis the potential of the system could be evaluated and a decision could be made whether to proceed or redesign.

4.1 Design Solution Using Current Device Technology

The first solutions developed were based on modifying the current technology in an attempt to overcome the specific problem areas. Prototypes were constructed for each concept and tested to determine the overall improvement.

4.1.1 Backlighting Using Transparent Belt

The first design changed utilized the same backlighting principle that was proven effective with the original system. The new system used a wide transparent belt and situated two steel rods beneath the belt to provide the electrostatic field as shown in Figure 4.1. The fibers would be introduced into the field and in theory lay on the belt extended between the two rods. The rods diverge as the fiber reaches the viewing area to avoid obstructing the view and causing measurement error similar to the original system. The strobe light was placed beneath the belt and the camera is above the belt similar to the original system.

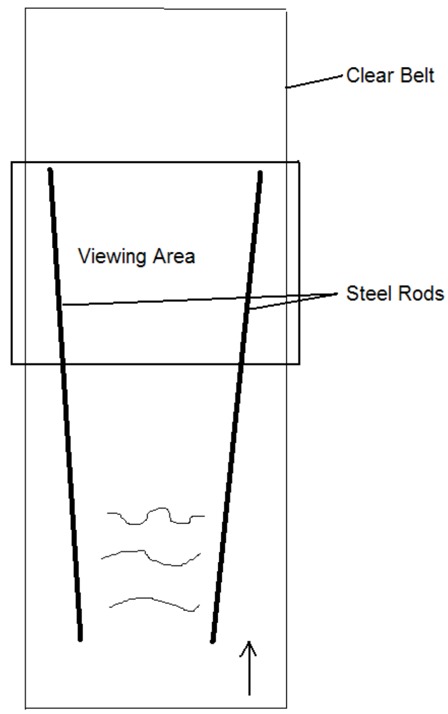

Figure 4.1 Transparent Belt Diagram

4.1.1.1 Components and Operation

A number of belt materials were tested, however, it quickly became evident that the belt would build up static attract the fibers to the belt and not allow them to be easily removed. Since the fiber stuck to the belt due to static and not the electrostatic field, they were not oriented properly and also could not be easily removed with suction.

The final belt was 3" wide and made from clear nylon to eliminate the static and allow the fibers to be controlled by the electrostatic field and removed using suction after imaging. Two ½ inch diameter steel rods were placed beneath the belt and were charged to provide the electrostatic field and cause the fibers to fall elongated and in the desired area. The rest of the machine remained relatively unchanged by using the same comber roll to individualize and introduce the fibers into the electrostatic field and a simple motor and motor controller to drive the belt. A schematic is shown in Figure 4.2.

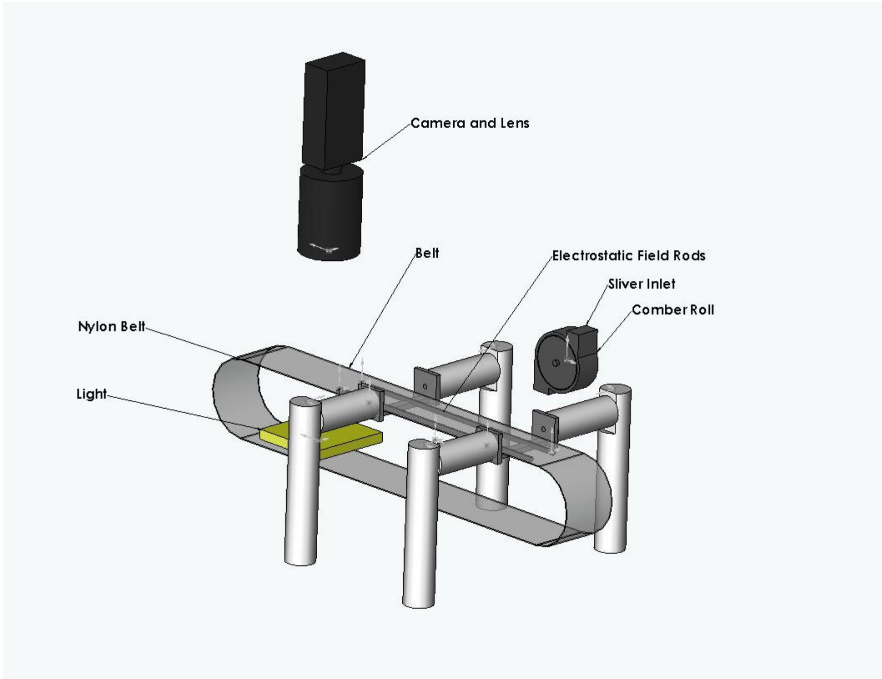

Figure 4.2 Transparent Belt System

Figure 4.3 Transparent Belt Image

4.1.1.2 Preliminary Tests

The first test run consisted simply of running the comber roll to populate the belt with fibers and running the camera continuously to evaluate the image quality and the fiber orientation. A sample image is shown in Figure 4.3. The original evaluation showed promise and while the image quality was not perfect, it was good enough to warrant further evaluation. To further test the viability of the new system, the samples captured from the continuously running camera were analyzed using a free standing version of the software. The software was modified slightly so that it would simply threshold the fiber. By only thresholding the fiber it was easy to see the quality of the image from a software analysis standpoint.

4.1.1.3 Evaluation of System Feasibility

By looking at Figure 4.3 it is evident that the general orientation of the fibers is in the proper direction. However, the fibers are not stretched between the rods as expected and the convolutions in the fibers promote fiber overlap. While there are algorithms to compensate for overlap, they are not perfect and add error into the system so overlap needs to be avoided. While this is not detrimental to the design, it is a downside and was considered during the evaluation. Also evident from the sample image is that the fibers were not confined to the viewing area, leaving an unknown portion of the fiber unseen by the camera. Widening the viewing area is an obvious solution to the problem however, since there needs to be metal rods under the belt to provide the electrostatic field. If the viewing area becomes too wide the rods will obstruct the fibers. By observing the behavior of the fibers as they reacted to the electrostatic field, it was apparent that the fibers were not being controlled well enough to assume a specific area where the fibers would fall. Another issue that became evident when the image was thresholded was the effect of scratches. Scratches on the belt show up in the image and when thresholded, appear as separate fibers or as additions to actual fibers. While it may be possible to select a belt material or drive roller material that reduces scratches, it is unlikely that scratches can be completely eliminated. While the system performed similarly to what was expected, there were serious issues that quickly became obvious. While each problem in itself may not have been insurmountable the combination of problems yielded a system that was no better than the original design.

4.1.2 Frontlighting Using Opaque Belt

The next system was similar to the one previously discussed, only it used frontlighting against a black belt instead of backlighting to illuminate the fibers see Figures 4.4 and 4.5. By using frontlighting, many of the problems with the previous backlighting would theoretically be eliminated. The electrostatic field can be created underneath the belt and since the belt is opaque and the fibers are viewed via frontlight, the fibers will no long be obstructed and the whole fiber will be seen by the camera. The light sources were situated at a low angle of incidence in a lighting technique known as grazing (shown in Figure 4.4) in which the light will reflect off of fibers and be viewed by the camera, however, the light reflected off the belt will not be seen by the camera. Aside from the lighting, the rest of the machine remained the same with the comber roll individualizing and introducing the fibers into the electrostatic field and the same motor and controller being used to drive the belt.

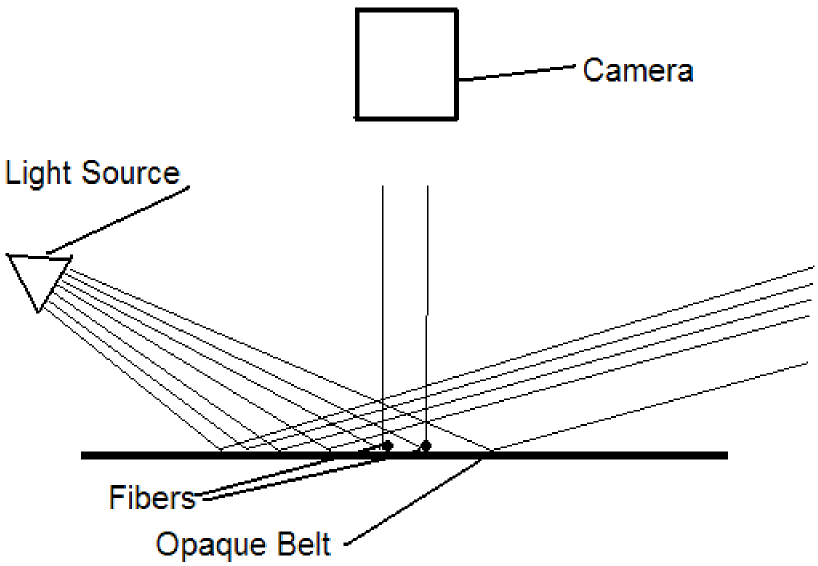

Figure 4.4 Opaque Belt Diagram

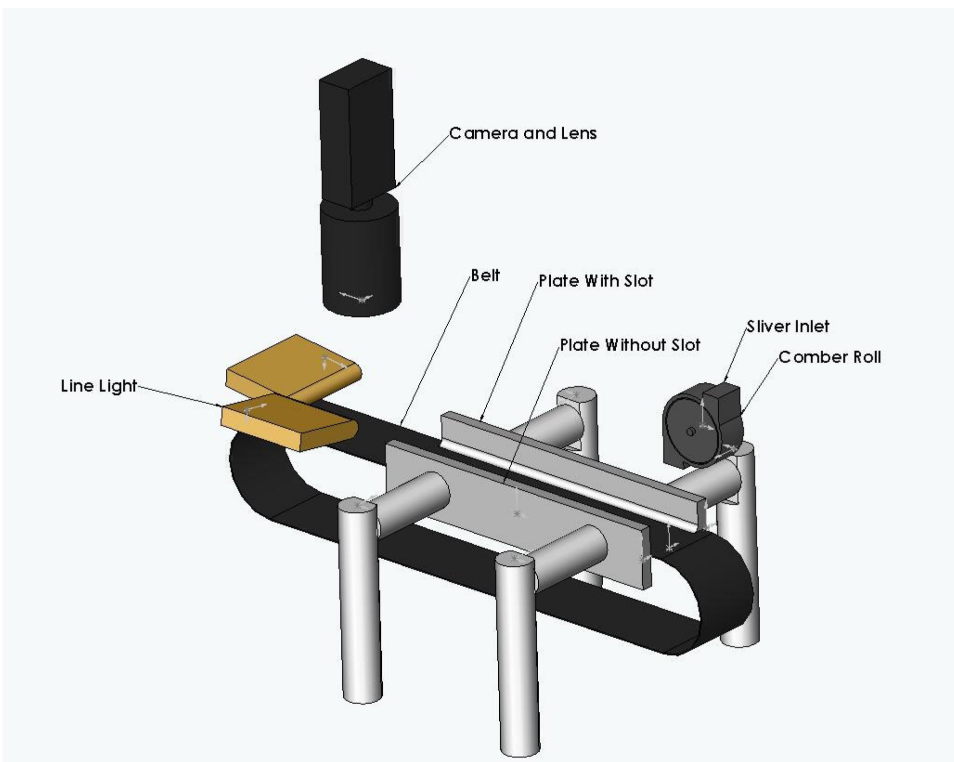

Figure 4.5 Opaque Belt System

4.1.2.1 Overview of Components and Operation

Selection of the belt material was the first problem in that a black material that was insulative enough for the fibers to stick while not accumulating static and preventing the removal. The belt also needed to be very smooth so that a minimal amount of light would be reflected back up to the camera. Nylon was again chosen as the material of choice and the back side was painted black to provide a contrast with the fibers. Nylon was proven as an effective material in the backlighting experiments and again proved superior to other materials. The light source was the next obstacle to overcome. A fluorescent ringlight was used to provide 360 degree illumination and reduce any shadows cast by the convolutions in the fiber. Due to the aluminum plates and the electrostatic field, the ringlight could not be placed close enough to the belt to provide a low angle of incidence and illuminate the fibers instead of the belt. The next attempt was with two incandescent lights, one placed at the end of the belt facing the front, and the other perpendicular to the belt (Figure 4.5). The lights were able to illuminate the fibers, however, its not possible to strobe these lights and therefore they were unable to produce clear images. Two led linelights along with a strobe controller were purchased from Advanced Illumination® to replace the incandescent lights [25]. The linelights were placed similarly to the incandescent lights however, due to their small size, they were able to be situated at a lower angle of incidence to the belt and therefore were able to better illuminate the fibers and provide excellent contrast with the background. The linelights worked well and with the ability to strobe, were able to freeze the motion of the fibers leading to much better image quality. The first design was very similar to the backlight system except for the belt and lighting. Many of the same problems were experienced including the tendency for fibers to extend out of the image. It was obvious that a better way to control fibers was required to ensure that the whole fiber would consistently be captured in the image. A solution would combine the original system with the new belt to allow front lighting. The belt would be horizontal at the imaging area and vertical where the fibers are introduced into the electrostatic field. The fibers would enter and jump back and forth between the plates just as they did in the original system and as they were drawn toward the center they would come into contact with the belt at the point where the belt fits into the slot.

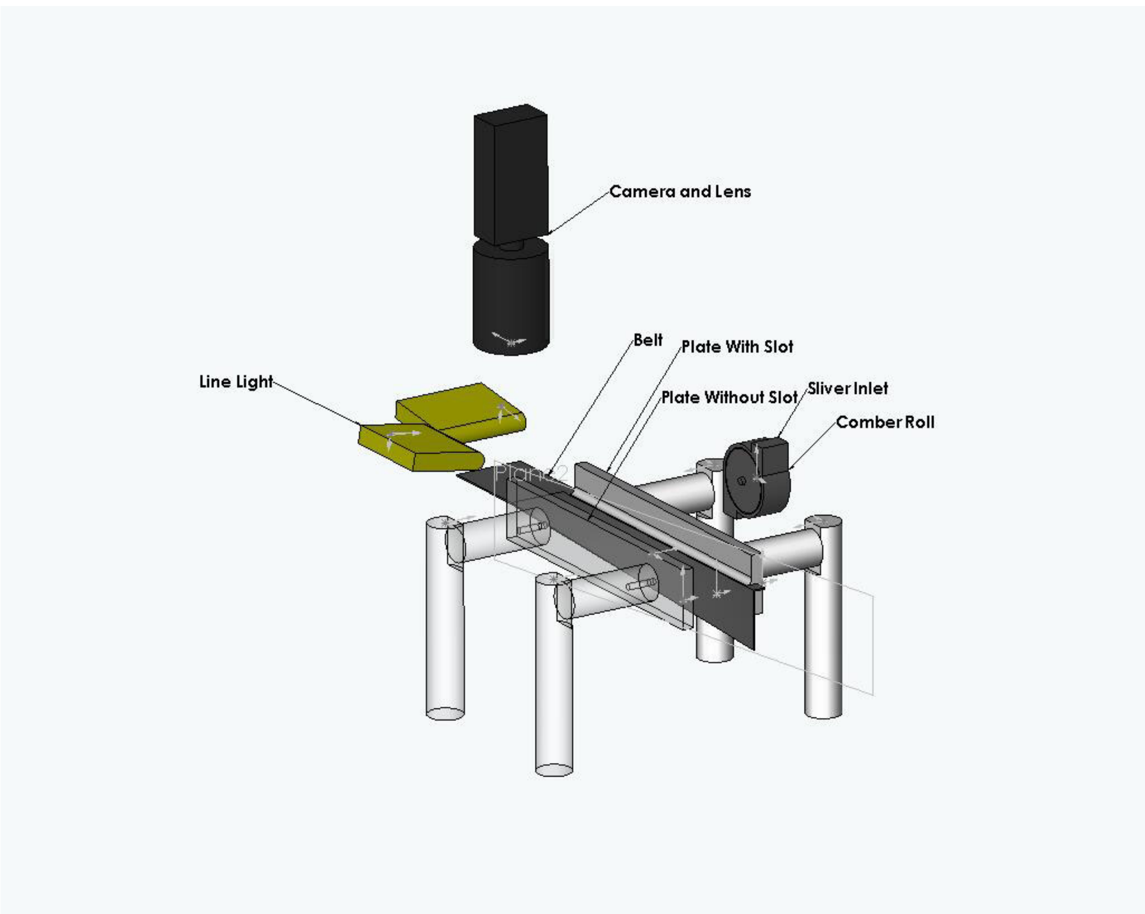

Figure 4.6 Rotating Belt System

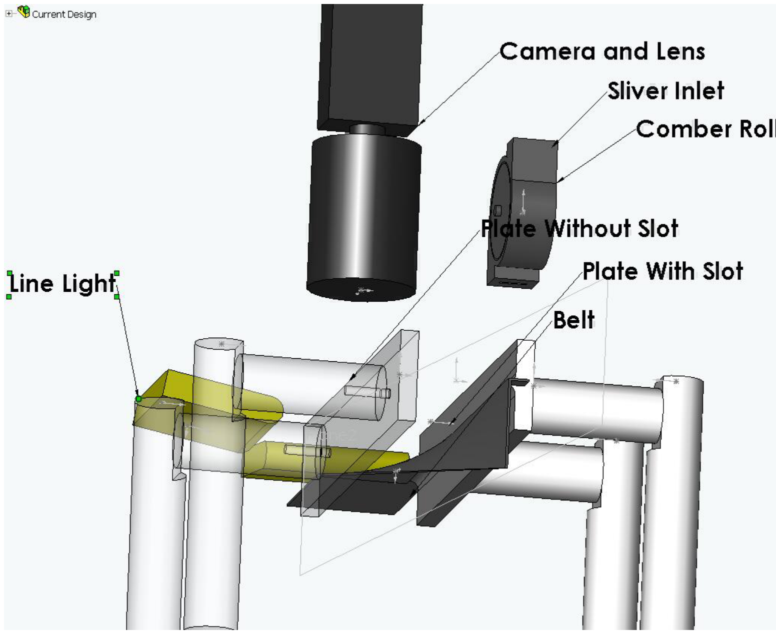

Figure 4.7 Rotating Belt Close Up

As the belt moves toward the viewing area it rotates up and the fibers end up laying on the belt perpendicular to the direction of the belt. A section is removed from the end of the slotted plate so that any fiber end that would extend under the slot would not be lost. This design change worked well and allowed the fibers to be controlled and delivered to the viewing area on top of an opaque belt.

4.1.2.2 Preliminary Testing

Preliminary tests began with running the machine and viewing the samples in a continuous video stream. This gave a general idea of how the fibers looked and allowed the camera and lighting settings to be optimized. During the continuous run, individual images were captured for closer visual analysis and thresholding to evaluate the processability of the image.

4.1.2.3 Evaluation of System Feasibility

The first design showed good contrast once the linelights were used instead of the incandescent lights or the ringlight, however, the fibers were scattered throughout the image and showed little orientation.

Figure 4.8 Opaque Belt Image

After implementing the new belt design in which the belt would rotate as it neared the viewing area the orientation increased significantly. Fibers were still out of frame but that was not a concern and by either widening the frame or removing them programmatically would solve the problem.

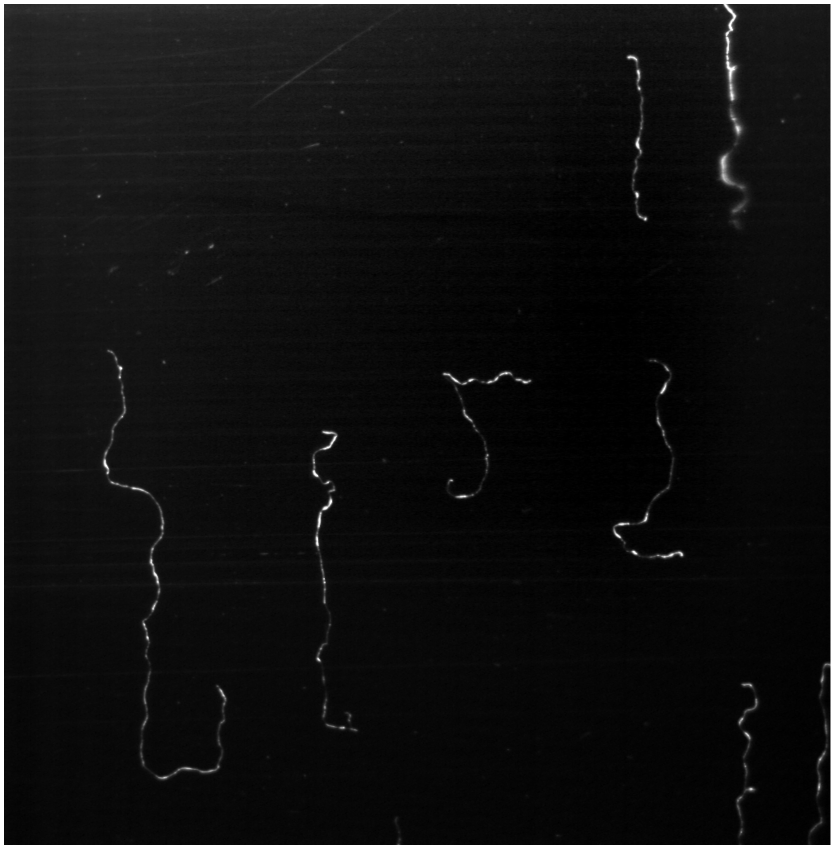

Figure 4.9 Rotating Belt Image

The main problem with this design was a fundamental problem with the lighting in that the natural convolutions in the cotton fiber would cast shadows on itself and cause broken skeletons or areas where there is not enough contrast for the software to differentiate fiber from background. This was not a small problem and each fiber exhibited many areas where broken skeletons would be created. The belt also acquired scratches very similarly to the belt in the case of back lighting and these scratches created artificial fibers, and additions to actual fibers which would lead to erroneous length measurements. The final problem was another downside to frontlighting and due to the constant motion of the belt. If the belt is not completely flat, the light will reflect off of the belt and reach the camera creating areas of glare that either wash out the fibers or render the image useless. Since the belt has to be bent to fit in the slot and since the belt is in constant motion it is almost impossible to ensure that the belt is constantly flat.

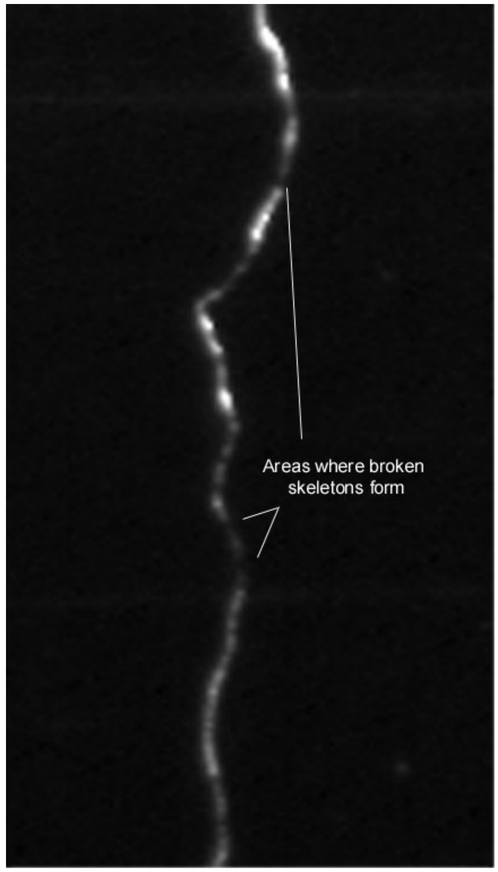

Figure 4.10 Broken Skeleton Closeup

Considering the number and difficulty of the problems associated with the design it was determined unfeasible and would not have been a significant improvement over the existing solution.

4.2 Control Without Contact

The modification of the original system did not prove a successful solution to the problem at hand. The different modifications and experiments clearly showed that backlighting was a superior lighting technique when compared to frontlighting. By casting a silhouette instead of relying on reflected light, the broken skeletons can be significantly reduced. With this knowledge, the future designs would all enable the fibers to be backlit when they are presented in the viewing area. The commonality with all of the previous unsuccessful concepts was the belt, and more generally contact with the fibers. When the fibers are in contact with part of the machine, it is impossible to avoid the point of contact obstructing a portion of the fiber or causing some addition to the fiber (in the form of scratches in the clear and opaque belt examples). With this realization, future designs focused on controlling the fibers in a manner that would deliver them to the viewing area and present them to the camera with no physical contact.

4.2.1 Control Without Contact Using Electrostatic Plates

The first design concept for controlling the fibers without any physical contact involved a more extreme modification of the existing machine. If the fibers could be released from the belt at the instant they were in the field of view and be captured in an image as they moved toward the opposite plate there would be no obstruction and the entire fiber could be caught within the frame. This design would not require many of the components to be redesigned and it incorporated the belt and electrostatic field which was a proven method of controlling fibers.

4.2.1.1 Proposed Methodology

The behavior of the fibers was reasonably well understood and fiber and conductivity was a key property. When the fibers are first introduced into the field, a charge is induced on the fiber ends. This causes the fiber ends to be attracted to the electrostatically charged plates. When the fibers come into contact with the plates they discharge and are attracted to the opposite plate. This behavior continues until the fiber comes into contact with the urethane belt which is not conductive and does not allow the fibers to discharge, causing the fibers to remain stuck to the belt and rarely jump off. The focus of the investigation was to create a situation in which the fibers would jump off the belt predictably when the belt reached the viewing area. The first idea was to find or build a belt which is semi-conductive and would allow the fibers to slowly discharge until they reach some critical charge at which point they would jump toward the opposite plate. Polymers are commonly mixed with carbon to provide some conductivity and eliminate or reduce static buildup. Another proposed solution involved placing a conductor at the viewing are that would contact the fibers as they traveled past on the belt. Upon contacting the belt, the fibers would discharge and jump off the belt into the viewing area.

4.2.1.2 Analysis of Feasibility

The proposed solutions contained fundamental flaws that prevented further investigation. The semi-conductive belt would not have worked for a number of reasons involving fundamental problems with the theory. The belt would have been impossible to engineer so that the fibers were released at a consistent point. Fibers differ in length and thus have different charges so the time it takes for the fiber to discharge would vary from fiber to fiber. This would cause the fibers to jump off at different places along the belt and even if some were in the viewing area there would be a significant length bias in that a certain length fiber would consistently jump off the belt at the viewing area. The fibers move quite rapidly in between plates and it would be impossible to ensure that a fiber is within frame each time. The speed of the fibers would not be consistent due to the different masses, aerodynamic characteristics, and charge so it would be impossible to predict the position of the fibers after they release from the belt. This could result in most of the fibers not being captured at all or being partially in frame. These fibers cannot be analyzed since some unknown portion of the fiber is not visible. Sensing the fibers as they are released was considered but again thought unrealistic because no such sensor was available or practical in such a configuration. Also even if a sensor were available there would not be enough time to sense the fiber and trigger the camera before the fiber would have passed through the viewing area. The second scenario using the conductor to contact the fiber and allow the charge to discharge causing the fiber to release from the belt suffered from many of the same shortcomings as the semi-conductive belt design. In addition, there was a good possibility that since the conductor would be a charge concentration that fibers would be attracted to this point. This would cause fibers to jump back and forth between the plate and the conductor which would be in the middle of the viewing area. This would likely cause entanglements or erroneous readings from measuring the same fiber multiple times. Overall, while the thought process was in the right direction the concepts developed were theoretically unfeasible and thus more potential solutions were needed.

4.2.2 Control Without Contact: Air Stream

Due to the growing realization that an electrostatic-based solution would not yield the best possible machine, the focus shifted to an entirely new design, and therefore all solutions were considered and not bounded by current technology. The most intriguing and realistic solution to the problem focused around using an air stream to deliver individual fibers to the viewing area. The impetus for this design was to benchmark an existing machine used to measure cotton fibers. AFIS® (Advanced Fiber Information System) is an accepted method to measure the cotton fibers and uses an air stream to deliver individual fibers to a pair of sensors that sense the presence of the fiber [8]. The sensors are placed a known distance apart and the speed of the fiber is determined by the time it takes to pass between both sensors, while the length is determined by using the speed and the time it takes to completely pass one sensor. This method proved that an air stream could effectively control and deliver a fiber to a viewing area, however, instead of measuring speed a camera would capture an image of the fiber. The fiber would be free of contact with any surface and therefore the entire length would be captured in the image.

4.2.2.1 Proposed Methodology

The design utilized suction to pull the fibers through a small tunnel to an opening in which the fibers passed over a strobe into another tunnel and be removed (Figure 4.11). The opening would serve as the viewing area and allow the fiber to be backlit by the strobe and have an image captured by the camera with no obstruction to hide a portion of the fiber. The first aspect of the design dealt with the problem of capturing an entire fiber in the field of view. By running the camera and strobe continuously, there would be a problem similar to the solutions above in that there is no way to ensure that a fiber is entirely in the viewing area when an image is captured. The images are captured essentially at random since the time of the next image depends on the processing time for the previous image, and the fibers are introduced at random since a fiber is introduced each time the comber roll removes a fiber from the sliver. It would be impossible to synchronize these two random uncontrollable events and therefore a method was needed to trigger the camera when a fiber was present. It immediately became obvious that some sort of sensor would need to be purchased or developed to sense the presence of a fiber and trigger the camera. If the presence of a fiber was known downstream from the camera, it would be possible to synchronize the camera and sensor so that when a fiber was seen there would be a high probability that it would be captured in its entirety. The next section of the design was the light source which needed to be bright enough to provide high contrast with the silhouette of the fiber but also strobe fast enough to freeze the motion of the fiber with minimal blur. The strobe also needed to be integrated with the camera and sensor so that the strobe would illuminate the fiber just as the fiber entered the viewing area and the camera captured an image. The final and likely most important area of the design that needed to be addressed was the camera. The camera needed to have a high resolution so that a large viewing area could be used to minimize the negative affects of different fiber speed due to differing masses and aerodynamic properties. It was also critical that the camera have the capability to be triggered by the sensor and provide output to control a strobe light. Finally the camera would eventually need to be controlled by software written specifically for this machine as many images would need to be captured and analyzed so that slivers of cotton could be evaluated for quality.

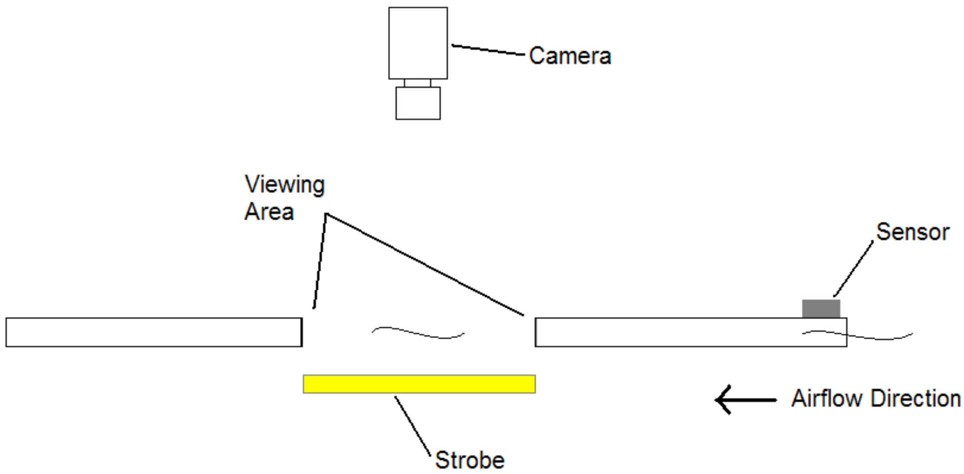

Figure 4.11 New System Concept

4.2.2.2 Analysis of Feasibility

Before anything was constructed or tested the feasibility of the system was evaluated to avoid wasting time on ideas doomed from the beginning. Knowing that much of the theoretical operation was based on a proven technology increased the apparent feasibility of the system. It is well established that vacuum is an effective method of controlling and transporting individual fibers so there was little doubt that portion of the design was sound. A camera with the required triggering and control capabilities had already been acquired for previous experiments and it was believed that camera would be more than adequate for the new design. A strobe light was already available and used extensively for the previous designs. The intensity and duration of the strobe was variable and it also provided the option of having an external trigger which was exactly what was needed for the application at hand. The final piece of the puzzle and the most difficult to theorize was the sensor. Based on the operation of AFIS® it was known that a sensor capable of detecting single fibers was possible but it was not known what sensor specifically was used or even if such a sensor was commercially available. Despite the uncertainty about where to purchase such a sensor, or how to make one, the fact remained that it could be done and that, along with the viability of the other components was enough to move forward and construct a prototype of the machine.

5.0 Final Design

After theoretically concluding the viability of using an air stream to control fibers, the next step was to build a prototype to prove the validity of the design. There were many components that could have been the focus of the initial efforts but because the fiber sensing system was key to effective implementation, the fiber sensor was the first system to be designed.

5.1 Fiber Sensor

There were a few criteria that needed to be addressed in either the selection or design of such a sensor. First, the sensor would have to reliably detect the presence of a single fiber, while not giving erroneous readings when fibers were not present. Second, the sensor required a very short response time since the fibers are moving at a high speed and are only present in front of the sensor for a short time. Third, the sensor has to detect a fiber without any physical contact with the fibers. If the sensor were to contact the fibers there would be a high probability of fibers becoming entangled with the sensor creating a clog in the input area. With these criteria a search for existing sensors began.

5.1.1 Method

Selecting a sensor was difficult because fiber detection is not common, therefore existing technology and knowledge is limited. In an effort to quantify, to some degree, the specifications of a required sensor many phototransistors, photodiodes, and photoresistors were purchased for experimentation. Each potential technology was integrated into a circuit so that the presence of light would result in a voltage change. The circuit was tested using a multimeter with millivolt resolution to measure the voltage output of the circuit under different lighting conditions. The circuit was then tested using fibers to determine if there was a measurable voltage change. The next experiment incorporated an op-amp into the circuit to amplify the voltage to a more measurable range. The first experiments were based on the idea that fibers would obstruct the path of light from an IR emitter enough to register a measurable voltage change from the photodiode, or change the state of the phototransistor.

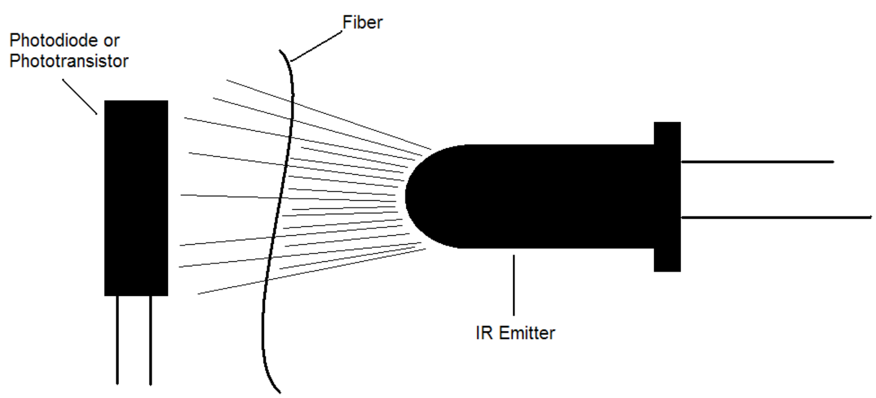

Figure 5.1 IR Emitter / Detector Diagram

Initial testing saw little success with the photodiode showing no voltage change when the fiber was present compared to when no fiber was present. An op-amp was integrated into the circuit to amplify the voltage to a range that the measurement device, a simple multimeter, could measure. The voltage was higher but the output became indistinguishable from the noise and even though at times there appeared to be change due to the fiber, it was not consistent and therefore impossible to incorporate into a viable sensor. It soon became obvious that existing phototransistors and photodiodes along with the corresponding IR emitter could not effectively sense individual fibers. The reason for the poor results was thought to be the relatively low intensity and the diffuse properties of the IR emitters. To solve this problem, an intense and concentrated light source was needed and led to the use of a small laser modified from a laser pointer. In the first test, the laser was aiming at the photodiode with the fiber breaking the beam.

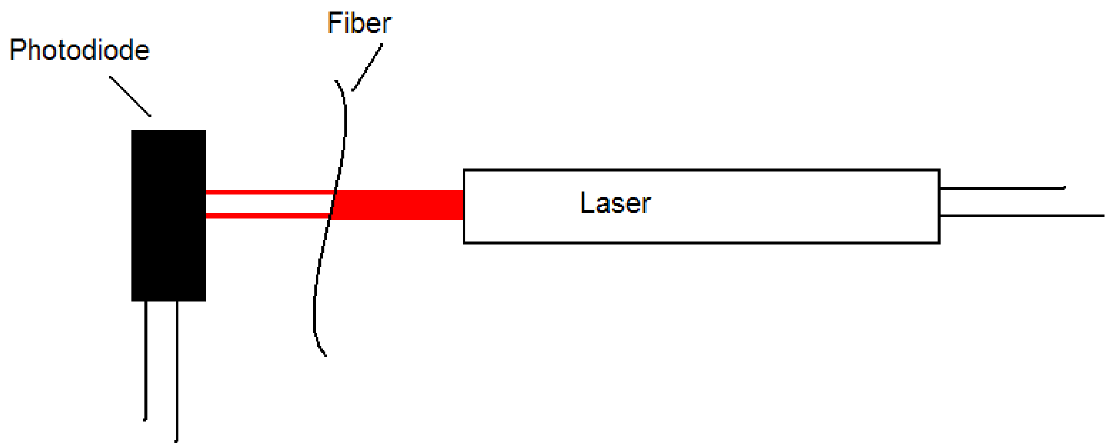

Figure 5.2 Laser / Photodiode Diagram

The photodiode could easily detect the presence of the laser beam but could not detect when a fiber obstructed the beam. During this experiment, it became obvious that while the light obstructed by the fiber could not create a measurable voltage change, the light reflected by the fiber could produce a measurable voltage. The reflected light could easily be detected by a photodiode, phototransistor, or photoresistor positioned above the fiber, 90˚ from the path of the light.

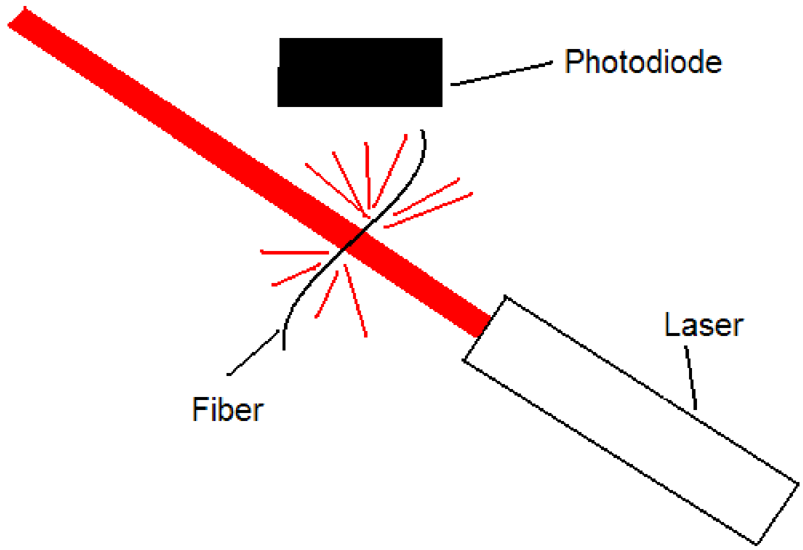

Figure 5.3 Reflected Laser / Photodiode Diagram

The parallel nature of laser light ensured that when there was no fiber present very little of the laser light would reach the photodiode, however, when a fiber was present the laser would illuminate the fiber and reflected light would reach the photodiode. Initial experimentation used both a photodiode and a photoresistor incorporated into a simple voltage divider to create a voltage change along with the change in resistance. The photoresistor initially worked better than the photodiode registering a larger voltage change, however the response time was very slow. The photoresistor required a significant amount of time to ramp up once a fiber was present and even longer to decay once the fiber was removed. This was a significant problem considering the photoresistor would not create a voltage change when the fiber was moved through the beam quickly. This would not be suitable for the application at hand and thus the final design focused on a photodiode with a laser positioned perpendicular to the sensor face.

5.1.2 Final Design

The fiber sensor was designed using a laser positioned perpendicularly to both the fiber direction and the sensor. The fiber would pass through the laser and the light would reflect off of the fiber illuminating the sensor causing a voltage change. Once the concept of the fiber sensor was developed, a working prototype had to be designed and integrated so that it could control the camera. At the heart of the sensor is the OPT101® photodiode from Burr-Brown, which was chosen due to a good spectral response to the lasers wavelength and an integrated op amp [22]. The spectral response is critical because in order to achieve the largest possible voltage change, the sensor must be sensitive to the same wavelength of light that the laser is producing. The OPT101® has a wide response band, and while the peak is not at the 630nm wavelength of the laser, there is still an acceptable response to that wavelength [22].

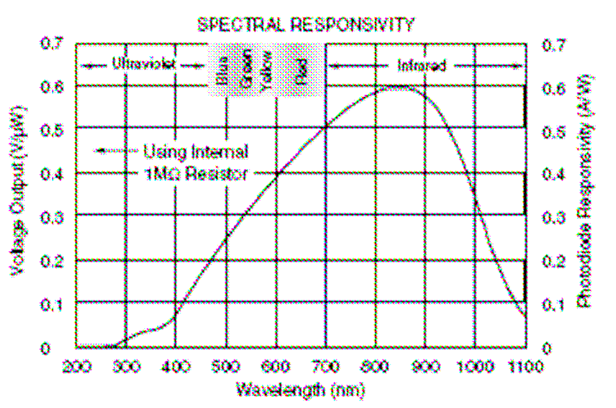

Figure 5.4 Photodiode Spectral Response [22]

The integrated op amp was desirable since the actual voltage change when a fiber is present is on the order of a hundredth of a volt and therefore difficult to integrate into a circuit without amplification. Shown below is a schematic of the circuit contained within the photodiode.

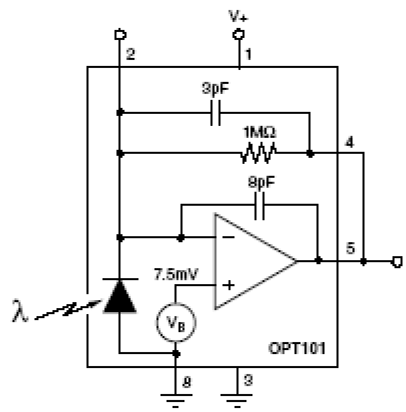

Figure 5.5 Photodiode Amplifier Circuit [21]

Photodiodes are more sensitive to certain wavelengths of light than others. Therefore matching the lightsource to the photodiode became the main criterion when selecting a laser. It quickly became apparent that lasers were primarily available at red wavelengths, however, some could be found in blue or green wavelengths. The red wavelength was selected because it provided the best response from the photodiode, was available in configurations which would be easy to integrate into a circuit. The laser could be relatively simple, requiring no special features or optics besides an adjustable focus. The adjustable focus would allow the beam to be concentrated on the point by where each fiber would pass. While the laser is primarily parallel, it is not completely parallel and diverges slightly. By adjusting focus, the beam can be focused on a point beneath the photodiode thus reducing the amount of light reaching the photodiode when no fiber is present. The chosen laser had a wavelength of approximately 650nm which fell within the optimal response range of the photodiode. The laser had a power rating less than 5mw and was similar to a laser pointer but was smaller, required an external power supply and had an adjustable focus. The laser required 3volts at 45mA which was easily provided by the 13.8 V power supply and a simple voltage divider. To effectively control the camera, the photodiode needed to switch a NPN transistor on in the presence of a fiber and off when there is no fiber. The threshold voltage for transistors is .7 volts therefore to cause a state change and trigger the camera the photodiode must output a voltage above .7 when a fiber is present. The sensor must output a voltage lower than .7 volts when no fiber is present and a voltage above .7 when a fiber is detected. Careful placement of the sensor relative to the laser could ensure the above conditions are met. This would not be effective considering ambient lighting levels change along with slight variations in the positions of the photodiode and the laser. A more robust solution was needed to allow the sensor to be adjusted to accommodate slight variations in the system. The voltage range could change due to a number of factors including ambient light, focus of laser, proximity of sensor to fiber, and the section of fiber that is illuminated by the laser. To achieve the required voltages consistently and in different lighting conditions a difference amplifier as shown in Fig 5.6 was used.

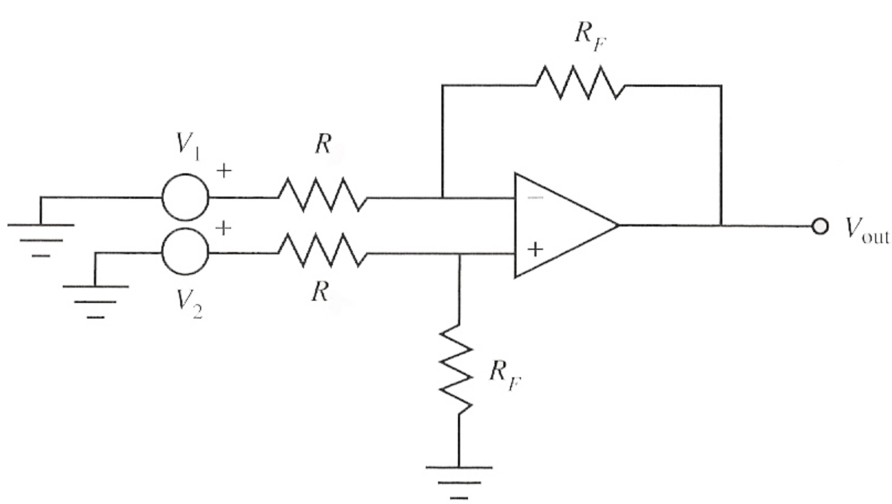

Figure 5.6 Difference Amplifier [5]

$$V_{out} = \frac{R_F}{R}(V_2 - V_1)$$

Equation 5.1 Difference Amplifier Equation [5]

A difference amplifier is an op amp, configured to accept two voltages as inputs, that outputs the difference between V_2 and V_1 multiplied by a constant which is set by the resistors chosen for R and R_F. To achieve an acceptable multiplication constant R was set to 1KΩ and R_F was set to 6.2KΩ yielding a multiplication constant of 6.2. Experimentation was used to determine the constant because a constant too low would not yield the required voltage change when a fiber was present, and a constant too high would make the sensor too sensitive and cause erroneous readings. The amplified photodiode is shown in equation 5.1 as V2 and a potentiometer configured as a voltage divider is V1. The potentiometer allows the second input voltage to be adjusted to closely match the base voltage output from the photodiode in different lighting conditions. By carefully adjusting the potentiometer, the output of the difference amplifier lies just below the .7 volts needed to change the state of the transistor when there is no fiber present. When a fiber is introduced the voltage on V2 is increased causing the output of the difference amplifier to increase above the .7 volts needed to switch the transistor. A circuit similar to the one described in the camera manual was designed using an inverter to trigger the camera. A transistor was used with the output of the difference amplifier connected to the base to switch it on and off, a 5 volt signal connected to the collector, and the emitter connected to the inverter as the rising edge positive as shown in figure 5.7. By using the potentiometer with no fiber present, the input voltage to the transistor could be slowly increased until the transistor changed state, and then dialed back slightly to achieve a value just below the voltage required to trigger the camera. By using a transistor, the required rising edge TTL signal could easily be integrated with the trigger circuit required for the camera as shown in Figure 5.8.

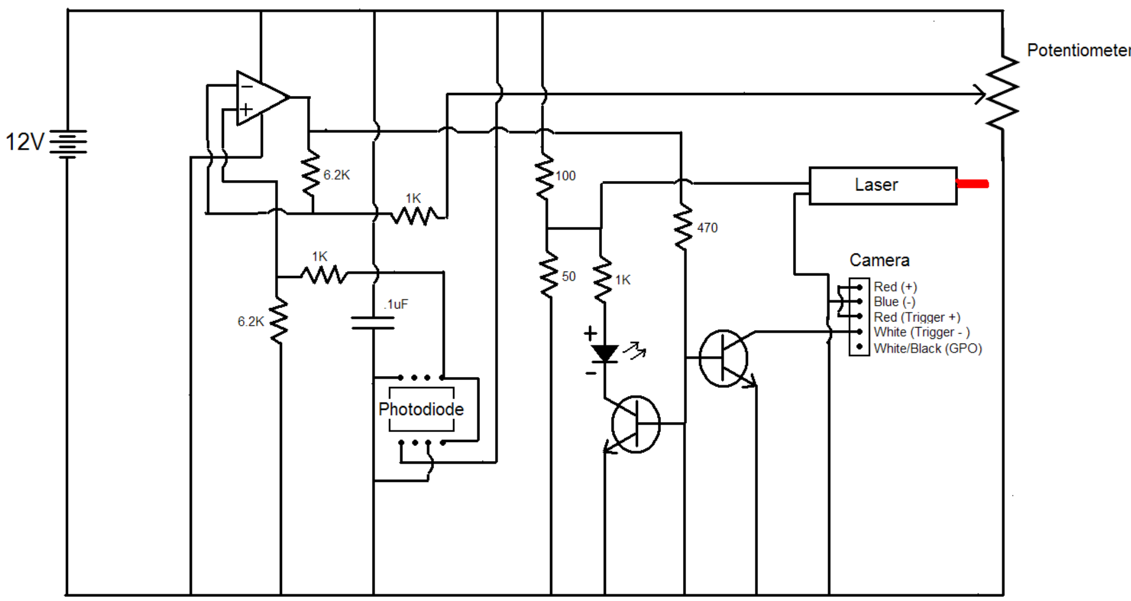

Figure 5.7 Sensor Circuit Diagram

The circuit below came from the camera manual and provides a way to trigger the camera using the rising edge trigger created by the Figure 5.7 circuit. The rising edge trigger will be inverted by the NOT gate which will show a ground on the other side of the circuit. The five volts will now flow through the optoisolator tripping the phototransistor and causing the camera to capture an image. An optoisolator is used to isolate sensitive electronics from potentially harmful voltage or current. Since there is no physical connection between the two sides of the circuit there is no chance that the camera circuits would be damaged.

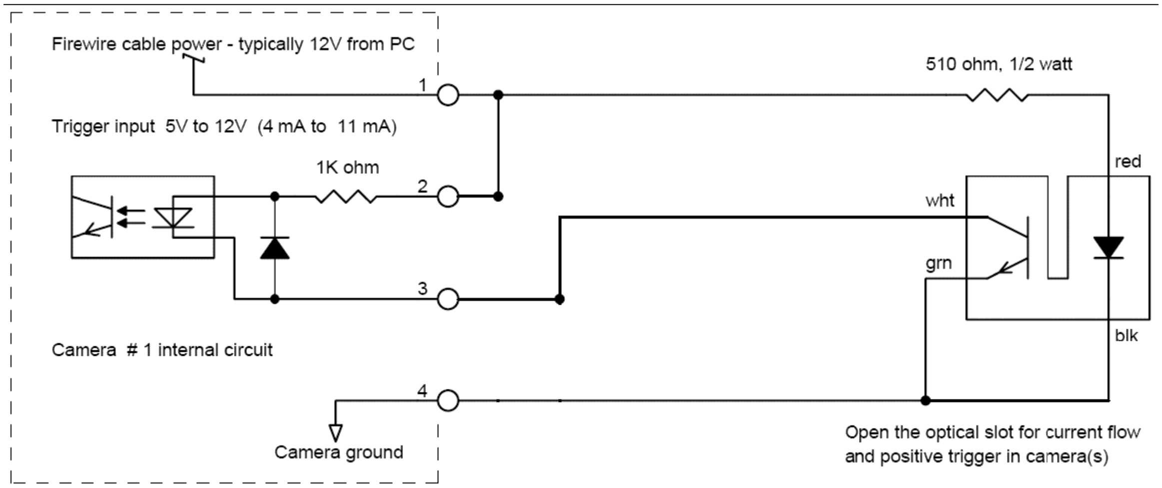

Figure 5.8 Camera Trigger Circuit [25]

5.1.3 Analysis of Effectiveness

Initial attempts to evaluate the effectiveness of the sensor consisted of manually moving a single cotton fiber into the laser beam. A LED was used to simulate the camera and provide a visual representation of when the camera would be triggered. The sensor was able to reliably detect the presence of a single fiber each time one was present. The next test evaluated the ability of the sensor to detect moving fibers. Once again fibers were moved through the beam manually only this time they were moved quickly. Once again the sensor proved effective and could detect fast moving fibers.

The next step in evaluation of the sensor was to integrate it into the system and test the effectiveness as part of the entire device. The sensor was connected to the camera and a large object was used to ensure that the sensor could properly trigger the camera. The sensor was placed in a test enclosure to allow fibers to move past the sensor. The fibers were introduced to the system individually by hand and moved past the sensor using suction. The enclosure blocked some of the light beam causing a bright area however, by adjusting the potentiometer, the system was made to compensate for the increased brightness. The sensor then was able to effectively detect the presence of each fiber introduced into the system.

5.2 Fiber Transport Enclosure

Once the sensor had been developed and proven effective in detecting fibers, a method was needed to move the fibers from the comber roll, past the sensor and in front of the camera in a reliable and repeatable manner. A variety of ideas were theorized and in the end many were tested leading to an effective method of controlling and distributing fibers to the viewing area.

5.2.1 Method

The new design focuses on controlling the fibers without any physical contact. Suction is a widely utilized method of controlling fibers and was at the heart of all the potential solutions. To ensure the best solution the ideal solution was first theorized and involved the fibers moving through air with no material between the fiber and the camera. This solution proved impractical and further design was needed to arrive at a workable solution. Preliminary designs sought to deliver the fibers to the viewing area unobstructed and thus incorporated a gap between two tubes in the hope the fiber would follow the airstream between the paths as shown in figure 5.9. Relying solely on air to transport the fibers between the input tube and the output tube proved ineffective and therefore a more controlled method was developed. New designs were theorized and tested which incorporated a clear tunnel which would contain the air stream and the fiber.

5.2.1.1 Air Gap

The first design sought to deliver the fiber in front of the camera so that there was only air between the camera and the fiber (Figure 5.9). This would eliminate the chance that anything would either obstruct the fiber or interfere with the quality of the image. Two tubes were used with a 1.5” gap between them to ensure that even the longest (1.25”) fibers would not be obstructed by the tubes.

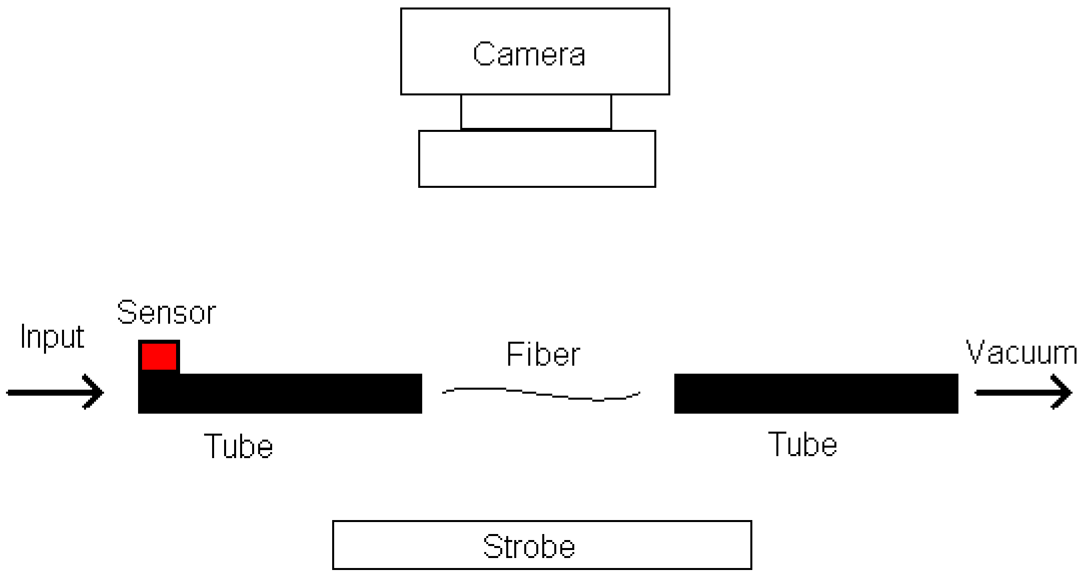

Figure 5.9 Air Gap System

A vacuum would be applied to the second tube and low pressure area would be generated in the first tube. The fiber would then be introduced into the first tube and be transported past the sensor and into the viewing area where the image would be captured. The fiber is then removed from the system for disposal. The theory was developed by thinking of air as an incompressible fluid like water and thinking that an air stream behaves similar to a stream of water from a hose. This stream would theoretically carry the fiber to the other tube at which point it would be disposed of. Unfortunately air is compressible causing it to become compressed in the tube and expand when it exits the tube. The fibers follow the air and since the air is expanding away from the tube exit there is little chance that the fibers will cross the imaging area consistently. Another downside is that the fibers would not be contained in a single plane making it difficult to accurately focus the camera resulting in blurry images.

5.2.1.2 Coanda Effect

The next design would utilize the coanda effect to cause the fibers to follow a slightly curved path. The coanda effect is one of the effects airplane wings utilize, causing the air to follow the curvature of the wing and be directed downward causing lift. In theory, the airstream containing the fiber would follow a curvature providing more control over the fiber resulting in better delivery to the viewing area. The diffusing plate from the backlight would be used as the path for the fibers to follow so that the contrast between the fibers and the background would be as high as possible while also simplifying the design. Testing once again showed that this method was ineffective and fibers were not able to be controlled effectively.

Theoretically the air would travel over the surface and the coanda effect would cause the air to follow the surface leading toward the tube providing the suction. The theory was sound and if the air speed was high enough the fiber could cross the gap. While the fiber could now be controlled the image of the fiber was very blurry due to the high speed. The image was too blurry to allow effective processing and therefore a fiber control method allowing slower fiber speeds was the focus of a new design.

5.2.2 Enclosed Transport System

After an open system proved ineffective a completely enclosed system was the next option. An enclosed system would allow the fibers to be completely controlled in the X, Y and Z directions. Multiple designs were constructed and tested to determine which design would provide the best control, while eliminating the possibility that a portion of the fiber would be obstructed from the camera

5.2.2.1 Preliminary Enclosed Fiber Design

The first iteration was simply a tunnel through which the fibers would travel, and an adapter at each end to smoothly transfer the fibers from the comber roll to the enclosure. This design shown in figure 5.10 was a good start but the machining was very complicated and a simpler design was needed. This simpler design shown in Figure 5.11 would make it much easier to build a prototype to test the theory before machining.

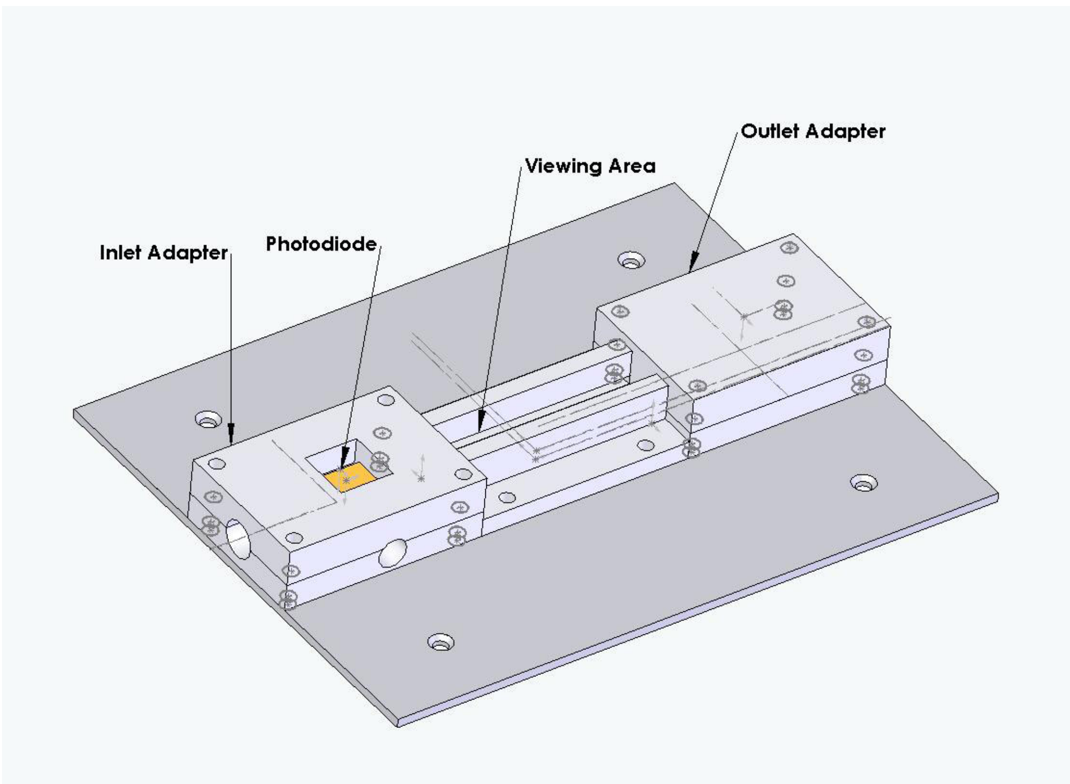

Figure 5.10 Preliminary Enclosed Design

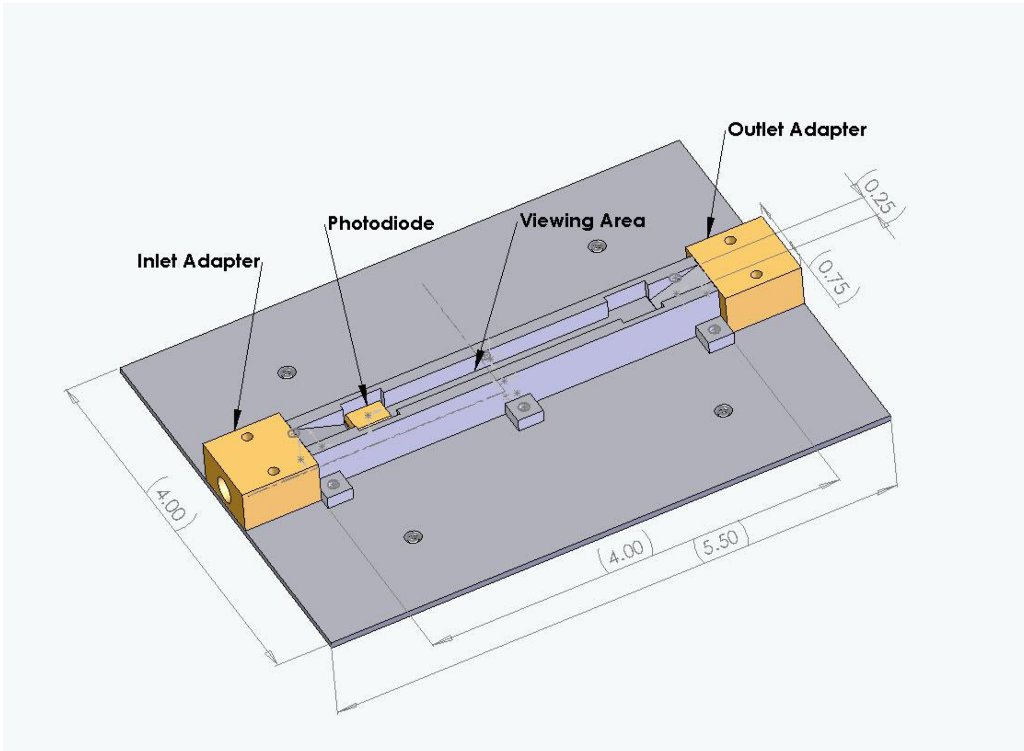

Figure 5.11 Redesigned Enclosure

The transition from input adapter to tunnel is accomplished by a simple angled piece channeling the fiber to the tunnel, where it is sensed and an image is captured. A simple prototype as shown in figure 5.11 was constructed and evaluated to determine if the design would effective deliver the fibers to the viewing area.

5.2.2.2 Preliminary Design Problems

The most evident problem was the presence of turbulent flow throughout the tunnel. The turbulent flow was investigated by placing a long yarn through the tunnel and observing the activity at the end when at different sections through the tunnel. The behavior of the yarn was highly erratic at the opening of the tunnel where the tube transitioned to the tunnel. The erratic behavior continued throughout the tunnel until it reached the opposite end where the fiber was stabilized by the suction. The turbulent flow caused the fibers to flutter back and forth which, when captured by the camera, appeared blurry. The design was also too narrow and there was no way to ensure that the fibers would not come in contact with the walls, obstructing sections of the fiber from the camera. The final problem was that the tunnel was not long enough. The camera has a reset time of approximately 8ms meaning that from the time it is triggered there is a delay time of at least 8ms before it can take a picture. To accommodate the inherent camera delay, the tunnel must be longer than the distance a fiber can travel in 8ms ensuring that the entire fiber is captured by the camera.

5.2.2.3 Redesigned Fiber Transport Enclosure

The next iteration shown in figure 5.12 was designed to solve the problems faced by the preliminary design. The tunnel was significantly wider than the first design to eliminate fibers touching the edges of the tunnel. By widening the tunnel the fibers would slow down due to the reduced air speed inside the opening helping to improve image quality. The tunnel was also made longer to account for the reset time needed for the camera.

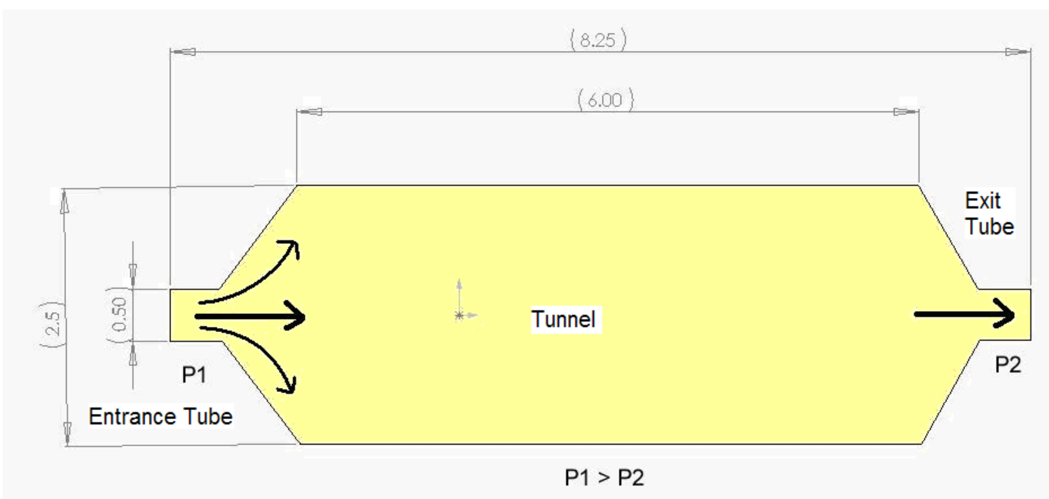

Figure 5.12 Viewing Area Contour

5.2.2.4 Redesigned Fiber Transport Enclosure Design Problems

The new design did not solve the problems it set out to solve however it did enable a better assessment of the specific problems. While the tunnel was longer the fibers continued to be captured at the end of the enclosure. The position of the fibers was not very consistent and an area containing the majority of fibers could not be pinpointed. The fibers also showed a tendency to move toward the edges of the enclosure creating the possibility that the fibers would either be partially out of frame or come in contact with the edges causing some obstruction. Turbulent flow again was a problem and was especially noticeable at the entrance to the enclosure. The turbulence caused the ends of the fibers to appear blurry on the camera and was also thought to contribute to the fibers proximity to the sides of the enclosure. The turbulent flow was theorized to be caused by the sharp transition from the small volume of the tube to the large volume of the viewing area thus allowing the air to expand quickly, causing turbulence.

5.2.2.5 Redesigned Fiber Transport Enclosure

The fourth design was aimed at solving the problem of turbulent flow. The design was similar to the previous design however it incorporated a longer taper from the input area to the viewing area. The turbulent flow was believed to be caused by the rapid expansion of air as it leaves the tube and enters the viewing area. To solve this problem the area the air enters was gradually increased to the final volume. This would allow the air to expand gradually instead of very quickly, resulting in decreased turbulent flow at the opening. The length of the enclosure was also increased to ensure that the location of the fibers within the viewing area could be controlled with the camera delay and the air speed.

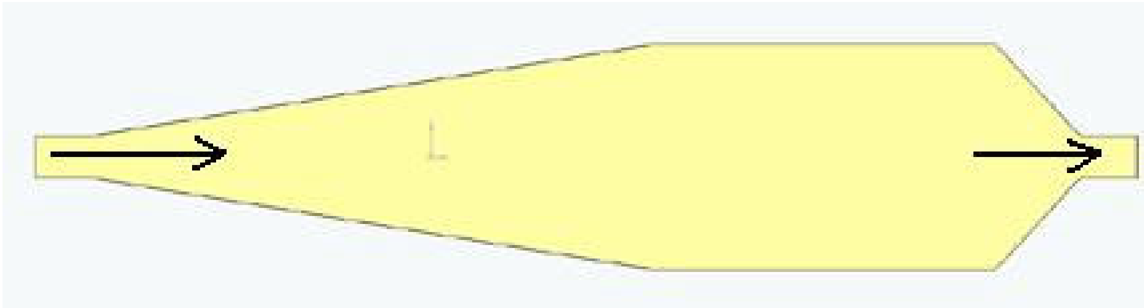

Figure 5.13 Tapered Contour

5.2.2.6 Redesigned Fiber Transport Enclosure Design Problems

The length chosen for the enclosure worked well, allowing the position of the fibers to be controlled with the air speed and the delay time. The turbulence of the fibers was not significantly decreased and some blur at the tip was noticeable. The turbulence was found to significantly decrease when the air velocity was decreased so reducing turbulence was no longer a significant problem. The number of fibers near or contacting the edges in the viewing area were significantly increased when compared to the previous design. This was a significant problem and attributed to the air following the contour of the enclosure. By gradually widening the enclosure the air, and thus the fiber, can easily follow the contour leading to the edges of the viewing area.

5.2.2.7 Analysis of Design Solutions

With limited ability to predict the behavior of individual fibers in an air stream, the design process benefited significantly from the ability to mock up simple and cheap prototypes to test the different design solutions. The first designs focused on the ideal solutions in which there would be no material between the fiber and the camera ensuring the best image quality possible. This design proved difficult due to the problems controlling fibers and the speed required to take advantage of the coanda effect. The focus shifted to an enclosed design and preliminary prototypes were developed to test each design change ensuring that time and money would not be wasted having flawed designs machined. After much experimentation and observation a final design was decided upon.

5.2.3 Final Design

The final design was simply a slight modification of a previous design with the wide viewing area and no tapered entrance combined with an elongated entrance tunnel as shown in figure 5.14. By controlling the fiber within the tunnel and releasing it into the viewing area from the center there was no chance the fiber would move toward the edge before it was redirected by the suction. The long entry tunnel also gave the camera time to reset before the image was captured allowing the position of the fiber to be controlled by the timing and the airspeed.

5.2.3.1 Theory

By applying the knowledge gained during experimentation, a design change was made and by modifying a previous design an effective enclosure was created. The entrance tunnel to the viewing area was lengthened significantly to allow time for the camera to reset between the time the sensor is triggered and when the image is captured. The tunnel was lengthened from about .5 inches in the original design to 5.25 inches.

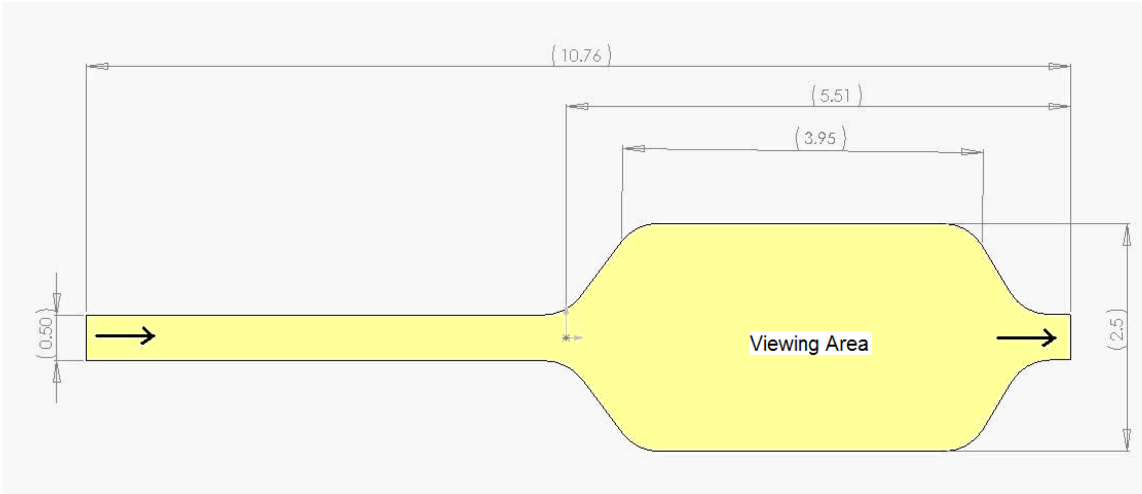

Figure 5.14 Final Enclosure Contour

The viewing area was shorter compared to the previous design to ensure the fibers would remain in the middle throughout the area. The viewing area was considered to be in between the tapers and was 3.25 inches long. This distance could easily accommodate a 1.25 inch fiber allowing room on either side to ensure the fiber is in frame. Like the previous designs, a preliminary prototype was built to test the design before the final prototype was machined. The prototype performed well, delivering fibers to the center of the viewing area while allowing time for the camera to reset after each trigger. No more design changes were needed and a final prototype was modeled using Solidworks® and machined.

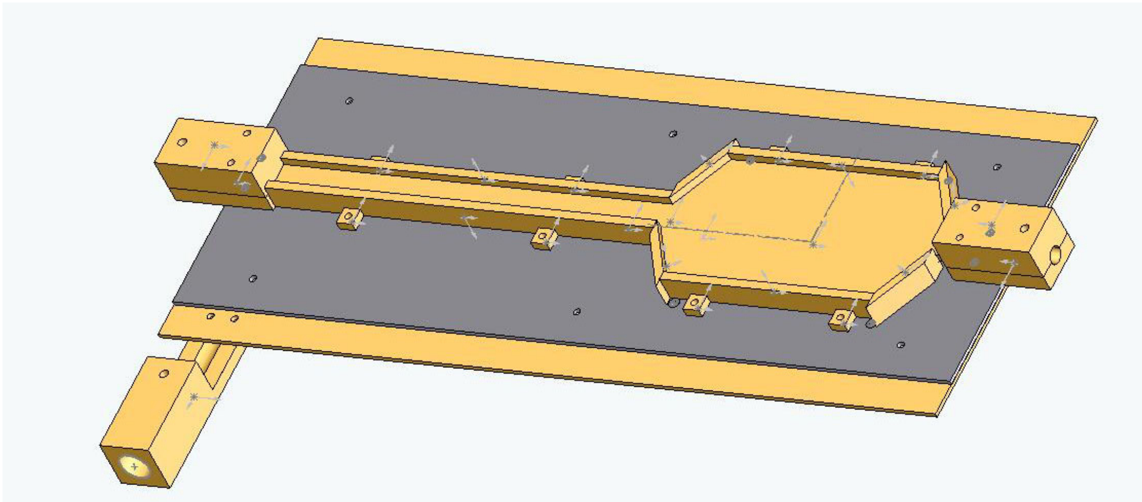

Figure 5.15 Enclosure Design

The prototype was constructed out of polycarbonate and was glued together avoid having to be professionally machined. The final design would require a good deal more precision to ensure the proper contour and a uniform gap between the top and bottom of the tunnel. It would have been difficult and time consuming to create a smooth contour and provide a uniform gap. Redesigning the prototype led to a much more elegant solution which ensured the uniformity of the tunnel height. As shown in figures 5.16, 5.17 and 5.18 a sandwich was made by using three layers of .125in thick static dissipative acrylic. The first layer was a rectangle and acted as the bottom surface for the tunnel, the second layer consisted of many acrylic pieces machined to create the proper contours for the tunnel and viewing area, and the third layer was a machined acrylic sheet that would overlap the second layer. The contours of the second layers were designed to create the desired tunnel shape. By using a sandwich structure the contour of the tunnel could easily be created while ensuring a uniform height throughout. This design also facilitated modification by either modifying or replacing select components resulting in a new contour.

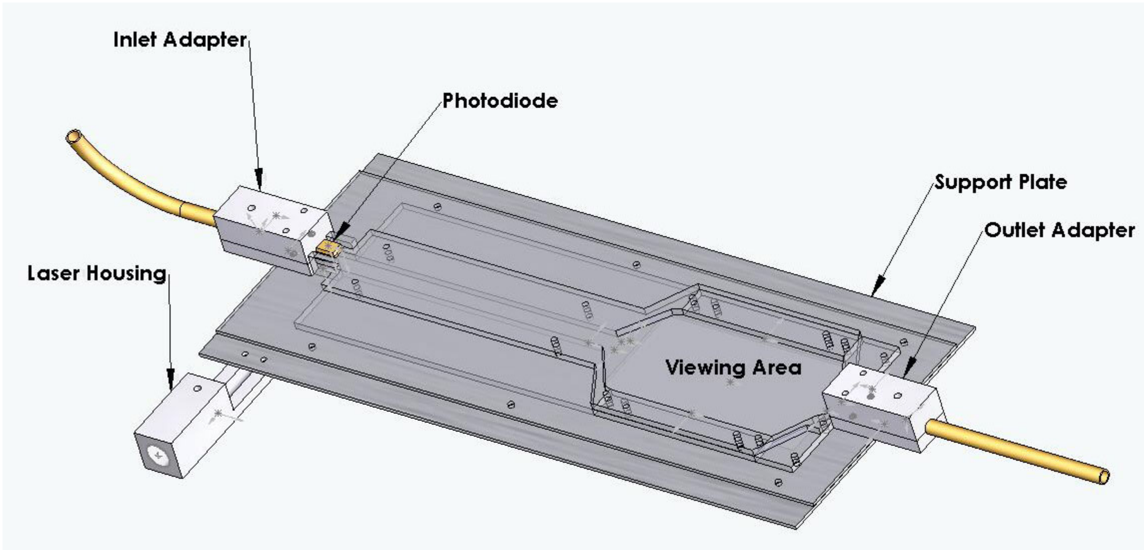

Figure 5.16 Sandwich Design

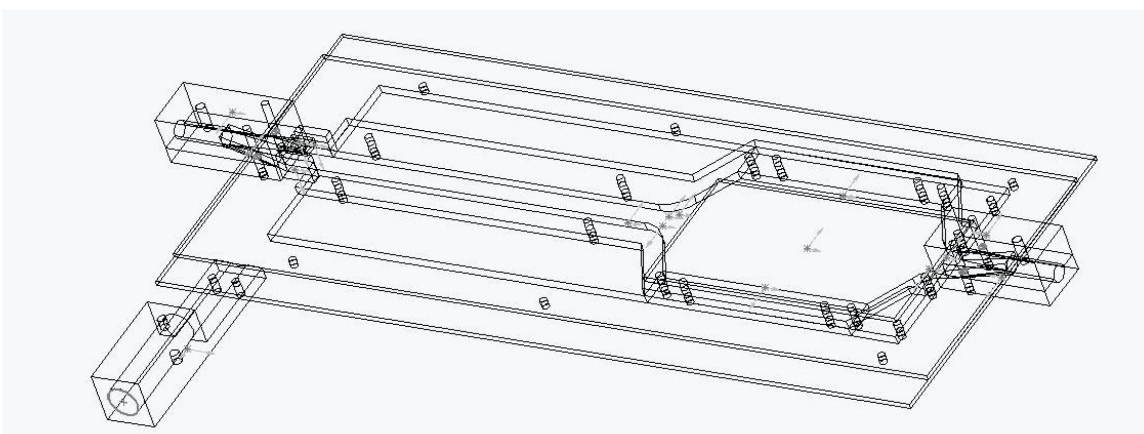

Figure 5.17 Wireframe Sandwich Design

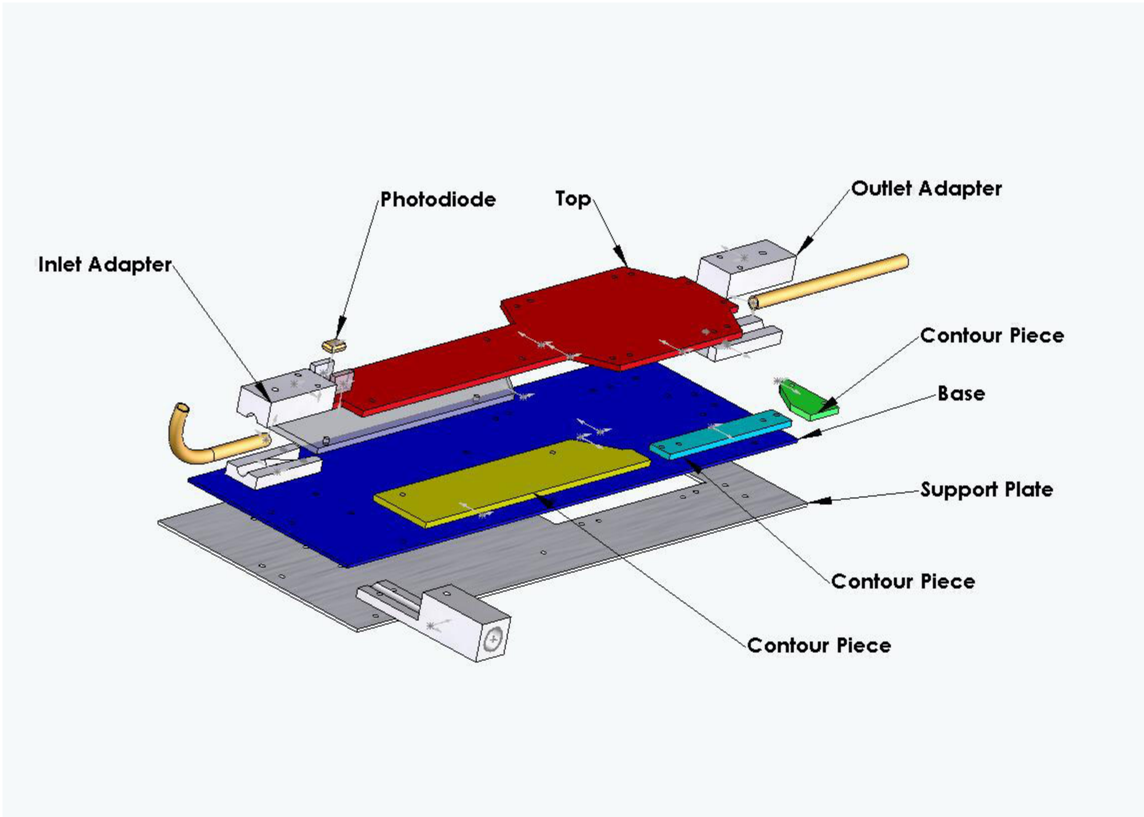

Figure 5.18 Exploded View

The sandwich allowed everything to be bolted together except for the area through which the laser beam would pass. The sandwich method could not be used for this area because the side that was machined would not be clear and would dissipate the laser light. The light would then illuminate the photodiode and make it difficult or impossible to sense passing fibers. Sharp transitions between the entrance tunnel and the viewing area, and the viewing area and the exhaust tunnel were smoothed to try to eliminate any turbulence caused by the sharp edges. The intake and exhaust blocks at the ends consisted of two interlocking pieces that would clamp the tube and channel the air into the gap between the acrylic plates.

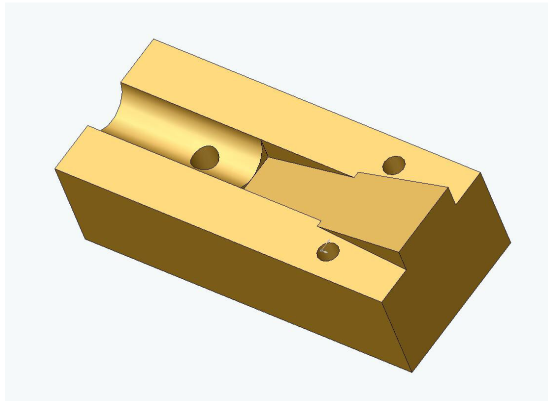

Figure 5.19 Entrance Adapter Top

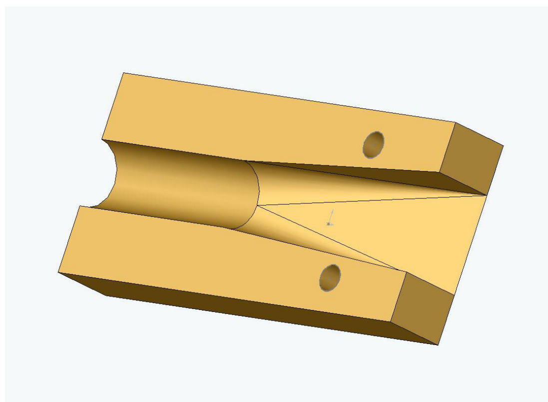

Figure 5.20 Entrance Adapter Bottom

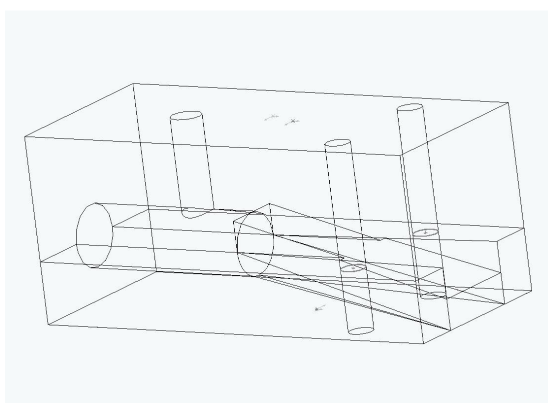

Figure 5.21 Entrance Adapter Wireframe

The design as shown in figures 5.19, 5.20, and 5.21 contained some complex geometry, however the machining was not a problem and only required minor finishing by hand to remove a small amount of material ensuring a smooth path for the fiber. The design provided a smooth transition from the round intake tube to the rectangular tunnel. A smooth transition was important to avoid fiber entanglements or fibers getting stuck which would either increase error due to excess entanglements or cut off flow of the fibers to the viewing area rendering that run useless. Overall, the design was an effective method to deliver fibers to the viewing area in a consistent and controlled manner.

5.2.3.2 Material Selection

When experimenting with preliminary prototypes, a significant number of fibers would stick to the top or bottom of the enclosure due to the static that had developed on the surfaces. This was a major concern for the final design since fibers stuck in the enclosure would cause erroneous readings. This problem had to be completely eliminated for the machine to be successful. By using a static dissipative acrylic for all of the surfaces, the static was eliminated. While slightly more expensive than normal acrylic or polycarbonate the cost was not prohibitive and the material proved to be very effective in reducing static and resulted in the problem being completely eliminated.

It was important to have rigidity so that the input and exhaust tubes could be securely mounted to the enclosure and so all of the plastic enclosure pieces could be bolted tightly together ensuring minimal air leaks. An 1/8" aluminum plate was used as a base to provide sufficient rigidity. Aluminum was chosen because of its ease to machine and ability to provide the rigidity needed.

For the adapter shown in figure 5.19, 5.20, and 5.21 delrin was the material of choice. Strength was not important however cost and ease of machining were considerations. Delrin is relatively inexpensive and was available in stock sizes close to what was needed so it was an easy choice.

5.2.3.3 Final Design Evaluation

The final design was very effective, however, like any design there are opportunities which need to be considered. The first is the tendency for fibers to occasionally get stuck at the end of the intake adapter. The problem appears to be caused by the gap created when the top and the bottom pieces fit together. The fiber enters the gap and the natural crimp of the fiber causes it to become stuck between the two pieces. The fiber will then flutter in and out of the laser constantly triggering the sensor. This eliminates any chance of synchronizing incoming fibers with the camera which causes all subsequent images to be empty. This problem could be fixed by remachining the adapter pieces with a tighter tolerance, or out of a solid piece. A more robust solution would simply be to move the sensor down the path an inch or so. This way even if a fiber did get stuck it would not be able to trigger the camera eliminating the problem. This would require that a few parts be remade and since the problem is not significant there is not an immediate need to make this design change.

Another problem noticed once images were taken and analyzed was a slight increase in blur caused by the acrylic. Images of fibers within the enclosure were compared to images on top of the enclosure and a 1-2 pixel increase in blur was discovered. This blur while slight has an affect on the final data since it only compounds the already low contrast between the fiber and the background caused by the motion of the fibers. The blur is caused by the diffusion of the light passing through the plate and is unavoidable. Glass and polycarbonate were tested as possible replacements for the acrylic but due to static built up on the surfaces, the fibers immediately stuck to the material proving that it would not be a viable solution.

The final design effectively solved all of the problems associated with controlling individual cotton fibers and delivering them first past a sensor and into a viewing area in a continuous and repeatable manner. The dimensions of the enclosure ensured the fiber would be controlled and not allowed to contact the edges during imaging while ensuring there was ample time between sensing and imaging for the camera to reset itself and capture the image. The materials chosen eliminated static while providing the clearest image possible to increase the chance of accurate software analysis. The overall design was simple and easy to build and modify while solving the major design criterion associated with the problem.

5.3 Light Source

The backlighting configuration chosen in the final design requires a uniform, strobing light source to provide illumination resulting in a high contrast silhouette of the fiber, optimizing the image for processing. The ability to strobe is required to freeze the motion of the fiber eliminating blur and resulting in a clear image. The camera must trigger the light source in order to synchronize its shutter and the light so that the image is captured when light is triggered and a fiber is present in the viewing area.

5.3.1 Method

There are essentially two possibilities when selecting a strobing light source. LED arrays are commonly used because they can be triggered and can provide uniform light for short durations. Xenon strobes are also a possibility, providing high intensity short duration flashes. The duration of the strobe and the intensity of the light are related in that the shorter the duration of the strobe the lower its intensity. The imaging chip on the camera has 6.6 million photodetectors with each photodetector representing a pixel in the image. When the shutter opens, or in the case of a digital camera, each photodetector is reset and allowed to react to the light reaching it, a voltage proportional to the light at that photodetector is created. At the end of the integration period (when the shutter closes) the camera reads the voltage from each photodetector and relates it to a pixel value between 0 and 255, 0 being black meaning no light reached the pixel and 255 being white meaning that the pixel was saturated with light. If the strobe light is only on for a fraction of the shutter speed of the camera, the only light reaching the camera during the exposure time is that from the strobe along with a small amount of ambient light. Ambient light is reduced and the remaining light reaching the camera is insignificant when compared to the intensity of the strobe. If the strobe has a very short duration, the fiber in the image will only move a very short distance during the time the light is on, creating an image in which the fiber appears to be stationary. Even though the fiber continues moving after the flash no more light reaches the camera and the pixel values remain unchanged. If the strobe duration is too short, or the intensity too low, not enough light will reach the camera causing the image to appear very dark. The goal is to maximize the intensity and minimize the strobe duration while maintaining the ability to precisely control the strobe and provide a uniform background.

5.3.2 Existing LED Backlight

The original machine used an LED backlight array with a diffuse plate to ensure a uniform background. The LED array was made by CCS and the duration and intensity of the strobe were controlled using a controller which could either strobe at a set interval or be triggered using an external source. The controller would be triggered by the camera and could be set to keep the light on between 1μs and 99μs.

Tests with the existing strobe showed good results using 50µs to 60µs strobe duration. The images were clear enough to visually inspect but the intensity suffered in the quest for shorter duration and were not able to be processed effectively using the existing software. A thorough search of commercially available backlights was performed and little practical information about luminous intensity could be obtained. Since it was difficult to compare the brightness of the lights and the lights were rather costly, deciding on one was difficult and there was uncertainty as to whether the purchase would lead to the required increase in intensity.

5.3.3 Ultra bright Led Array

To solve the intensity problem, a custom light array was designed and built to provide the required intensity while maintaining the short durations necessary to eliminate blur. LED's were the focus of the search for a new backlight due to many positive attributes. LED's are commonly used in both front and backlighting for machine vision applications and have a very long life. LED's also provide a low voltage and low current lighting solution which simplifies the design while also increasing safety by not using high voltage or high current. Finally and most importantly LED's can be strobed very fast which ideally suits the current application. A search for ultrabright LED's was performed and the Luminex Emitter III was clearly brighter than any other LED's commercially available.

5.3.3.1 Theory

The Luminex Emitter III was available in a variety of wavelengths so special care was taken to purchase the LED which would emit a wavelength closest to the maximum spectral response of the camera (Figure 5.22).

Figure 5.22 Camera Spectral Response [25]

As seen in the graph the highest spectral response occurs at a wavelength of 630nm which fortunately is a wavelength of light that could be chosen for the LED's. The difficulty with creating an LED array is ensuring that it provides a uniform background for the fiber. If the background is not uniform it is difficult to analyze the image. By using a current limiting LED driver, the current through one or a series of LED's remains the same while the voltage is changed depending on the number of LED's being driven, ensuring a uniform intensity from all LED's on the circuit. The recommended driver was the BuckPuck which could drive 3 LED's in series and allowed for external triggering [1]. The strobe duration was related to the trigger signal in that the light would stay on as long as the signal was high. However, the minimum strobe duration was approximately 50µs which was well within the range determined using the original strobe light. The LED drivers were equipped with a control pin which allowed relatively simple integration of the LED and driver with the camera triggering mechanism using a simple transistor as shown in figure 5.23.

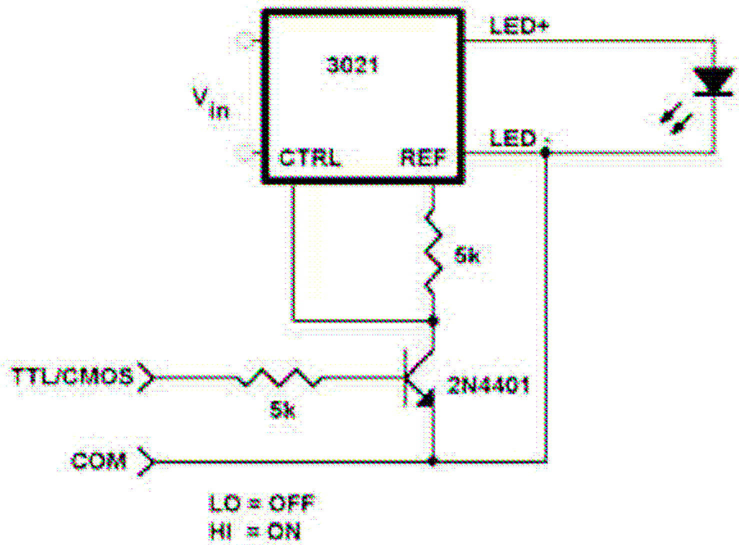

Figure 5.23 LED Driver Circuit [1]

Six LED's were purchased to determine if they would provide the intensity needed for the application and were configured in an arrangement consisting of two rows of three LED's situated one inch apart horizontally and vertically. While the uniformity was satisfactory, the brightness was not, so more LED's were needed. The next trial used eleven LED's to increase the brightness to a level sufficient for analysis. The increase was significant and allowed the fibers to be frozen and analyzed successfully. The LED's were configured as seen below and along with a translucent plate provided a fairly uniform background at the desired intensity. To accurately trigger each light simultaneously, all the drivers needed to be triggered at the same time. Four circuits were built identical to the schematic shown in figure 5.23 and the TTL input for each controller was connected to the TTL output from the camera. By using the output from the camera to trigger each driver the combined current draw was more than the camera could handle. To remedy this problem a single transistor was controlled by the camera and used to provide the input signal to the controllers. This allowed the triggering circuit to draw very little current from the camera while still simultaneously controlling all of the lights. The background was fairly uniform; however it did not provide the uniformity required for accurate software analysis. To remedy this problem a more LED's would have needed to be purchased and placed in the areas needing increased brightness.

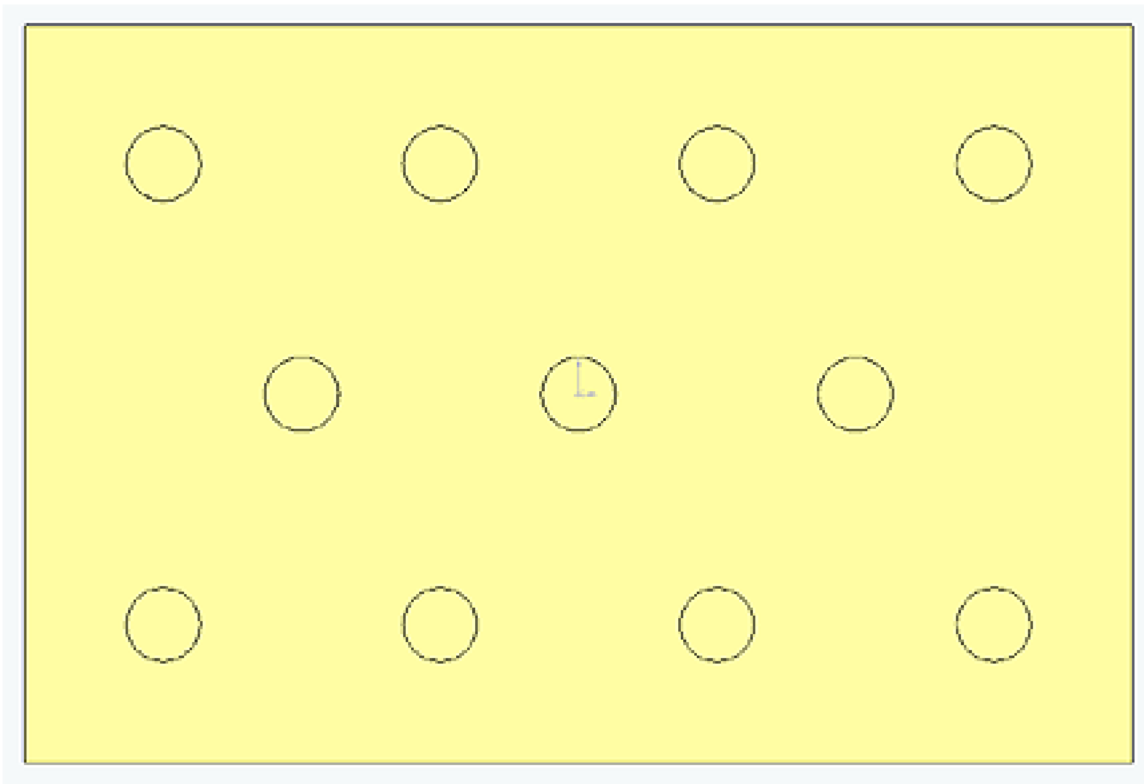

Figure 5.24 LED Array Design

Tests were run with the new light source to evaluate the image quality and determine if more time and money should be invested.

5.3.3.2 Ultra bright Led Array Feasibility

The first images showed significant blur in the areas of the fiber that are perpendicular to the direction of travel. This problem was initially attributed to camera focus, and excessive fiber speed, and thus more tests were run to attempt to refine the settings and achieve a better image. The focus was precisely set with the use of a long yarn, which could be inserted and held in place inside the viewing area. This allowed the camera to be focused in the plane between the two plates ensuring the best image possible. Adjusting the fiber speed was not as simple as the focus in that if the fibers go to fast they create a blurry image and if they go to slow they will get stuck in the duct and throw off readings of subsequent images. The suction used to move the fibers is created through the use of a venturi, and is adjusted with a simple regulator, which adjusts the input pressure to the venturi. The gauge on the regulator is designed for use with air tools and therefore is more suited to regulating higher pressures. To create the low speeds desirable for viewing fibers, very low pressures are needed and the gauge will not register such small pressures and therefore cannot be relied on for any sort of readings. In order to analyze the image quality under different conditions, an accurate value for the speed of the fibers was needed. Since a delay time is needed to capture the fiber in the image and the fiber travels a known distance between the sensor and the viewing area, the speed of the fiber can easily be calculated. The resolution of the image can be calculated by placing an object of known length into the image and counting the pixels between the two end points. Once these two values are known, along with the strobes expected duration, the theoretical blur can be calculated. Preliminary calculations yielded a theoretical blur of about 3 pixels which was significantly less than the 10 to 15 pixel blur actually present in the image. Blur was calculated by determining the width of the blurred fiber and then subtracting the average thickness for a non blurred fiber. Actual and theoretical values conflicting on the order of 3 to 5 times indicated that there was significant error.

5.3.3.3 Analysis

An experiment was designed to isolate the problem. The experiment consisted of taking multiple pictures of fibers traveling at 2 distinctly different speeds, determining the actual blur, and calculating the expected blur. The first run captured 8 images at a faster speed using a delay of .03s. The second run was conducted with a delay time of .043s. By choosing different speeds and keeping all other variables constant, the error could be isolated. Each image taken for each time was manually analyzed, and the width of the sections of fibers perpendicular to the direction of the fiber was determined by simply counting the pixels. Care was taken to analyze the images consistently in order to minimize variation caused by human error. Fifteen values were gathered from each group of samples and average values were used for calculations. The blur value was the average width in pixels of the blurred fiber minus the average width of a clear fiber, which was about 4 pixels. For the fast samples the blur was found to be 17.07 pixels while for the slower samples the blur was found to be 11.79 pixels.

Table 5.1 Fiber Speed Calculations

.030 Delay (Fast Speed)		.043 Delay (Slow Speed)		Resolution (Pixels/in)
				1148
blurred area	21.07	blurred area	15.79	
pixels moved	17.07	pixels moved	11.79	**Flash Speed (Assumed)**
				0.00001
Speed based on Flash speed		**Speed based on Flash speed**		
1486.64	in/s	1026.63	in/s	
Speed Based on Delay Time		**Speed Based on Delay Time**		
250	in/s	174.4186	in/s	
Difference		**Difference**		
5.946574	x	5.886013	x	
Expected Blur (Pixels)		**Expected Blur (Pixels)**		
2.87		2.002326		
Difference		**Difference**		
5.946574	x	5.886013	x	
Actual Flash Speed		**Actual Flash Speed**		**% Error**
0.0000595		0.0000589		1.02%

The next calculations were aimed at calculating the velocity of the fibers using two different means, the first being the flash speed and the second being the delay time. If the flash duration was actually .00001s the fibers would need to travel 1486.64 in/s or 1026.63 in/s respectively to achieve the amount of blur found on the fibers. The actual speed of the fibers calculated using the camera delay and the distance traveled was 250 in/s and 174.42 in/s respectively. If the actual strobe duration was equal to the theoretical the calculated speeds should be the same. In both cases the speed based on the flash speed was about six times greater than the speed based on the delay time indicating that either strobe duration or camera delay time is incorrect. Since delay time is directly controlled by the camera it is unlikely that it is the cause of the error and therefore it is reasonable to attribute the error to the strobe. Separately calculating the actual flash speed based on the values collected from each run of the experiment yields approximately the same value, .0000595s for a delay time of .030s and .0000589s for the .043s delay time. There is only a 1.02% error between two values calculated from different fibers traveling different speeds. The error is attributed primarily to manually counting the blurred pixels, but may also be caused by some slight variation in the actual strobe duration. A value of .000059s is significantly different value than the .00001s flash time that was set through the camera. The reason for the discrepancy is the driver used to provide a constant current source to the LED's. When the drivers were purchased a minimum strobe duration of .000050 s - .000060 s was the target value and the .000050s minimum strobe duration of the driver was adequate and not a concern. However it has been proven that a strobe time of .000050s is far too long and needs to be reduced.

The initial target strobe duration was determined by placing fibers into the airstream by hand and allowing the suction to pull them through the system. The feeding of the fibers was then automated by implementing a comber roll to individualize and introduce fibers into the system. The comber roll individualizes the fibers and blows them into the suction tube. The air being blown into the tube significantly increases the speed of the fibers. The increased speed of the fibers due to the comber roll was not considered during initial testing because it was thought to be negligible. Since the comber roll is needed to individualize and introduce fibers it cannot be eliminated leaving the strobe duration to be reduced in order to eliminate the blur.

5.3.4 Xenon Strobe

A new lighting approach was needed and the focus shifted from LED's to xenon strobes which are frequently used in high speed photography because of their high intensity and short durations. An internet search was performed to find a suitable light source which would provide the desired brightness, duration, and triggering ability. There were many options, however all were rather expensive and provided more features than what was needed for the application. Since building a strobe is rather simple and plans are readily available online building one proved to be an economical option.

5.3.4.1 Theory

The solution was to use a combination of circuit plans to build a strobe that would provide the necessary intensity and for the required duration, when triggered by the camera (shown in figure 5.25). The core of the circuit is two large capacitors and two diodes configured as a voltage multiplier to ramp up the input voltage of 120 VAC up to about 300V DC and provide the primary power source for the strobe. The duration of the flash is related to the size of the capacitors in the circuit: smaller capacitors allow for shorter flash durations, however, smaller capacitors do not store as much charge and therefore create a less intense flash resulting in an image of insufficient quality for the software to effectively analyze. The key was to choose the largest capacitor that would not blur the fibers beyond what the software could analyze. The strobe is triggered using a capacitor to drive a trigger coil, which is triggered using a silicone controlled rectifier (SCR) coupled to an optoisolator and a transistor. The trigger coil is simply a transformer used to increase the voltage to approximately 4kV which is needed to ionize the gas in the strobe tube and allow the current to flow between the anode and the cathode causing the flash. The SCR functions like a transistor and allows high voltages to be switched on and off accommodating the high voltages needed to operate the trigger coil. An optoisolator was used to eliminate the possibility of damaging the low voltage circuitry on the camera side. An optoisolator is an LED and a photodiode combined into one integrated circuit allowing light to connect two electrical circuits eliminating any chance of damaging the camera. The transistor was used to trigger the optoisolator, which in turn triggers the SCR, which then switches on the trigger coil at which point the gas is ionized, increasing its conductivity, and causing the capacitors to discharge across the gap causing a flash. Theoretically, the capacitors could be continually decreased to decrease the flash time, however this was only realized to a certain degree. The first capacitors used were 22µf, which worked well causing a bright flash however the flash was too long and the images were blurry. The next capacitors were 4.7µf which proved to decrease the flash duration along with the intensity of the flash. The blur was decreased a noticeable amount and the intensity was still at an acceptable level. While the blur was reduced it was still a problem and more experimentation was needed. A 2.2µf capacitor was chosen next to try and further reduce the strobe duration. To increase the intensity a circuit was built that would trigger two strobe lights simultaneously to ensure a bright uniform image. The circuit was essentially two independent strobe lights running off the same power source and triggered by the same trigger coil. Any delay between the two strobes would cause the background of the image not be uniform and impossible to analyze. By combining two strobes using smaller capacitors the intensity was not decreased significantly and the duration was decreased to approximately 6µs which is sufficient for quality images [6, 13].

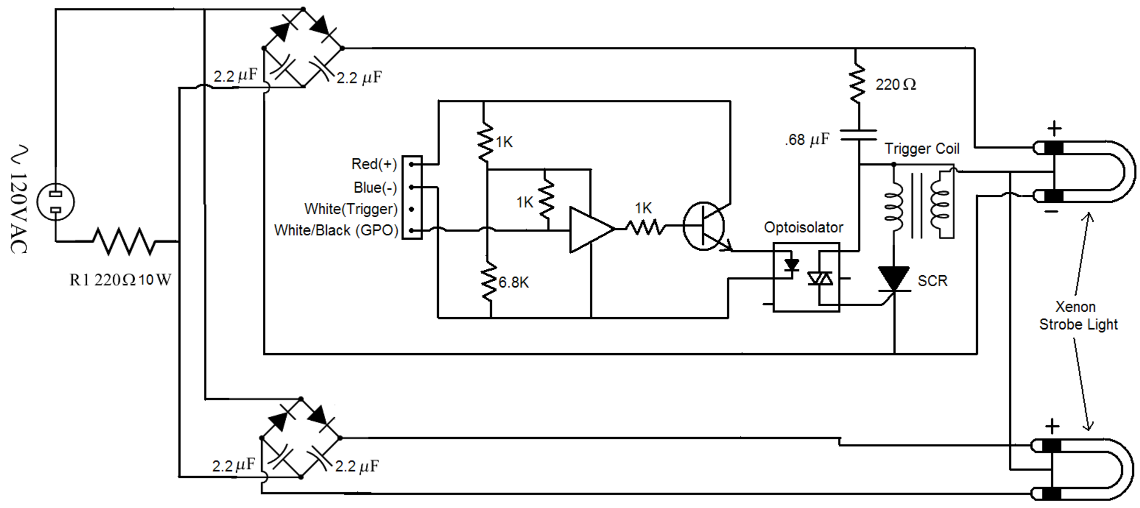

Figure 5.25 Xenon Strobe Circuit Diagram

5.3.4.2 Xenon Strobe Feasibility

The xenon strobe effectively provided a short duration flash that could “freeze” moving fibers allowing a clear image to be captured. However, despite the overall success of the strobe there were some problems that while not immediately significant, would need to be remedied. The first problem is a slight variation in intensity from flash to flash. The software can easily compensate for the variation by thresholding the image based on the average grey value for that image. Even though the software could compensate there is an optimal intensity that will provide the best contrast between the fiber and the background. If the image is too dark the fiber can not be distinguished and if it is too light the fiber gets washed out and portions of the fiber are not visible.

After significant use, the trigger coil used to ionize the gas within the xenon strobe bulb begins to wear out. This has the affect of causing the strobe not to fire when it is triggered resulting in a completely black image. The trigger coils are not expensive and for the current prototype, replacing the trigger coil after a couple months of use is acceptable.

The primary problem with the xenon strobe is the strobe duration. While this is by far the most effective lighting system yet attempted there is still blur in some images that limits the software's ability to analyze the image.

5.3.4.3 Analysis

The xenon strobe light configured with two strobe bulbs along with smaller capacitors was an effective method of providing short duration high intensity flashes for backlighting the images. The inexpensive and easily customizable xenon strobe was an excellent method of proving the concept of the machine without having to test multiple commercially available backlight systems. The actual flash speed could be calculated using the same method used for the ultra bright LED's. The flash speed for the xenon strobe is approximately 6.5 μs which is approximately 7.5 times faster than the ultra brigtht LED's. The xenon strobe significantly decreases the strobe duration while increasing the intensity resulting in far superior images. Even with such a short duration the fibers still blur approximately 4 pixels which results in areas of the fiber that are difficult to effectively analyze. The xenon strobe is definitely the best lighting source for this application, however there is room to improve image quality. The duration of the flash could be reduced by using smaller capacitors at a higher voltage. A xenon strobe light specifically designed for very short flash durations could be purchased and integrated into the system. To achieve less than a pixel of blur a flash duration of about 1μs is required. With this criterion a suitable product could be selected and implemented into the system.

6.0 Camera

The camera is responsible for capturing the image and if the images are not clear the success of the rest of the components is irrelevant. Aside from image quality the camera has a number of other features that are required for successful integration into overall system.

6.1 Required Features

The primary feature required in a camera is high resolution. When analyzing backlit fibers the software is comparing pixels looking for contrast and with higher resolution there will be more pixels in the transition between a fiber and the backgound. With more pixels the pixels of the fiber will not be averaged with the backgound causing a lower pixel value for the center pixels, resulting in easier processing and better results. Since each pixel will be compared to the average for the image the darker the pixels associated with the fiber the better the post thresholding image will be. While the lower resolution image will still be analyzed there will be more broken skeletons causing false fiber length readings. Broken skeletons are areas of the fiber where there is not enough contrast between the fiber and the background resulting in areas of the fiber that show up as background creating multiple fibers where there should only be one.

Figure 6.1 Resolution Example

Figure 6.2 Resolution Example

The camera also needed the capability to be hardware triggered to ensure that the fiber sensor would be able to control the camera. Hardware triggering refers to the ability to either provide a high signal or ground to a wire connected directly to the camera to cause it to capture an image. Software triggering and continuously capturing images are other common configurations for controlling cameras however they are not required for this system. The original system used a camera configured to continuously capture images and proved to be very effective. The fibers were moving much slower and at any given time there were many fibers within the frame. The new system however has a few quickly moving fibers and if the camera were to capture continuously, images would rarely contain fibers. The software trigger could potentially work, however it would require an analog input into the computer which would then need to determine if it is a signal high and then trigger the camera via software. This would require a significant amount of software integration along with a data acquisition system. While possible it was not practical and while software and continuous triggering may be beneficial for testing purposes hardware triggering is necessary to successfully integrate the camera into the system.

Another feature integral to the successful design of the machine was a camera output signal. The output signal is used to trigger the strobe from the camera which simplifies integration of sensor, camera, and strobe because all timing can be precisely controlled through the cameras software.

6.2 Camera Integration

The camera was designed to be easily integrated with external electronics used to both trigger and be triggered by the camera. The camera manual provided connection examples for a variety of situations for both input triggering and output triggering.

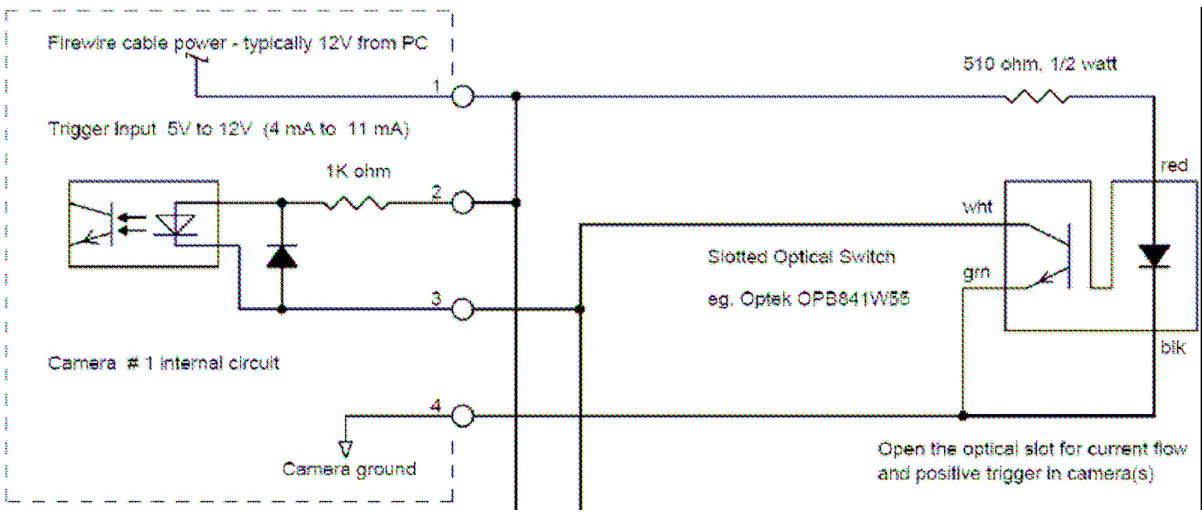

Figure 6.3 Camera Trigger Diagram [25]

Above is the wiring diagram used to control the camera using a phototransistor, however instead of using a photosensitive transistor a regular transistor coupled to the fiber sensor was used as described in the previous section. The above example takes advantage of the negative trigger function in which the camera will trigger when the signal goes from high to low. The fiber sensor provides a high signal when a fiber is present and the positive trigger function was used to trigger on a low to high transition.

Not only can an external circuit control when the camera captures an image but the camera can be used to output a signal used to strobe a light. The following circuit uses an inverter and a resistor to create a logic high voltage, which is used to switch a transistor.

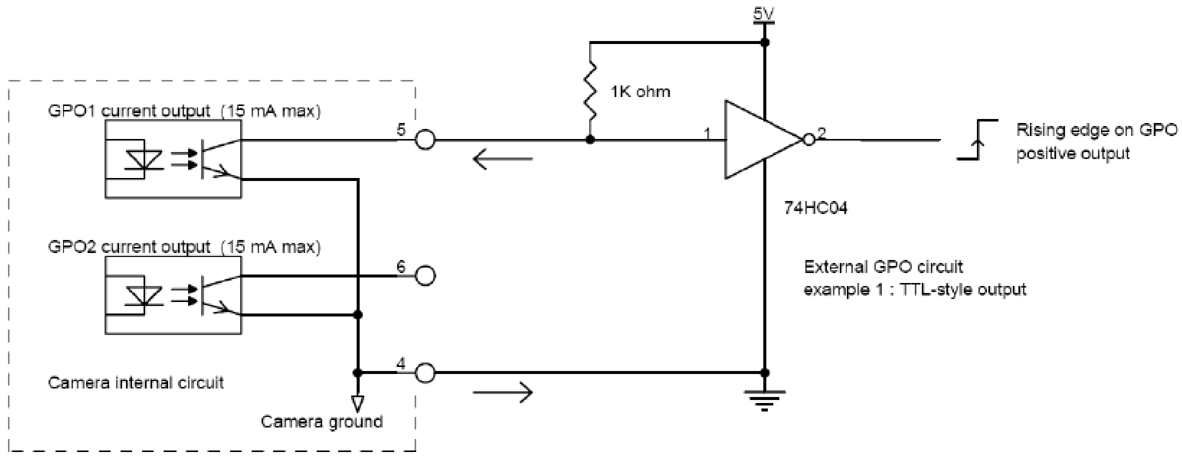

Figure 6.4 Camera GPO Diagram [25]

The transistor then triggers an optoisolator and then that in turn controls the strobe light. By using the camera to control the strobe light the timing can be precisely set allowing the camera, light, and fiber to be synchronized allowing there to be a fiber in the field of view each time an image is captured.

6.3 Conclusion

The camera is perhaps the most important component of the machine and not only are the features mentioned critical but image quality is crucial as well. Many cameras commercially available meet the above criterion and few differences exist between them. Once all criterion were met the deciding factor came down to cost. The Pixelink PL-A781 was the camera of choice due to its ability to satisfy all the needs of the machine while remaining relatively cost effective when compared to other similar cameras.

7.0 Software

The existing analysis software allowed the image to be captured and analyzed to return the lengths of the individual fibers in the image. Many of the pre-existing algorithms could be applied to the new system however many also required modification and even then new algorithms were still needed. The visual interface controlled the analysis software calling the functions to operate the camera and extract the lengths of the fibers from the image. The visual interface then displayed the data in graphical form and performed a number of important statistics to describe the sample. Samples were saved to a database and made available through the visual interface for review.

7.1 Existing Software

The existing fiber analysis software was very effective in analyzing captured images and determining their lengths. However, while effective, the software was designed specifically for the old machine and could not effectively analyze images from the new system.

The software first thresholds the image based on an average pixel value of the image. Each pixel would be compared to the average pixel value plus or minus a pre determined value based on the contrast between the fibers and the background and turned black if the pixel was greater (lighter) than the threshold value and white if the pixel is less (darker) than the threshold value. This process results in an image that is completely black and white where the background is black and the fiber is white.

Next the image was thinned to decrease the width of the fiber to one pixel for the entirety of its length. By ensuring the fiber was a single pixel wide other assumptions could be made simplifying further processing. Many fibers were single and elongated but some overlapped the belt or crossed over each other. By counting the ends for each fiber crossovers could be approximated or one fiber attached to the belt in a u shape appearing as two fibers could be connected. While not perfect the approximations were better than if no attempt were made to compensate for the error.

When a fiber is thinned areas where noise was near the fiber or areas of blur around the fibers sometimes create nubs, or small "hairs" coming from the sides of the fiber. These nubs not only would create erroneous length readings but would make fixing any of the crossovers or u-shapes impossible. An algorithm identified the nubs and removed them by first identifying places where a pixel has 3 neighbors indicating a nub. Then the algorithm counts out and if the nub is longer than a set number of pixels it is treated as a crossover and if it is less it is a nub and is removed.

Once all of the nubs are removed the fiber is ready to be outlined to determine the length. An algorithm searches the image for a fiber and when a fiber is found the algorithm walks around the perimeter of the fiber. Each pixel is counted with a vertical or horizontal movement counting as 1 and a diagonal movement counting as 1.41. When the algorithm returns to its starting position it stops and returns the final count of pixels divided by two.

The software is controlled with a visual interface written in visual basic. The visual interface allows the user to set the number of fibers to measure and returns the lengths of the fibers along with various useful statistics. The visual interface links to a DLL (Dynamic Linked Library) which then creates a text file with all of the lengths. The visual interface then reads all of the values from the text file and creates two graphs displaying the lengths and the statistics. The program also allows old data to be recalled and viewed. All of the samples are saved by name in a folder with a name of the date the sample was taken. While an effective method of storing data it limits the amount of useful data that can be saved for each run, and the ease at which it can be recalled.

7.2 New Fiber Analysis Software

Creating the new software began with the same algorithms as the old software used. A number of required changes were known ahead of time but many would need to be assessed as the images were tested.

7.2.1 Image Capture Software

Since a new camera is used the software from the old camera can no longer be used to acquire the images from the camera. All algorithms modify the image in the form of a 2D array. This is a convenient form for an image because it makes visualizing what the code is doing very easy compared to other methods that could be used to store the image. The software must ensure that the image is captured and converted to the form the software is expecting. The software is also used to set all of the features of the camera most importantly the input and output trigger settings and delay times. A number of different functions were created to simplify the task of configuring the settings, and capturing images. Using many different functions would allow the visual interface to call each function to configure different settings. When capturing images the main control function can easily get a new image in the proper form by simply calling the appropriate function.

7.2.2 Image Processing

Once the image is captured and in the proper form the analysis algorithms are called sequentially to process the image. The first algorithm is the thresholding algorithm which remains unchanged from the previous program.

7.2.2.1 Thresholding

Thresholding is used to take an image that consists of 256 different grey levels and convert it into a form that is black and white allowing the subsequent functions to process the image. Many different methods were attempted to improve the results after thresholding and create more accurate length measurements. Global and local thresholding are the two main methods in which to threshold an image.

Local Thresholding

Local thresholding involves averaging the pixels surrounding the pixel of interest and then comparing the pixel of interest to that average plus or minus a predetermined value. This can be performed with the immediate neighbors of the pixel of interest or a block of any size surrounding the pixel. Local thresholding does not produce as much noise as global thresholding and is less sensitive to non-uniform backgrounds. It is difficult to create a perfectly uniform background and local thresholding compensates for the lack of uniformity. The downside is that the processing time is increased significantly especially if a large block of reference pixels is used.

Modified Local Thresholding

The edges of the images were consistently lighter than the overall image and would cause noisy areas around the edges of the image causing analysis problems due to the non-uniformity. A version of local thresholding was implemented to try and compensate for the lighter edges. The algorithm would begin at the outside and precede inward averaging each concentric rectangle and then comparing each pixel on that rectangle to the average. This created an overall more uniform image however on certain images would create faint light and dark rectangles created by large pixel variations at one or two edges of the rectangle. The variations cause as many problems as the bright edges so another method was required.

Fast Fourier Transform

Another attempt to create and ideal post thresholding image was FFT or fast fourier transform. This method was tested using an image processing package that is part of LabView and was extremely successful. LabView allowed the technique to be tested on individual images without any coding, ensuring that the method would be effective. The FFT would be run on the image and then the image would be thresholded using global thresholding. The Fast Fourier Transform filters out high or low frequencies from the image resulting in a smoother image. When thinking of an image in the frequency domain one can visualize the pixel values as points on a graph and as the value of the pixel varies slightly up and down when no fiber is present that is essentially noise.

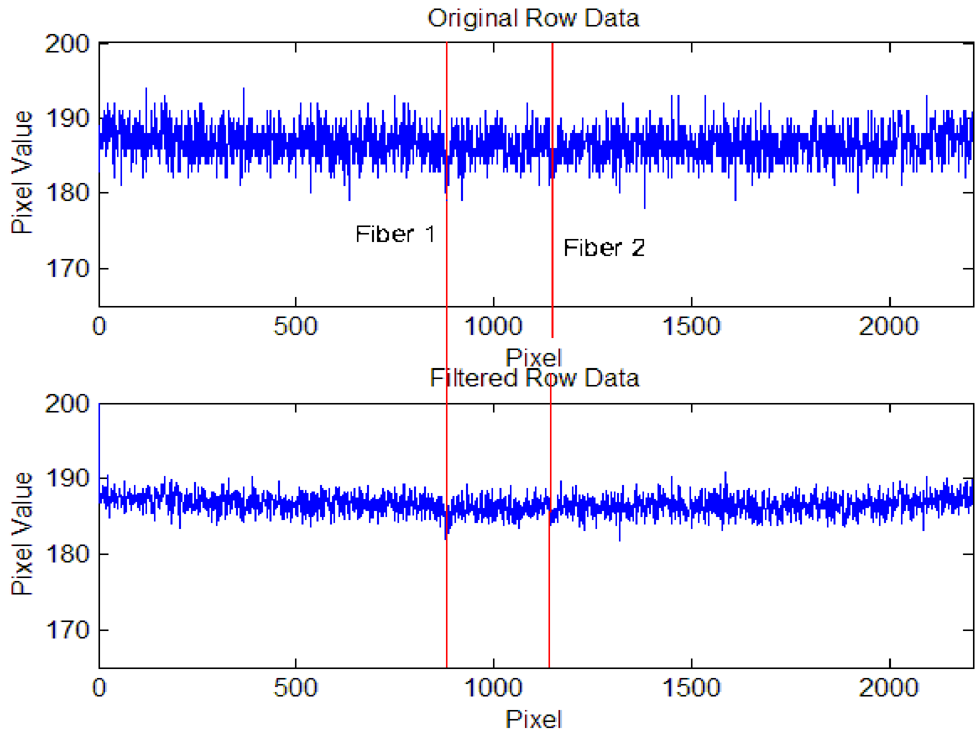

Figure 7.1 FFT Graph

Figure 7.1 shows a row of pixel values along with the same row after filtering using FFT. In this row a fiber exists around 881 and again at 1148 which are shown with the red lines. The changes are also present in the filtered data however much of the noise has been reduced making the change distinguishable from the background noise. This illustrates the effect that the FFT has on the image. Fortunately many FFT algorithms are available for free online in a variety of complexities. While more difficult than initially anticipated an FFT algorithm was eventually implemented and tested as a part of the fiber analysis program. The algorithm performs an FFT in the vertical direction and then again in the horizontal direction. The transformed image can then be filtered to remove the high frequency noise. The inverse FFT is then performed to transform the data back into an image.

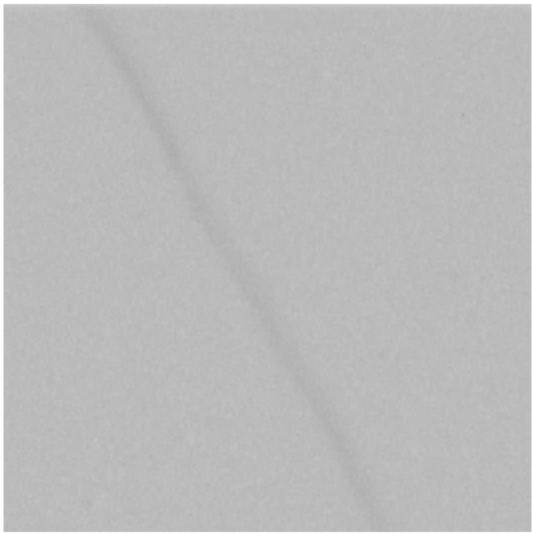

Figure 7.2 Original Image

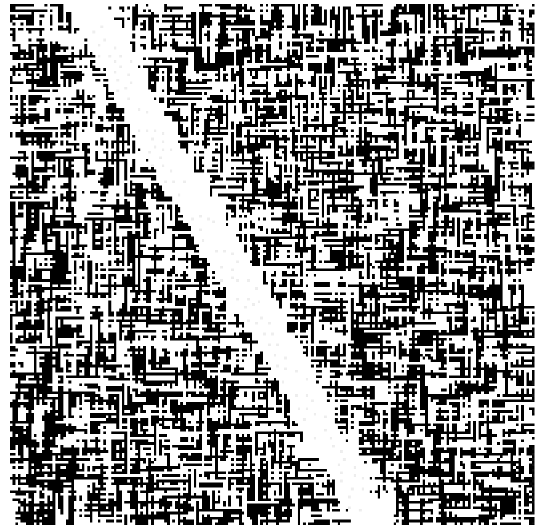

Figure 7.4 Thresholded FFT Image

Figure 7.3 Image Post FFT

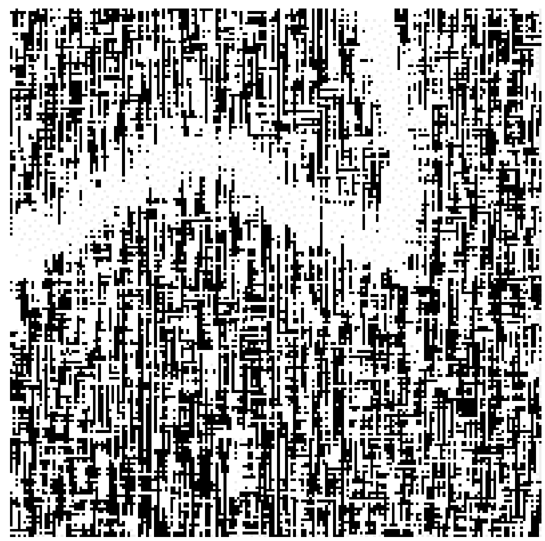

Figure 7.5 Thresholded FFT Image

By filtering noise vertically and then horizontally a cross – hatched pattern was formed on the image. Shown above is an original image and next to it is an image after the FFT has been applied to it. The cross hatch pattern is faint but noticeable, however when the image is thresholded the pattern becomes much more visible as seen in the next two images. The image on the left is quite good with a distinct fiber running through the center of the image. The fiber is thick, has no noise within the fiber and no places which could cause the fiber to become broken during further processing. The right image however appears the same as the left in the background area, and the fiber is still wide and quite distinguishable, however there is noise and areas of possible broken skeletons within the fiber. Both fibers were moving in the direction towards the top of the page and it is evident that the horizontal areas of the fiber are wider and noisier than the vertical areas. This is due to blur caused by the movement of the fiber, and while the fibers are wider at this point there is also less contrast between them and the background. The reduced contrast will create areas of dark within the fibers and often create two fibers instead of one once the image is thinned and outlined.

Consistent image quality was not the only drawback of using FFT to process images. Time is a concern because many samples need to be taken to provide statistically significant results so the faster each sample can be processed the better. FFT is a pretty slow process since it goes through each image twice, once vertically and once horizontally to completely transform the image. Once this is done the same process has to be reversed after filtering. While the processing time would not have been the deciding factor had FFT been very effective, it is however a downside.

All two dimensional FFT transforms require the number of data points to be a power of 2. In all the test cases images of 1024 x 1024 pixels were used however an image from the camera is 3000 x 2208 pixels and a lot of fibers or portions of fibers would be missed of such a small area were used. To use the entire image an array of 4096 x 4096 would need to be created and the image from the camera placed somewhere within that array. The extra pixels would be made zero and have no affect on the final image. Once processing was complete the image would be extracted into a smaller array.

While feasible the 4096 x 4096 would require the computer to process 16.7 million pixels instead of the 6.6 million pixels the current image contains or the 1 million pixels the test image used. This would take a very long time and would begin to be prohibitive.

Conclusion

None of the attempted thresholding methods consistently improved image quality resulting in some images with broken skeletons or additions to the fiber causing erroneous length measurements. All proposed methods increased the time it takes to process an image, and while it was not always a significant increase, any increase is undesirable. When compared to global thresholding none of the methods were dramatically better all around and therefore global thresholding was chosen as the method to use in the final software.

7.2.2.2 Filling

When the images from the new camera were thresholded using global thresholding the contrast between the fiber and the background was not very high and thus limited the quality of the thresholded image. With less contrast between fiber and background there will be significantly more background noise which creates problems for future algorithms. For example if the average pixel value for the entire image is 200 and the average value for a fiber is 180 the cutoff value can be placed at 185 to ensure all fiber pixels are changed to white since they are less than 185 and all background pixels are black since they are greater than 185. Conversely if the average for the image is 200 and the fiber is only 190 the cutoff could be placed at 195 and there is a good chance that many of the background pixels would be below 195 due to non uniformity of the background. This creates a distinct white area where the fiber is located however there is also a significant amount of noise in the background.

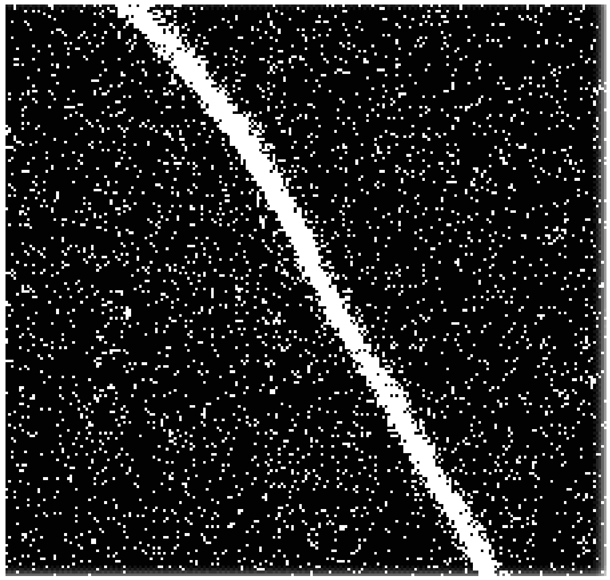

Figure 7.6 Thresholded Image

What also happens is that pixles within the fiber are over the cutoff value and therefore are turned black. This poses a problem during thinning because that section of the fiber cannot be removed and loops are created around the hole, which skew the length measurement. A simple function known as fill can fix both of these problems.

When fill is called it is told which type (white or black) of pixel to search for and how many neighbors of the opposite type it needs before it will be filled in. For example if the function is told to look for a black pixel with 7 white neighbors, the function will search until it finds a black pixel and then count the white neighbors. If the number is greater than or equal to 7 then the pixel is changed to white. This exact situation is used to change pixels within the fiber to white to avoid any measurement error. The same effect can be used to remove noise by searching for white pixels surrounded by black neighbors and then turning them black.

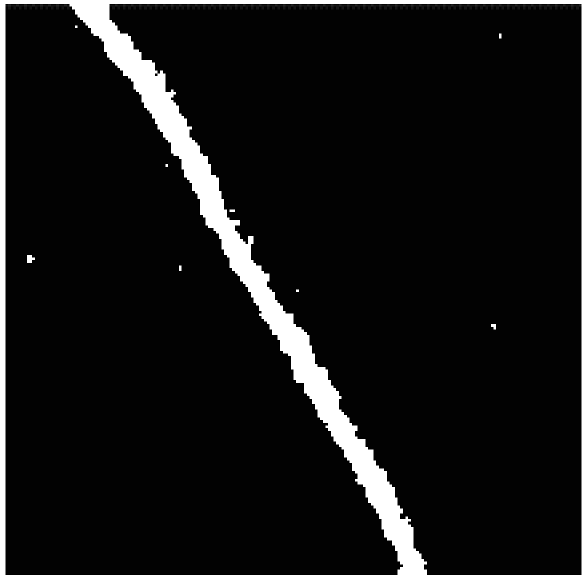

Figure 7.7 Filled Image

This function is very simple and effective in preparing an image for further processing. It can be called many times with varying parameters to create the best final image possible. The function is slow because it has to look at every pixel and then count the neighbors of the ones that it is seaching for. While not optimal, it, along with the global thresholding create the best overall images in a reasonable time.

7.2.2.3 Remove Noise

While filling serves to differentiate the fiber from the background there are still many pixel blocks in the background that are simply noise. The remove noise function remained relatively unchanged from the previous software and is very effective in identifying noise and deleting it from the image. The function searches for white pixels and then maps the size of the pixel block. If the pixel block is larger than a predetermined value it is assumed to be a fiber, and if it is smaller it is assumed to be noise and is removed. The function fairly efficiently removes all noise from the image ensuring that the only white pixels left in the image belong to the fiber.

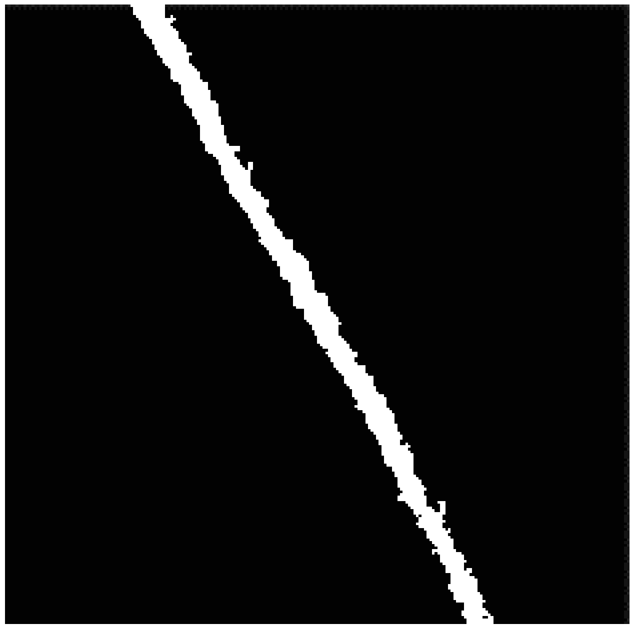

Figure 7.8 Cleaned Image

7.2.2.4 Thinning

Once a fiber has been identified and all noise removed from the background the next step is to thin the fiber so that it is one pixel wide for the entirety of the fiber. The function was modified from its original version to increase speed and efficiency. The function walks around the perimeter of the fiber and for each pixel determines if that pixel can be removed from the fiber. If the pixel can be removed it is deleted and the function moves to the next pixel. If the pixel cannot be removed the pixel is left in place since removing it would cause a broken skeleton.

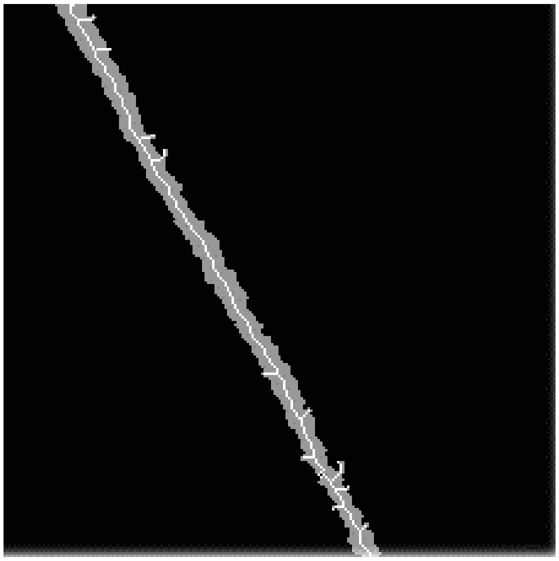

Figure 7.9 Post Thinning Image

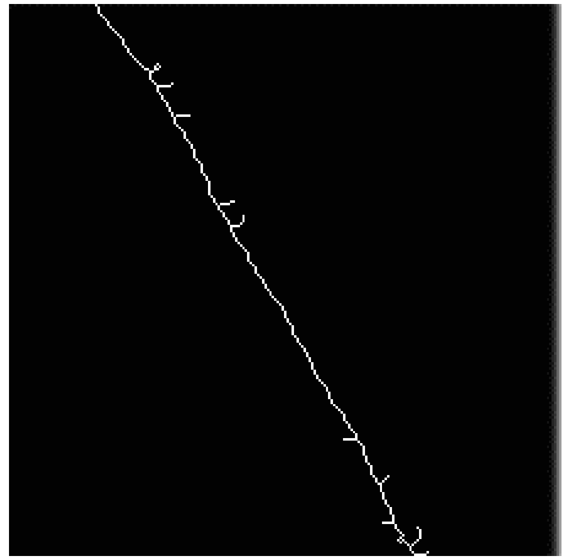

Figure 7.10 Thinned Fiber

The algorithm tends to leave “nubs” or small hairs protruding from the edges of the fiber as it outlines the fibers. This was a problem with the previous system as well, and an existing algorithm removed the “nubs” quite effectively. The same algorithm is used with the current system and has been very successful.

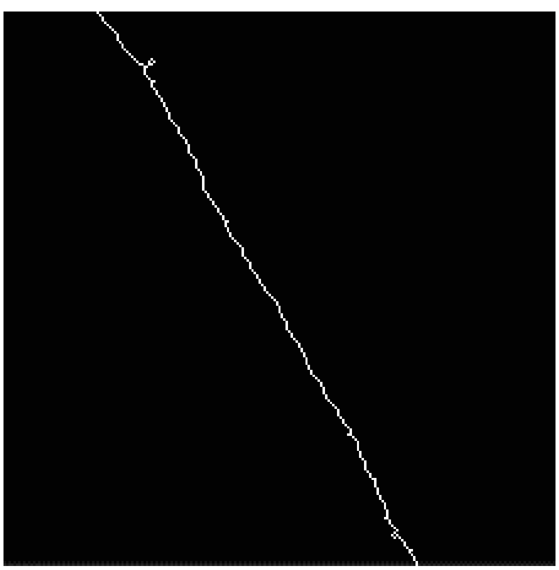

Figure 7.11 Cleaned Image

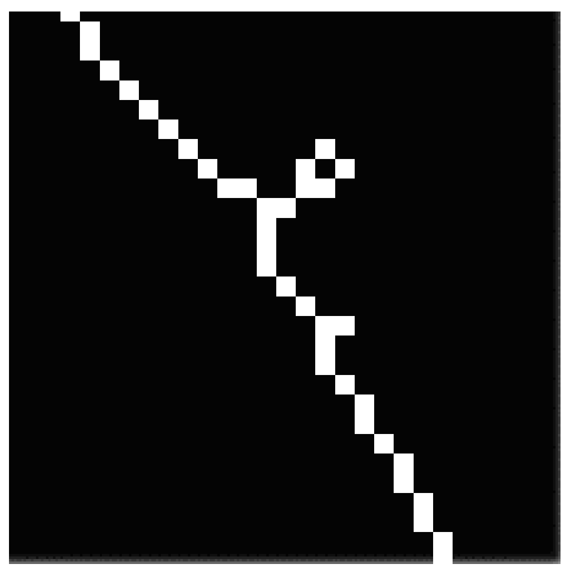

Figure 7.12 Cleaned Close up

The nub remove algorithm will not work on nubs that are also loops which consist of a black pixel surrounded by white pixels and connected to the fiber. This problem is one of the reasons the fill algorithm was created and while it fills most of the black pixels causing the problem, some are either missed or created during to noise removal or thinning so they remain a problem. While not optimal they are not significant and many other forms of error have a far more significant impact on the overall system error.

7.2.2.5 Calculating Fiber Length

The algorithm used to determine the length of the fiber was rewritten due to limited success in applying the original algorithm to the new images. The original algorithm would outline the fiber exactly once and count each pixel as it progressed. Upon returning to the original point it would break out and return the number of pixels counted. The problem was that the new images were not as high quality as the old image and the new ones contained some of the aforementioned loops, which would cause the function to crash the program. This was a continuous problem, and while it would sometimes work it was not consistent and needed to be fixed. Since the exact source of the problem could not be identified a new algorithm was needed.

A simple solution was already available and only needed slight modification. The noise removal algorithm was modified to count pixels instead of deleting them. While it was counting it could differentiate between a horizontal / vertical and a diagonal movement compensating for the 1.41 or $\sqrt{2}$ times length increase of a diagonal movement over a horizontal / vertical movement. This was a simple solution and turned out to be faster and much more effective than the original solution.

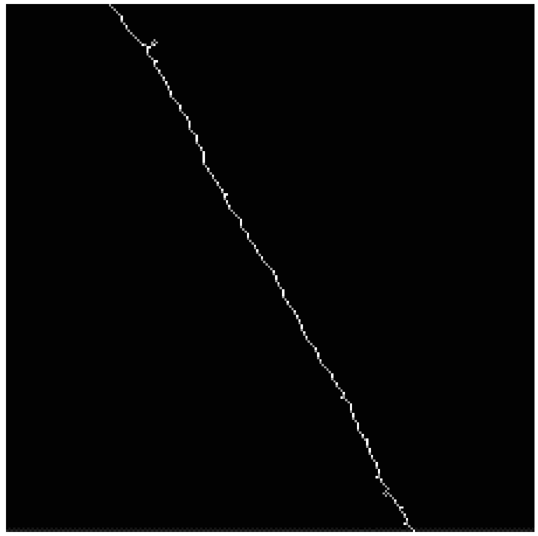

Figure 7.13 Find Length

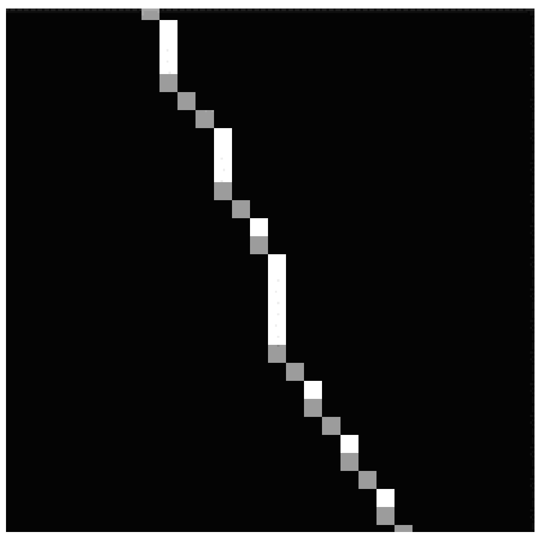

Figure 7.14 Find Length Close Up

The above images show the fiber after the length was determined, both in a close up view and a wide view. The close up view illustrates how the software differentiates between a diagonal movement and a vertical movement, the diagonal being colored grey while the vertical movement remains white. Compared to the previous method of outlining counting the pixels individually is faster, and introduces less error into the system.

7.3 Visual Interface

The software controlling the camera and the fiber analysis software are both written in C and the user must change the code and recompile when settings need to be changed. All output is either written to a file or output directly to the terminal window making collection and analysis of any significant amount of data very difficult and time consuming. This method works well during machine construction and software integration when many settings need to be optomized and data collection is not of interest. However the intent of the machine is to allow a user to measure the lengths of many different fibers and return the data in a format that is easy to analyze, store, and retrieve. A visual interface is needed to take commands, inputs and call all the functions of the machine from a central menu. An interface existed but had some inadequacies and needed to be replaced.

7.3.1 Existing Visual Interface

The original visual interface was written in Visual Basic 6 and provided a menu in which the user could navigate various functions such as running a sample, calibrating the camera, or viewing past data. The software used simple text files saved in dated folders to save the data and allow the data to be recalled. By saving data to text files only the filename, date, and data could easily be saved and all other data would have to be catalogued by hand. This proved inefficient when trying to assess the effectiveness of different changes made on the machine. The current visual interface worked well however with the changes in the analysis software, significant changes would need to be made in the visual interface, however instead of updating the existing software a new program would be written.

7.3.2 New Visual Interface

Visual Basic.net was the language of choice since it is the newest iteration of Visual Basic and the ease at which it allows integration with an MS Access database. The new visual interface was designed to be very similar to the existing software enabling the user to control the machine, camera, and save the data. With the use of an Access database the new software adds the ability to save many parameters not available on the first iteration. By using a database instead of text files to save fiber length data along with information about each sample much more information could be saved and recalled easily.

7.3.2.1 Database Design

The design of the database is a critical aspect of the visual interface since dictates how all the information is linked and recalled. To save all the data efficiently third normal form was used to eliminate data redundancies and ensure that all data is linked correctly. Below is a screenshot showing the organization of the database with each window representing a separate table and the lines showing the links connecting the all of the data.

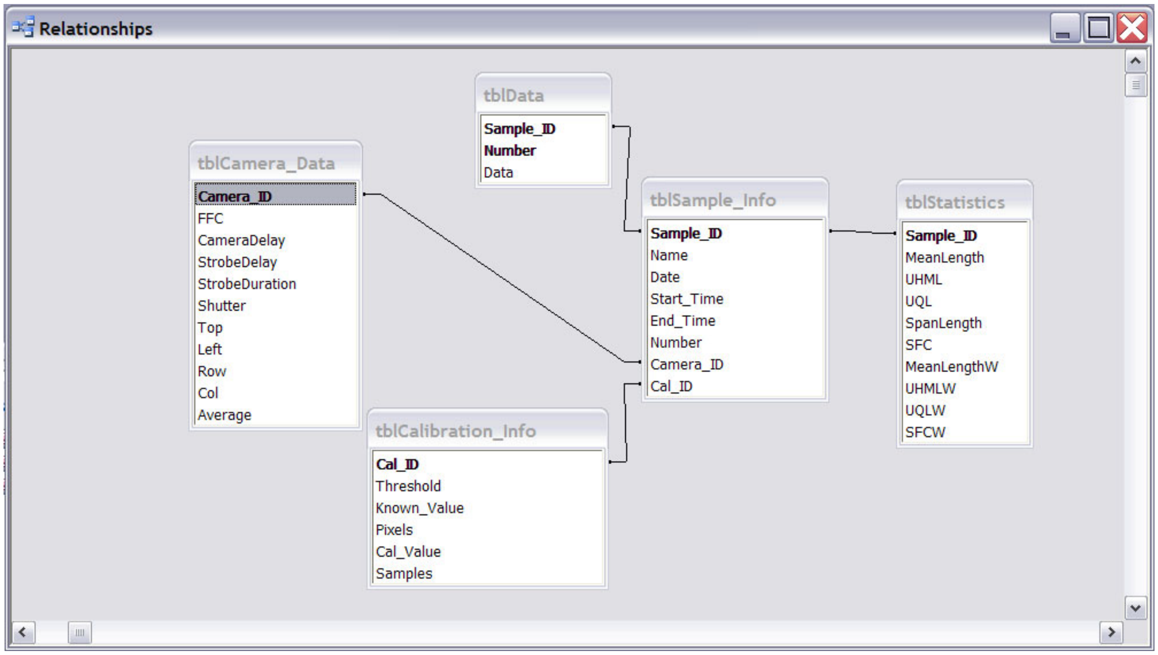

Figure 7.15 Database Design

The main table is the sample info table (tblSample_Info) which stores the Sample ID, name, date, start time, end time, number of samples, camera ID, and calibration ID. The sample ID is an arbitrary number assigned to each sample to ensure every sample has a unique primary key. The sample ID was used instead of asking the user for a unique name to allow the same name to be used multiple times. This was a consideration because it is often convenient to label samples as run1, run2 … instead of having to type a unique while still descriptive name for each sample. The date, start time, and end time are saved automatically when the sample is run and when the sample ends. The date is used when searching, to sort the samples and distinguish between samples which may have the same name. The start and end time are important when comparing the exact time of each run and evaluating different software algorithms in an attempt to optimize time. The number indicates the number of samples acquired during that run, and the calibration ID and camera ID link the sample to the calibration data and camera data used for that run.

The camera data table (tblCamera_Data) stores all of the data required to operate the camera and synchronize the strobe and camera. Most of the parameters will not be changed often however for testing it is helpful to be able to adjust the camera timing and strobe timing to try and optimize the system. All of the data is saved for each run and while most is not crucial the strobe duration, strobe delay, and camera delay are very important in determining image quality at different fiber speeds.

The calibration data table (tblCalibration_info) stores all of the data required to determine the resolution and apply it to a fiber to determine its actual length. The samples, known value, and threshold are all parameters input by the user before the camera is calibrated. The samples are the number of samples taken, the known length is the length of the sample, and the threshold is the value at which the image is thresholded. By averaging the resolution of the samples taken the final resolution in pixels/inch is determined. The data is then saved and the resolution is applied to each sample taken after it is calculated. When the program starts up the resolution defaults to the last resolution calculated and will not change until a new one is determined.

Finally the statistics table (tblStatistics) stores all of the important statistics calculated based on the fiber data. The statistics help describe the sample and enable the user to gather useful information quickly in regards to the quality of the sample. They also allow different runs to be compared to evaluate the accuracy of machine changes.

7.3.2.2 Visual Interface

A visual interface was needed to allow users to easily operate the machine, save data in the database, search, and recall the data for future analysis. The visual interface performs many functions, the most important of which is the ability to control the functions of the camera. Saving a variety of data describing the specific run along with the data itself in a form that can be easily searched and reviewed is another crucial function the software needed to facilitate. Finally ease of use is a concern as confusing menus and complicated controls would make it difficult to run the machine in a laboratory setting.

Menu

The menu is the first screen that opens when the program is started. The menu must be easy to navigate and the controls must be intuitive so that time is not wasted searching for certain items. A MDI Form is used for the menu because it allows a familiar menu bar at the top to be used for navigation. MDI Forms also contain all forms that are open within them so that when the MDI form is closed all windows within it close, saving the user from having to close each form individually. Using a MDI form as a menu also simplifies programming as it is difficult to keep track of different forms when they are not contained within a MDI form. The File tab on the menu bar allows the user to either open the database or exit the program. The last database opened is automatically opened when the program is run, however if a new database is to be used or this is the first time the program is run the user can browse the computer for a suitable database. If no database is loaded the Samples and Settings tabs are disabled and turned grey until a database is selected.

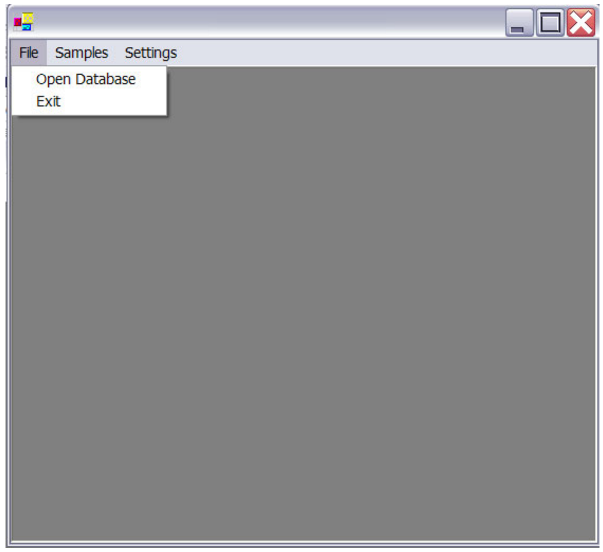

Figure 7.16 Menu

The samples tab allows the user to select if they want to Run Sample or View History which then brings up the respective screen within the MDI form and allows the user to perform the desired function. The settings tab allows for the Camera Settings, Camera Resolution, or Calibrate Camera to be selected, leading the user to the desired form.

Run Sample

The run sample screen allows the user to enter the name of the sample along with selecting the number of fibers to capture in the sample via the sliding bar. The progress bar is meant to display the percentage complete, however due to the way the visual interface interacts with the DLL (Dynamic Linked Library) the progress bar will simply indicate that a sample is being run. When a sample is run the visual basic program calls the main function of the fiber analysis DLL. By compiling the analysis program as a DLL certain functions can be accessed using Visual Basic. The function is passed the number of fiber images to collect and the camera settings. The fiber analysis program then returns an array with all of the lengths collected.

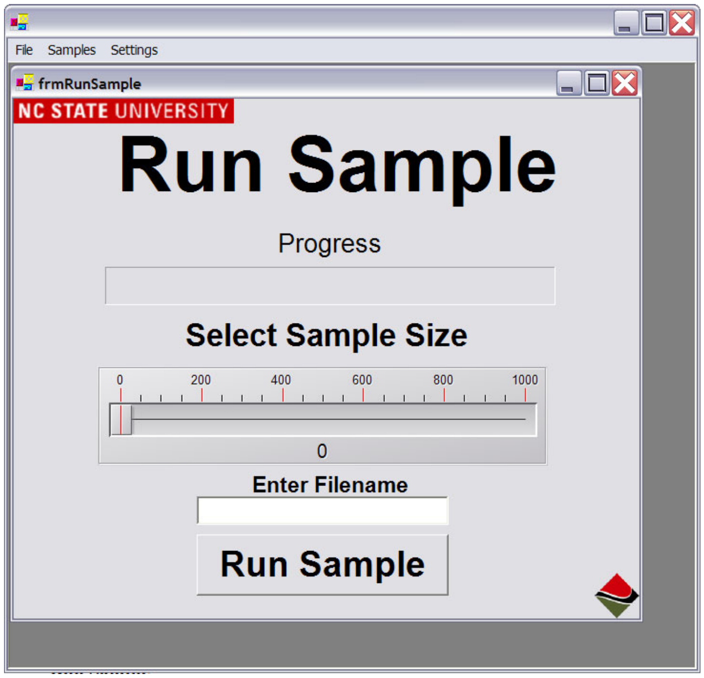

Figure 7.17 View History

Each length could be returned individually, however continually transferring small amounts of data between the programs would be time consuming and inefficient. Once the sample is finished the run sample form is closed and the data is displayed.

View Results

The view results screen displays the data in a histogram and fibrogram along with displaying all the statistics and information about the camera, calibration, and the time it took for the run. The fibrogram simply shows a graphical display of all of the fibers sorted from tallest to shortest. This allows the user to easily look at the data and assess the quality of the sample. The histogram splits the maximum possible length of a fiber into .05 inch bins and displays the number of fibers within each bin.

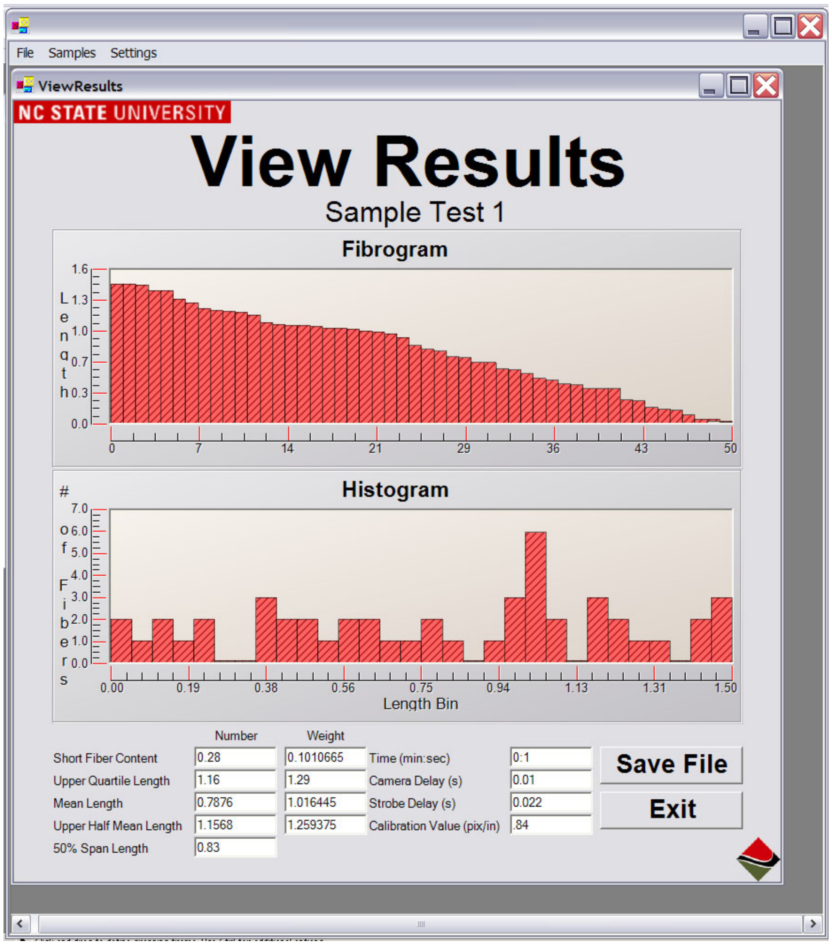

Figure 7.18 Camera Settings

All of the data is already saved in the database, however to simplify comparison of runs the user can save the data to a text file. All information displayed along with the actual fiber lengths are saved to a space delimited text file to allow all of the data to be easily placed into MS Excel for further analysis or comparison.

View History

Saving all the data in a database is useless if there is not a way to easily search and recall a specific sample. The view history screen loads and lists all of the samples in the select sample window by name, date, number of samples in the run, and sample ID. By clicking on a date in the calendar the runs made on that date are listed in the select sample box. All results in the select sample box can be sorted by Name, Date, Number, or Sample Id simply by clicking on the column heading to toggle an ascending or descending sort.

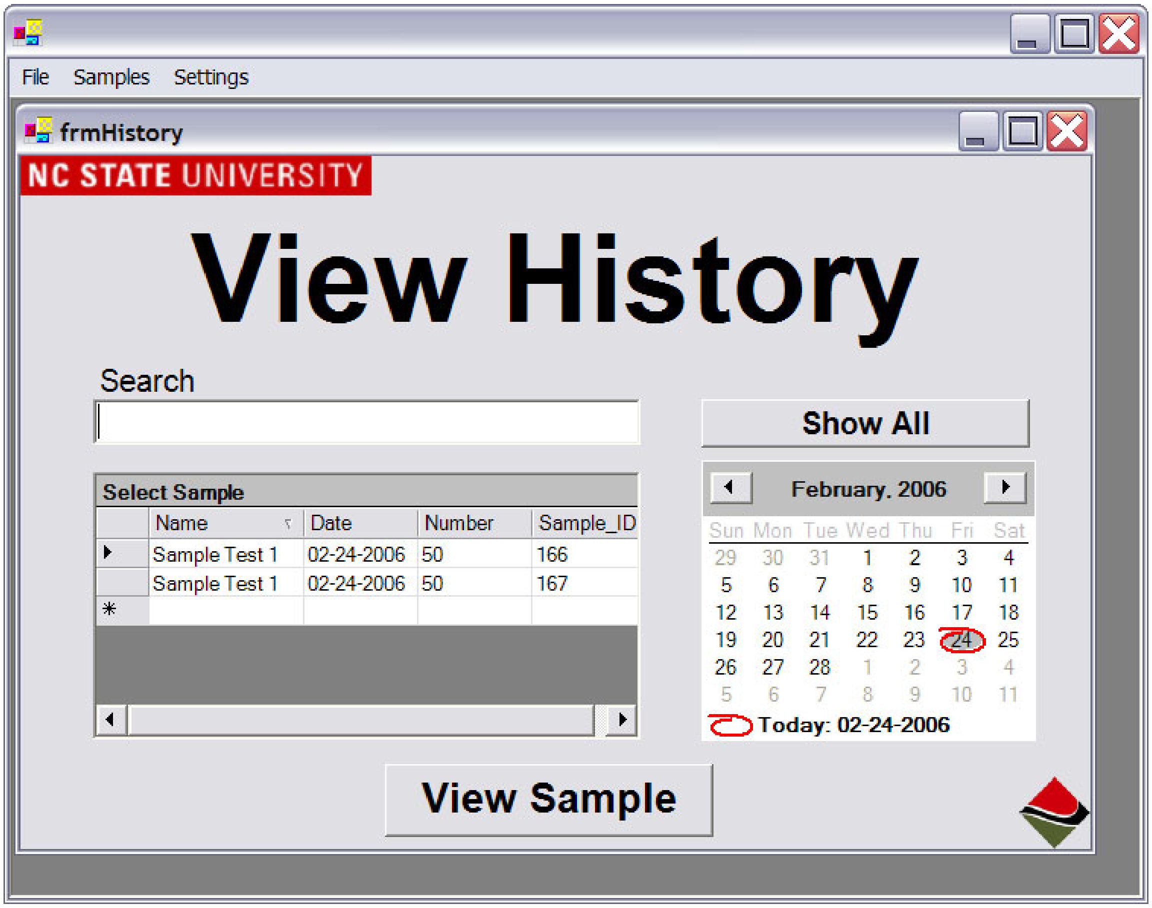

Figure 7.19 Calibrate Camera

The search box allows all of the records to be searched very effectively. Each time a letter or number is entered into the box the select sample box updates with the matching samples. The user can only search based on sample name, and date however sorting by name, date, number or sample ID is always possible. To create the Select Sample view a dataset is used and liked to the proper tables in the selected database. By manipulating SQL queries based on the users input the desired data can quickly and easily be selected and added to the dataset.

Camera Settings

When the program loads the camera settings from the previous run are loaded into a structure to allow the camera settings to be easily accessed by many forms. When the camera settings form is opened the fields are populated with the current settings. The user can then modify the settings and choose to update them.

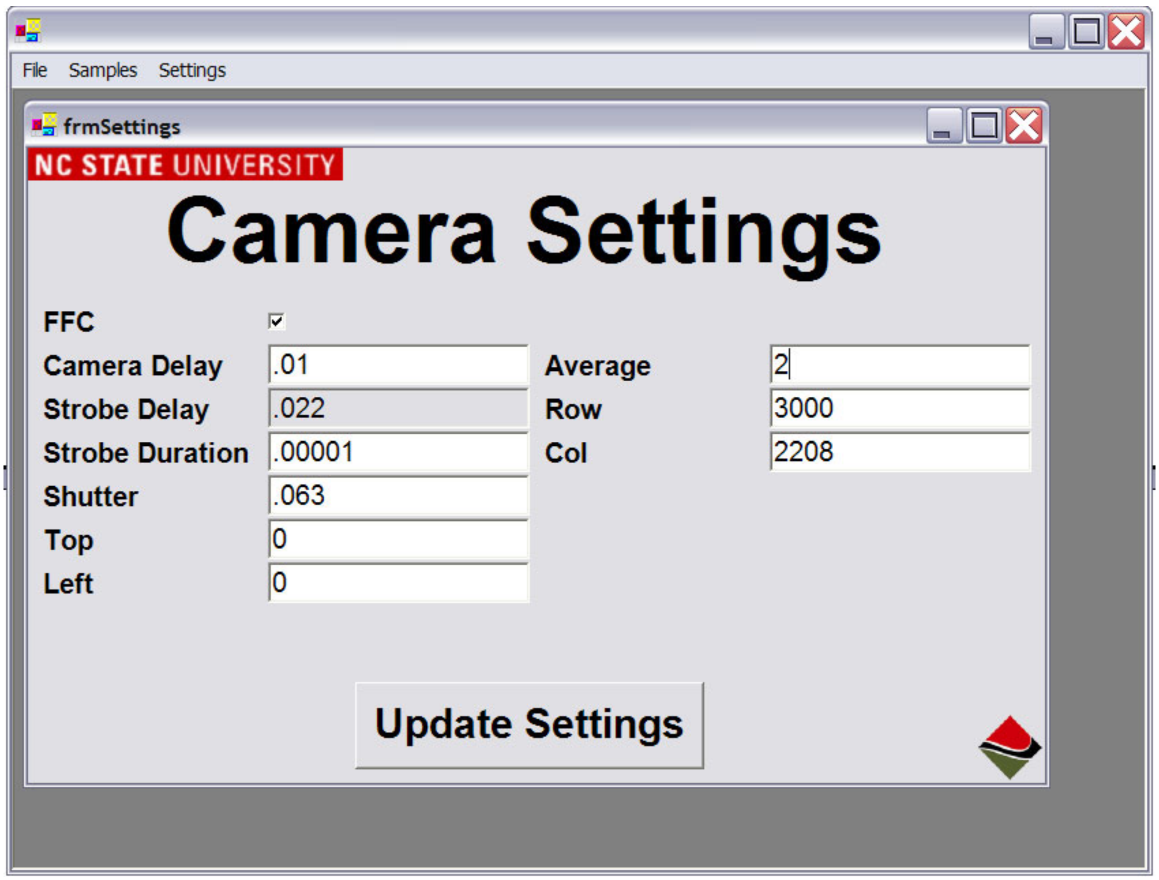

Figure 7.20 Calibrate Resolution

Each time the camera settings are updated the new group of settings are given an ID number to differentiate them from previous settings. When a sample is collected the current ID setting is saved along with the other data indicating which settings were used for the run. SQL queries allow all of the data corresponding to each run to be recalled so that the text boxes are populated with the current settings each time the form is opened.

Calibrate Camera

To calibrate the camera the visual interface simply needs to call a function in the DLL which then creates a mask to help eliminate variation in the background. The mask is created by taking 50 images with no fiber or any other object in the image. For each image taken the average pixel value is calculated, and then the difference between each pixel value and the average value. For each pixel the difference from the average over the 50 images is averaged to yield an average difference for each pixel. If there are any small scratches on the top or bottom plate, slight intensity variations from top to bottom, or other factors causing consistent variation throughout the image the mask will fix the error. The mask is then subtracted from each image as the data is taken to cover the known areas of error.

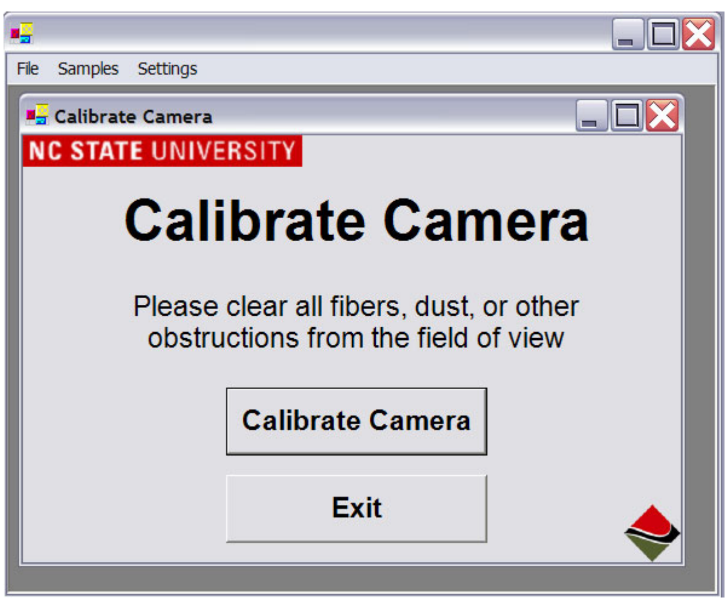

Figure 7.21 Calibrate Camera

Calibrate Resolution

The Calibrate Resolution is similar in function to the camera settings form in that each time the program is run the Calibrate Resolution structure is automatically populated. This ensures that unless the distance between the camera and the viewing are have change the camera will not have to be recalibrated. To calibrate the camera an object of known length must be placed in the image and a user defined number of images are taken. The images are analyzed just as if there were a fiber and the length of the object determined. Based on the average number of pixels calculated and the known length of the object the resolution can be determined. The new values are saved in the database with a unique calibration ID and also saved in the structure for future reference within the program.

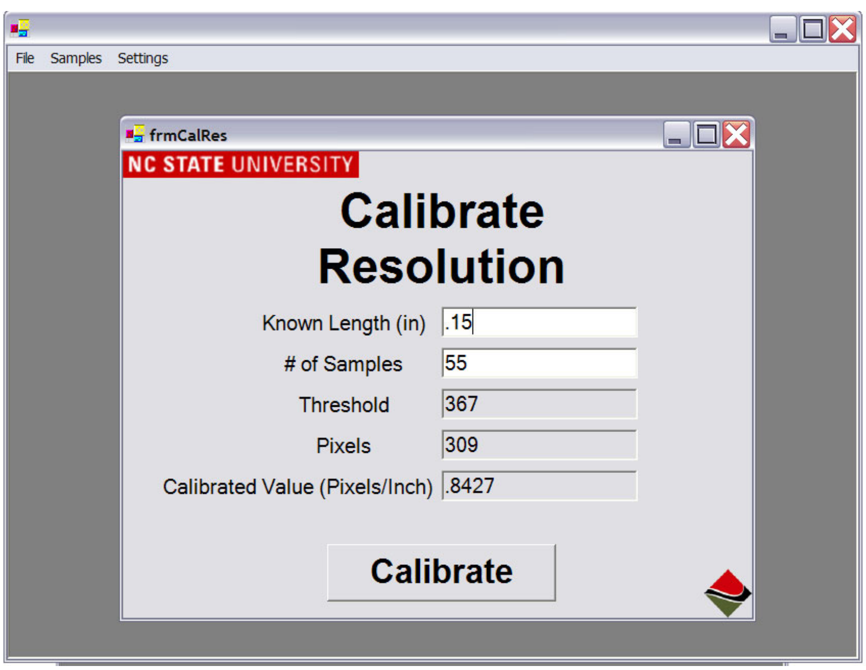

Figure 7.22 Calibrate Resolution

7.3.2.3 Conclusion

The software is an integral part of the machine and like the other primary components must work consistently to ensure that the machine is effective. Much of the machine was designed with the existing software in mind to try and limit the number of modifications that would need to be made. Fortunately with the addition of a few functions and the modifications of others the fiber analysis software was able to analyze images from the current system. The visual interface however, was not as adaptable and a new program needed to be written. Since a new program was needed the opportunity was taken to add additional functionality and improve the overall ease of use for the system.

8.0 Current State of Technology

Once the machine had been designed and constructed the effectiveness was evaluated. The accuracy and repeatability of the machine was quantified and compared to similar experiments conduced with the previous machine. This allowed the improvement over the previous system to be quantified.

8.1 Overview of System

The new system solved many problems inherent in the original system by allowing individual cotton fibers to be delivered to a viewing area with no physical contact resulting in an image of the unobstructed fiber being captured by the camera.

The fibers were delivered to the system using the same comber roller as the original machine. The comber roller uses a small rotating cylinder with pins around its circumference to remove individual fibers from a sliver and introduce them into the system. The rate at which fibers were introduced along with the speed of the comber roller could easily be controlled allowing the frequency of fiber introduction to be varied. With the design of the new system, no modifications were required.

The fibers were transported using suction, from the comber roller, past the sensor, through the viewing area, and finally disposed of. The transport enclosure was built using static dissipative acrylic to ensure no static would build up on the surface and cause the fibers to stick to the enclosure. The enclosure was designed such that the fiber would be introduced into the center of the viewing area ensuring the fiber would not contact the sides, avoiding imaging errors.

A sensor is placed at the entrance to the enclosure to detect fibers as they pass, and trigger the camera. The sensor consists of a photodiode which detects laser light reflected off of passing fibers. The collimated nature of laser light ensures that when no fiber is present the light reaching the photodiode will be minimal, however, when a fiber is present, the reflected light will produce a measurable change in the photodiode output. The output from the photodiode is input into an op-amp configured as a difference amplifier with the other input coming from a potentiometer configured as a voltage divider. This allowed the output from the difference amplifier to be adjusted just below the voltage required to turn a transistor “on”. When a fiber is present, the output voltage increases and triggers the transistor which then triggers the camera.

The camera is synchronized with the strobe and the sensor so that when the fiber enters the viewing area the strobe flashes and the camera captures the image. The strobe consists of two horseshoe shaped flash bulbs and the accompanying circuitry. The energy for each flash comes from a voltage multiplier that converts 120V AC to about 340V DC. The flash is triggered using an optoisolator coupled to a Silicone Controlled Rectifier and a trigger coil. The strobe provides an intense, short duration flash that “freezes” the motion of the fiber and provides an image of the silhouetted fiber.

After an image is captured, the software analyzes the image to extract the length of any fibers within the image. The first step in analysis is to apply a mask that was created during calibration to eliminate consistently dark or light areas in the image and significantly improve image quality. The image is then thresholded based on the average of the image to create an image containing only two grey levels in order to facilitate future processing. A number of analysis algorithms are used to isolate fibers from the background, thin the fibers, and finally count the number of pixels making up the fiber. The visual interface then converts the pixel number to a length based on a calibration value and saves each length in a database. The visual interface saves all individual fiber data along with a number of other parameters describing each sample.

The machine is controlled through the visual interface allowing the user to control the comber roller and the camera. To control the comber roller the software controls a PLC coupled to a relay which turns on and off the comber roller motor. The camera is controlled using C functions called by the visual interface through a DLL. The data collected from the samples are stored in a database which is also accessed using the visual interface. By allowing all aspects of the machine to be controlled through one interface, the operation of the system is greatly simplified.

8.2 Testing

Once all the components were integrated into a complete system, the machine was evaluated to determine its overall effectiveness. The first test was designed to evaluate how well the sensor and camera could be synchronized to capture fibers in the image. The second test evaluated the overall effectiveness of the system to accurately and repeatably measure the length of fibers.

8.2.1 Fiber Position Test

Fibers are moving at high speeds (~350 in/s) and the effectiveness with which the fibers are captured is determined by the consistency of the fiber speed and how reliably the sensor detects fibers. During testing it quickly became evident that not every fiber was captured completely within frame and still others were missed altogether. An experiment was conducted in an attempt to characterize the problem.

The machine was set up by first adjusting the sensor to ensure that every fiber would be detected while not falsely detecting any fibers. Next the camera and strobe delays were adjusted for the current air speed and comber roll speed to maximize the number fibers in the center of the imaging area. Once an optimal setting was attained, four runs of 50 samples each were collected. Cut length rayon fibers, .5 in long and 1.5 denier, were used for each of the samples in order to reduce speed variations caused by differing fiber geometry. The goal of the experiment was to investigate the average fiber location within the images.

8.2.3 Analysis of Results

The data was analyzed first to quantify the machines ability to effectively deliver the fibers into the viewing area. This was done by counting the number of images with no fiber, the number of images with partial fibers (one end of the fiber extends out of the frame), and the number of images containing complete fibers. The data was compiled into Table 8.1 which shows the number of fibers in each run along with a total. Overall 52% of the images contained fibers completely within the frame.

Table 8.1 Fiber Position Test

	Run 1	Run 2	Run 3	Run 4	Total	Percentage
No Fiber	17	17	13	6	53	26.50%
Partial Fiber	5	11	12	15	43	21.50%
Complete Fiber	28	22	25	29	104	52.00%

The second analysis was aimed at characterizing the position within the frame of the fibers completely contained with the image. The images without fibers or containing partial fibers were removed and the mean and standard deviation were computed along with performing an ANOVA. Figure 8.2 shows the pixel value of the leading edge of each fiber contained within the image. The image is 3000 pixels high and therefore a value of 3000 corresponds to the top of the image while a value of 0 corresponds to the bottom of the image. The different colored points correspond to each of the four runs.

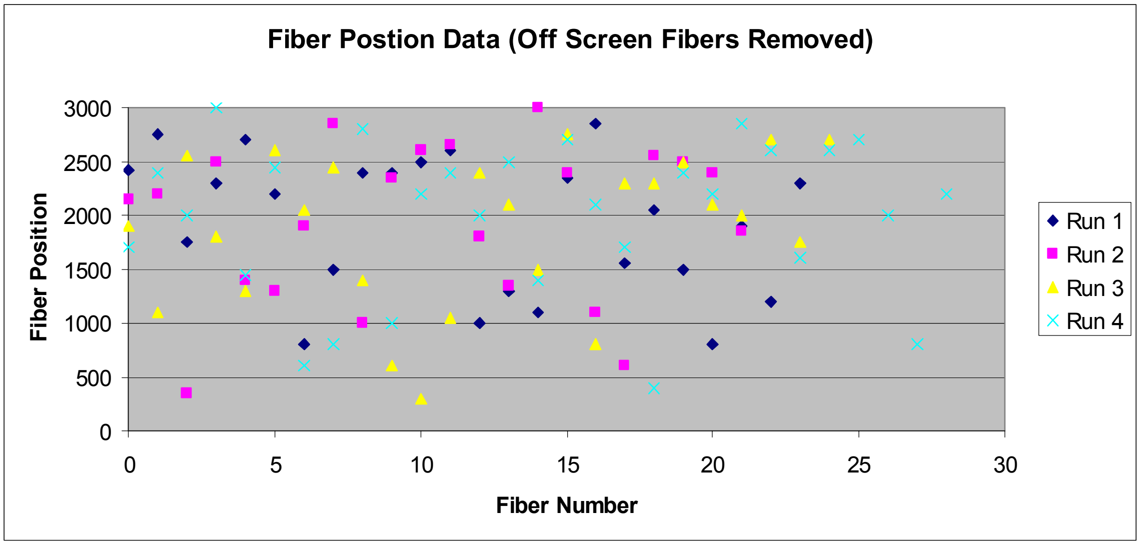

Figure 8.2 Fiber Position Test – Cleaned Data

The average mean for all four samples is 1934 indicating that the fibers are slightly above the center of the image. This position is desirable and consistent with how the machine was set up to ensure that all of the fibers remain within frame. The average standard deviation of all of the runs is 704 indicating that the machine does not deliver the fibers very precisely to the same point within the image.

Table 8.2 Fiber Position Test Statistics – Cleaned Data

Run 1		*Run 2*		*Run 3*		*Run 4*	
Mean	1925.8333	Mean	1945.2273	Mean	1880	Mean	1984.3448
Standard Error	132.48861	Standard Error	158.27824	Standard Error	140.68286	Standard Error	133.68779
Median	2125	Median	2175	Median	2050	Median	2200
Mode	2300	Mode	2500	Mode	2100	Mode	2400
Standard Deviation	649.05896	Standard Deviation	742.39073	Standard Deviation	703.41429	Standard Deviation	719.93076

An ANOVA was performed to determine if there was a statistically significant difference between the runs. The null hypothesis states that all of the runs are the same. A p-value of .96 clearly shows that the null hypothesis is true and all runs are the same. Since the same fibers and same machine parameters were used for each run this was the desired and expected result.

Table 8.3 Fiber Position Test ANOVA Results – Cleaned Data

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	150518.04	3	50172.68	0.1010807	0.9592114	2.6993926
Within Groups	47650816	96	496362.66			
Total	47801334	99				

8.2.3 Sources of Error

There are many potential sources of error that contribute to fibers not appearing completely within frame. The fluctuation of the air speed is thought to be the primary source of error causing different fibers to travel at different speeds. The vacuum is created using a venturi and controlled by regulating the air pressure to the venturi. Any inconsistency in the regulation of the input pressure would cause variation in the vacuum and cause inconsistent fiber speed. As the comber roll rotates, it blows air into the system increasing the speed of the fibers. Any variation in the speed of the air entering the system from the comber roll will also inconsistently change the speed of the fibers.

Ambient conditions affect the speed of the air within the system and thus the speed of the fibers. Even if the low pressure created at the exit to the enclosure remains constant, the speed of the air is related to the pressure differential between the exit and the entrance. The pressure at the entrance is dictated by the ambient pressure in the room and therefore changes in ambient pressure affects the speed of the fibers. The changes in the air conditioning and heating systems affect the temperature and pressure in the room and thus the speed of the fibers.

Fiber orientation affects the drag coefficient of the fiber and thus the speed. A fiber oriented perpendicular to the airflow direction will have a larger surface area in the direction the air is flowing causing more force to be exerted on the fiber due to the air. Conversely a fiber oriented parallel to the direction of the airflow will have a much smaller surface area and thus less force will be exerted on the fiber. The variation in force due to the differing fiber orientation will cause changes in speed.

As each fiber passes the sensor, it must break the laser beam at some point along its length to trigger the camera. There is no guarantee that each fiber will trigger the beam at the leading edge of the fiber. It is also possible for the trailing edge or some point along the middle of the fiber to trigger the camera. This will cause the position of the fiber at the time of imaging to be different than another fiber traveling the same speed. This is not thought to be a significant problem because the size of the viewing area allows a position difference of that magnitude with no problem.

8.2.4 Solutions to Error

To reduce the error caused by the variation in the fiber speed a controllable vacuum source should replace the venturi. This could be accomplished two ways: The first of which could use a vacuum regulator used with the current vacuum source and secondly a new, precisely controllable, vacuum source could be implemented to replace the venturi.

The variation in the ambient conditions could be decreased by placing the machine in a climate controlled environment. This would eliminate temperature or pressure fluctuations and thus speed variations within the machine. Another solution would involve building a climate controlled environment around the machine. As long as the temperature and pressure within the enclosure remained constant there should be no affect on the speed of the fibers.

In order to address the variation in fiber geometry an enclosure resulting in better fiber control could be implemented. If the entrance tunnel were narrow then the fiber would be less likely to rotate within the tunnel resulting in differing fiber orientation. This would also increase fiber speed, however, by designing the enclosure properly speed may be able to be decreased while improving orientation.

8.3.1 Evaluation of Measurement Accuracy and Repeatability

In order to evaluate the accuracy and repeatability of the system .5 in cut length rayon fibers were introduced into the system and measured. The measured lengths were compared to the known lengths of the fibers to evaluate the accuracy of the machine. Four samples were taken to evaluate the repeatability of the machine and investigate variability between runs.

The fiber sensor was adjusted so that the sensor could accurately detect each fiber while not providing false readings when fibers were not present. The image was calibrated by capturing 50 images and creating a mask which is then applied to all subsequent images to reduce background variation throughout the image. The timing was adjusted to ensure that the maximum number of fiber appeared within frame.

Four runs of 50 samples were conducted using .5 in 1.5 denier rayon cut length fibers. Many randomly chosen samples were selected and measured by hand using digital calipers and each sample was precisely .5 inches. All length measurement error was assumed to be caused by the machine instead of actual variation in the fibers. Each image was saved and analyzed after the entire run was complete in order to save time and allow the original and post processing images to be compared.

8.3.2 Analysis of Results

In order to achieve results representative of the final machine fibers partially within frame were removed along with erroneous readings caused by excessive noise or areas of non-uniformity throughout the image. Fibers contained partially within the image pose an obvious problem and can be removed during processing. The resulting data was analyzed two different ways. The first left broken skeletons and crossovers in the data to be analyzed. This error was left in because it represents error inherent in the machine due to the motion of the fiber or poor image quality. The second method removed all broken skeletons and crossovers leaving only fibers that were analyzed properly. By removing broken skeletons, the capability of the machine could be investigated under a best case scenario. The primary investigation was to determine the accuracy of the machine in determining the fiber lengths. Machine repeatability was also a concern and was investigated.

The accuracy of the machine was determined by computing the mean and standard deviation of each run along with the mean and standard deviation across all runs. First, statistics were computed for the raw data with all the broken skeletons and crossover left in. The overall mean was .49 in which is slightly below the nominal value of .5 in and had a standard deviation of .12 in. The standard deviation was higher than hoped for, but is almost completely due to the broken skeletons and the crossovers.

Table 8.4 Average Accuracy Statistics

	Compiled Data
Mean	0.488375347
Standard Error	0.012073597
Median	0.5318335
Mode	#N/A
Standard Deviation	0.119522515

Table 8.5 Individual Accuracy Statistics

Run 1		*Run 2*		*Run 3*		*Run 4*	
Mean	0.522214	Mean	0.513941	Mean	0.466904	Mean	0.474843
Standard Error	0.023512	Standard Error	0.010788	Standard Error	0.034692	Standard Error	0.023016
Median	0.531682	Median	0.533248	Median	0.529171	Median	0.536031
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.119886	Standard Deviation	0.047025	Standard Deviation	0.169956	Standard Deviation	0.126063

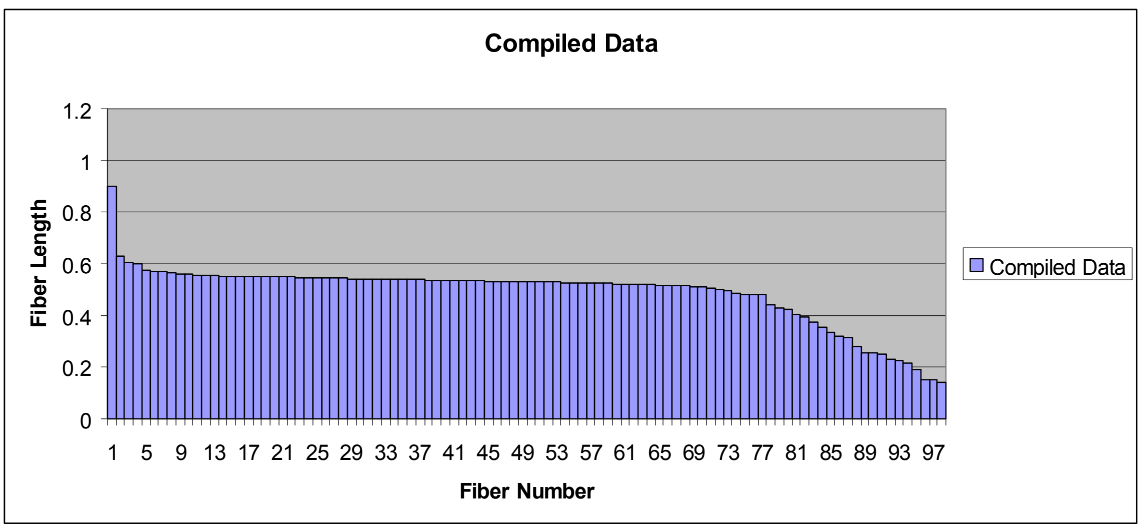

Figure 8.3 Fiber Length Graph

In order to get a better representation of the capabilities of the machine, broken skeletons and crossovers were removed and the statistics were recalculated. The mean of the recalculated data is .537 in. The standard deviation of .025 is much smaller than the previously calculated standard deviation. The mean is about 4 hundredths of an inch longer than the actual value of the fibers, indicating that length is added during the analysis process. More experimentation is required to determine the proper method to compensate for that error.

Table 8.6 Average Accuracy Statistics – Broken Skeletons Removed

Compiled Data Broken Skeletons Removed	
Mean	0.537077211
Standard Error	0.002843109
Median	0.536284
Mode	#N/A
Standard Deviation	0.024785649

Table 8.7 Individual Accuracy Statistics – Broken Skeletons Removed

Run 1		*Run 2*		*Run 3*		*Run 4*	
Mean	0.532695	Mean	0.527468	Mean	0.543211	Mean	0.54518
Standard Error	0.005206	Standard Error	0.005803	Standard Error	0.005445	Standard Error	0.00547
Median	0.531872	Median	0.533841	Median	0.54124	Median	0.543439
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.024967	Standard Deviation	0.023925	Standard Deviation	0.020372	Standard Deviation	0.025657

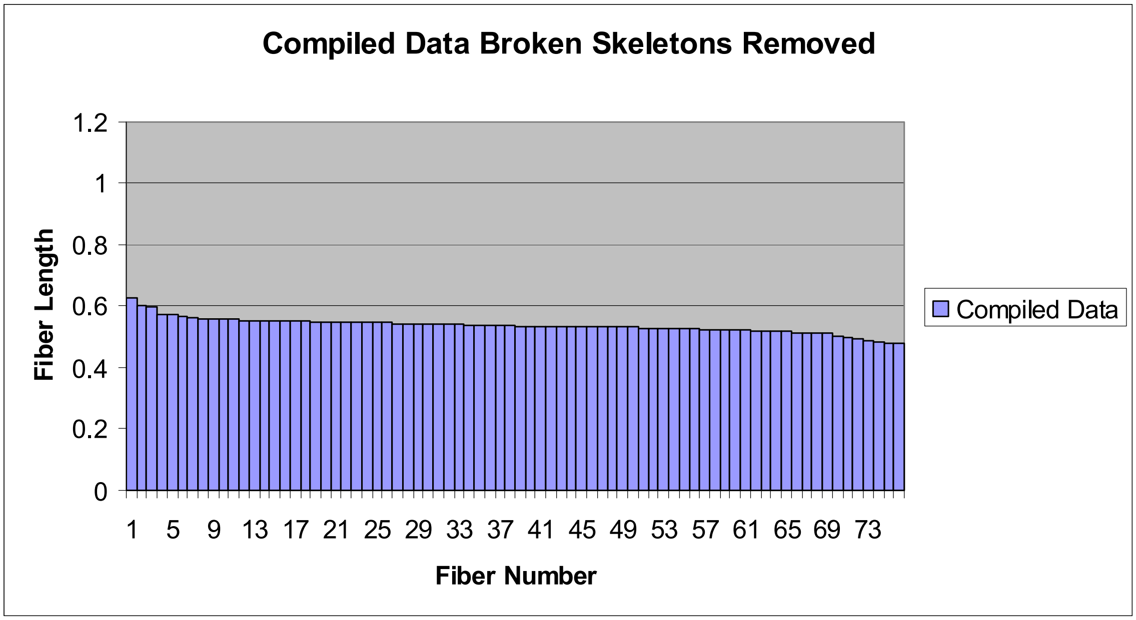

Figure 8.4 Fiber Length Graph – Broken Skeletons Removed

The accuracy of the machine was quite good, however, it was still uncertain whether or not the machine introduced variability from run to run. An ANOVA was conducted to determine variation from run to run with the raw data and the data with the broken skeletons removed. When the variation was computed for the raw data, a p-value of .32 was attained indicating that there was no significant difference between the runs and that the machine did not introduce any significant variation.

Table 8.8 Fiber Length ANOVA Results

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.056755	3	0.018918	1.179034	0.321933	2.700409
Within Groups	1.524342	95	0.016046			
Total	1.581097	98				

The same test was computed for the data with the broken skeletons removed and with a p-value of .09 proved that the variation between runs was not statistically significant.

Table 8.9 Fiber Length ANOVA Results – Broken Skeletons Removed

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.003983	3	0.001328	2.270843	0.087564	2.731807
Within Groups	0.042092	72	0.000585			
Total	0.046075	75				

8.3.4 Sources of Error

Measurement error is primarily due to poor image quality caused the motion of the fiber. The error can be divided into two categories; error that increases length, and error that decreases length. Motion and poor image quality create broken skeletons which can be removed but at a cost. Loops are created when there are dark pixels within the fiber and the thinning algorithm does not remove the pixels surrounding the dark pixel. This situation increases when fibers are blurred and the contrast at the edges of the fiber is not as high as that in the center. The blurred fibers are more likely to contain lighter pixels within the area of darker pixels. When thresholded, the lighter pixels within the fiber are converted to black like the background, and the rest of the fiber is changed to white. The fill algorithm is designed so that it fills in as many dark pixels within the white fibers as possible, however while most are filled some of the larger dark blocks within the fiber are left with a single black pixel resulting in a loop. The pixels in the loops are counted along with the pixels in the fiber, effectively increasing the measured length of the fiber.

The motion of the fiber itself may also cause an increase in measured length due to the blur at the tips of the fiber. The fiber moves a certain distance during the time the strobe light is on effectively increasing the length of the fiber and affecting the final measurement. The design of the machine makes this problem a necessary evil, however, the effect can be significantly reduced. By reducing the strobe duration the fiber will move a much shorter distance than with a longer duration, decreasing the overall effect on the fiber length.

Error causing decreased length is due to broken skeletons. Broken skeletons occur at places in the fiber where there is low contrast between the fiber and the background. The areas of low contrast, when thresholded, result in background pixels appearing within the fiber effectively separating a single fiber into two smaller fibers. Broken skeletons can occur at any point along a fibers length resulting in any number of situations ranging from creating two fibers of equal length to creating one fiber with a small portion of an end removed. Broken skeletons are caused by poor contrast between the fiber and the background which is caused by the movement of the fiber. Contrast is related to the amount of light reaching the background pixels compared to the amount of light reaching the fibers pixels. When a fiber is not moving or a very short duration strobe is used, the fiber blocks all of the light and the only light to reaching the fiber pixels results from diffusion of the light and a small amount of ambient light. If the fiber is moving, the fiber only blocks the light for a portion of the time the strobe is on. This causes the fiber pixels to be brighter since light is allowed to reach the pixels for a fraction of the time the light is on. Since the pixel value of the fiber pixels is closer to the pixel value of the background there is a higher probability that the thresholding algorithm will interpret the fiber as the background in certain areas resulting in broken skeletons.

8.3 Evaluation of System Improvement

In order to evaluate the overall success of the new system, it needs to be compared to the previous system. The comparison will evaluate accuracy and repeatability of the length, along with variation between runs.

In order to evaluate the effectiveness of the new system, data was compared to data collected using the previous system. Both sets of data were analyzed to obtain the average difference from the known value, and the standard deviation in an effort to quantify the accuracy of the system. An ANOVA was run and the P-values were compared to evaluate the variation introduced by the machine. The tables below compare the values from each system; table 1 showing the raw data from the samples, and table 2 showing the data from the best case scenario.

Table 8.10 System Comparison

	Old System	New System
|Measured Mean – Actual Mean|	.21 in	.01 in
Standard Deviation	.15 in	.12 in
P-Value	0	.32

The new system is an improvement in every area evaluated. The difference between the average of the measured value and the actual values for the previous system is .21 inches while the mean for the new system is .01 inches away from the actual value. The standard deviation of the old system was .15 inches while the new system only had a standard deviation of .12 inches. The p-values indicate the variation between runs collected. The p-value for the old system is 0 indicating that there is a highly significant difference between the runs. Since all of the samples were exactly the same the variation must be caused by the machine. The new machine however, has a p-value of .32 indicating that there is no significant difference between the runs. A high p-value is what was desired and expected. The data from the best case scenario was also compared in an attempt to quantify the maximum capability of each machine.

Table 8.11 System Comparison Best Case Scenerio

	Old System	New System
|Measured Mean – Actual Mean|	.025 in	.04 in
Standard Deviation	.05 in	.025 in
P-Value	Highly Variable	.09

The difference between the mean and the actual value for the best run from the previous system is .025 in showing that the machine was capable of accurately measuring fibers. The new system measures fibers on average .04 in longer than the actual value showing that it is capable of accurately measuring the length of individual cotton fibers. While the best run from the previous machine is slightly more accurate than that of the new system, the variation of the samples is much higher. The previous machine had a standard deviation of .05 while the standard deviation of the new system was half of that. This indicates that while the fibers may have been measured slightly longer than the actual value the error was more uniformly distributed. The most significant difference between the samples comes from a comparison of the consistency from run to run. There was only one run from the previous machine that could be considered a very good run. This prevented an ANOVA to be conducted to evaluate the variance, however one was not needed as the fact that there was only one good run illustrates that there is significant variation between the samples. The new machine, however, did have a number of good runs and their p-value was calculated as .09 which is not statistically significant however it does show that there is variation between the runs. This variation is thought to be due to the different number of samples for each run due to the removal of samples with no fiber within the image and fibers that are partially outside the image.

The new design is a significant improvement over the previous design in that it increased accuracy, decreased the variation within a sample, while significantly decreasing the variation between runs. The previous machine was capable of accurately measuring the length of cotton fibers however due to the problem with fibers overlapping the belt the measurements were not repeatable. By eliminating the possibility of overlap, the repeatability of the machine was significantly increased while maintaining the ability to accurately measure the length of individual fibers.

9.0 Conclusion

The existing system was first modified in an attempt to improve the various sources of error that had previously been identified. The modifications, while mildly successful in some areas did not provide a significant improvement to the overall accuracy and repeatability of the system. A entirely new system was conceptualized, designed and built.

The new system employed an air stream to control individual cotton fibers with no physical contact. The air stream drew the fibers through an enclosure designed to direct the fibers past a sensor, and into a viewing area with minimal speed variation. The sensor allowed individual fibers to be detected as they traveled at high speeds. The sensor, upon detection of a fiber, would trigger the camera which after a predetermined delay time would trigger a strobe light and capture an image. A xenon strobe light was used to provide the illumination for the fiber and provided a very intense, short duration flash effectively freezing the motion of the fiber. The camera would, at the same instant, capture an image of the fiber as it is passing through the viewing area.

The image upon capture is analyzed by software to extract the exact length of the fiber. The software thresholds the image, and differentiates the fiber from the background. Next the fiber is thinned and the number of pixels are counted and converted to a length based on a predetermined resolution value.

The new system has proven able to accurately and repeatably measure the length of cut length rayon fibers. In a comparison to the previous system the new system exhibits a distinct improvement in accuracy, variation within a sample, and variation between samples.

10.0 Future Work

While the machine in its current state proves that a fiber can be captured in mid air and analyzed effectively, there needs to be individual optimization of each component along with optimization of the overall system. Further work is required to optimize the function of the sensor along with improving the method and effectiveness of calibration. The light source needs to be improved to reduce the strobe duration and increase the intensity through either modification of the existing light or the purchase of a new light. The visual interface and analysis software need optimization and also need to be integrated so that the visual interface can control the analysis software.

To function effectively, the sensor requires very precise adjustment of a potentiometer to in order to output the desired voltages when there are and are not fibers present. The position error of the fiber may in part be caused by the sensor and therefore more work is required to characterize the specific contributions of the sensor to the overall error and implement a solution.

A first step in characterizing the error of the sensor would be to investigate the output of both the sensor and the difference amplifier using an oscilloscope. This would allow the actual signal to be seen and indicate whether filtering would be useful in improving the effectiveness of the sensor. I anticipate the use of a low pass filter or a band pass filter being incorporated in order to filter out the 60 hz noise caused by the comber roller motor.

Secondly, incorporating a microcontroller or output from the computer in order to allow the sensor to either be precisely calibrated or automatically calibrated to accommodate different lighting conditions would eliminate the need for a potentiometer.

This would provide for more consistency from run to and eliminate the need to adjust the sensor by hand.

Lastly, the sensor should be moved further down the inlet tunnel away from the opening. The transition between the adapter and the tunnel causes fibers to get stuck and move in and out of the laser repeatedly tripping the sensor. Simply moving the sensor about 1.25" away from the inlet would eliminate this problem. This would require a slight redesign of the enclosure, however the overall geometry could remain the same and only a few dimensions would need to be modified.

Reducing the duration of the strobe could significantly improve image quality by reducing the number of broken skeletons and the processing time required for each image. A strobe duration of <1µs is a target, however experimentation would be necessary to determine the actual duration that would provide the best image quality. This may be accomplished by reducing the size of the capacitors used in the existing circuit. Ideally a commercially available strobe with a <1µs duration and the necessary intensity would be purchased. This would allow the exact duration to be known and controlled while improving the ease of integration and the safety of the machine while also reducing maintenance.

The visual interface written in Visual Basic needs to be interfaced with the image analysis software written in C. The image analysis software needs to be converted to a DLL (Dynamic Linked Library) and then linked to the visual interface. This will allow all functions of the machine to be controlled via the visual interface along with displaying and saving the data collected by the analysis software.

The software in no way has been optimized for efficiency or accuracy and while effective still needs improvement. Large areas of noise caused by bright spots on the image often cause the program to crash. The outlining algorithm used in thinning is effective however certain fiber geometries will cause it to enter into an infinite loop. This has been avoided by implementing a timer to break out of the loop after one second. This solution, while effective, is not ideal and may contribute to the excessive processing time.

A new camera, while not necessary may improve image quality increasing the accuracy and repeatability of the machine. The light source should first be replaced, or improved and the effectiveness of the machine evaluated. If further improvement in image quality is necessary a new camera, likely using a CCD chip may improve the contrast and reduce the blur when compared to the current CMOS camera. All of the features mentioned in Section 6.0 are still valuable and should still be included in the new camera, however CCD technology may result in improved image quality when compared with the current CMOS camera.

The machine in its current state can capture an image of a fiber in mid air, and accurately and repeatably determine its length. Each component, while functional, is not optimized and it is this optimization that will result in a significant increase in the accuracy and the repeatability of the measurements made by the machine. Once each component is optimized individually the machine needs to be optimized before it is ready to be a commercially viable test method.

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