Final Design Report

Team 13

No Contact Gap Measurement

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ABSTRACT

This project arose from the necessity of measuring a micro gap between two cylinders that are used to hot roll raw material into thin films. The thickness of these films varies between 80 to 200 microns, and it is important to accurately gauge the thickness of the film samples as they are used in material property testing. The rollers used in this process are about 30 cm long, 6 inches in diameter, and are made of highly polished steel, making them expensive to manufacture and important to keep from scratching or denting. The current method used in measuring the gap employs the use of feeler gauges, which are thin metal wands with known thickness that are placed in the gap. Initial ideas for a non-contact method leaned heavily on the concept of laser triangulation systems or micrometers that would shine light through the gap to determine its thickness, however, laser products proved to be entirely too expensive for the project budget of $2,000. High resolution photography and long distance microscopy were considered as well, but optics proved to be impractical in this application. Research into capacitance sensors and their high resolution helped provide a sensor to design around, so the final design involves rigidly mounting arms to the roller positioning blocks and measuring the representative gap with capacitance sensors. A microcontroller is necessary to handle inputs of the capacitance sensors and the device will be calibrated to account for thermal expansion and irregularities in the rollers through experimentation and analysis.

ACKNOWLEDGMENTS

Thank you to the following people who offered their support throughout the completion of this project:

- Dr. Jim P Zheng for his involvement in the initialization of this project.
- Dr. Nikhil Gupta for his willingness and generosity in letting the team use his high resolution photography equipment, as well as assisting with design conceptualization.

1. Introduction

General Capacitance is the company sponsoring this project, and the problem they presented to the design team stems from measuring a micro gap between two polished steel cylinders used to hot work raw material into thin films. These thin films are made of a variety of materials that are used in batteries, and they are fabricated with the intention of doing material property testing, specifically capacitance. The specifics of the materials being used and the details of their future application was spoken of in general terms to protect the intellectual property.

This report will review the current method used in measuring the gap and further analyze the objectives that developed from the need statement presented by the project sponsor. There will also be an overview of the background research completed that investigated the various types of non-contact measurement devices that are available currently. The following section will outline how the final design was selected based on research, engineering properties, and decision matrices. The final section summarizes future plans to assemble the final design and the experimentation necessary to properly calibrate the measurement device to give accurate readings.

2. Background and Literature Review

Determining what products were available and currently being used in non-contact gap measurement was a significant portion of the work involved in developing a design that was in the project scope, accomplished the defined objectives, and remained under the allotted budget. Dozens of products were considered and researched through product catalogue data sheets, email correspondence with engineering specialists of companies, and feedback from the project sponsor and advisors. The reoccurring themes that surfaced while researching available technology typically fell under the umbrella of either lasers, optics, or capacitance based sensors. Each option had its advantages and disadvantages, with capacitance sensors eventually prevailing because of its relatively low cost and its practicality to the project scope.

2.1 Laser Based Technology

The micro scale of the gap is one of the first hurdles involved in the problem solving process. Initial experimentation done in the lab with the machine revealed that it was difficult to observe white light passing through the gap with the naked eye, but light does pass through. The no contact constraint on the design placed working with laser or light sensors at the top of the brainstorming list. During the first meeting with project sponsor, Dr. Jim Zheng, the team was provided the product data for several of Micro-Epsilon's products that involved laser technology.

2.1.1 Laser Triangulation

Dr. Zheng had previously researched existing non-contact gap measurement systems and provided the team with some of his findings. Micro-Epsilon is a company that specializes in displacement and position sensors, and they have a device called gapCONTROL that is designed specifically to be used to make non-contact gap measurements. It is uses the triangulation principle to measure the gap. This principle uses trigonometry to determine how far away the object being scanned is away from the sensor, as the distance between the camera and the laser emitter is known, as well as the angle that the emitter is positioned.

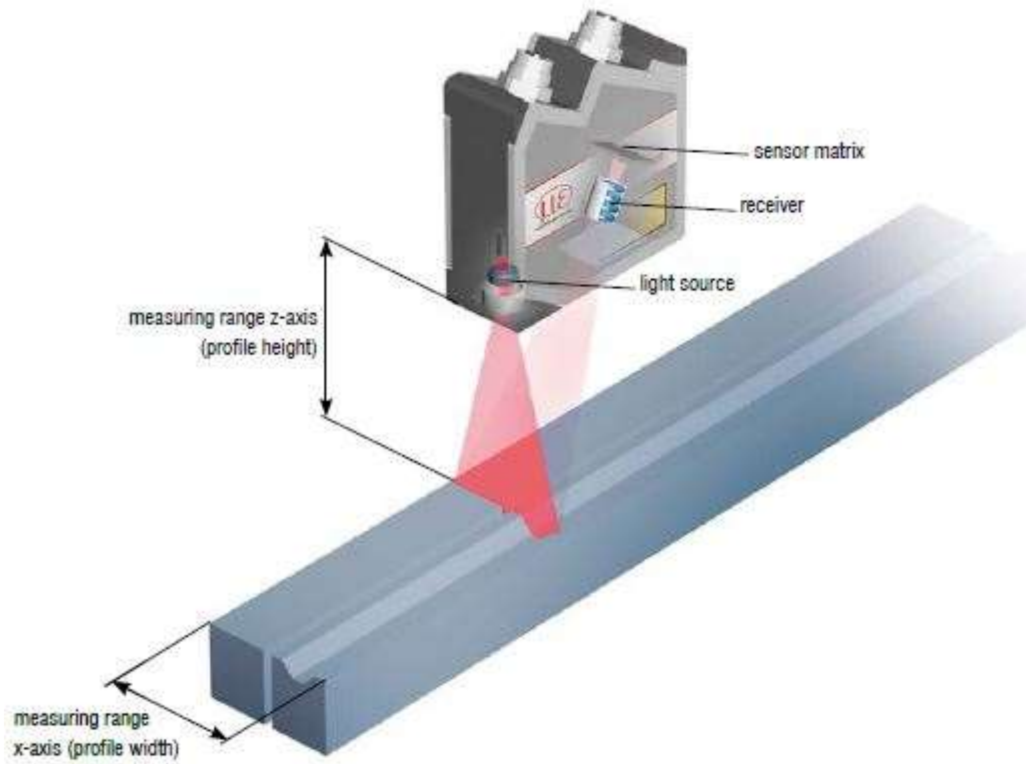

Figure 1. Laser triangulation gap measurement device from Micro-Epsilon.

The non-contact gap measurement device show in Figure 1 is ideal because it has the necessary scanning range, working distance, and resolution needed for the project, but it retails for around $10,000. The triangulation method would be effective in imaging the rollers to determine the gap between them, but it is not practical for this project as it is out of the allotted budget.

2.1.2 Laser Micrometers

Laser micrometers work effectively and are relatively simple. The idea behind laser micrometers is shining a laser at a gap and measuring the amount of light that makes its way through the gap. After knowing the amount of light that was initially sent through the gap and the amount of light that made it through, the gap could be determined using ratios. This is a quite effective way of measuring the distance between two objects, and the schematic of a Micro-Epsilon micrometer can be seen in Figure 2. The two main disadvantages of using laser micrometers is their price and spatial requirements. The first disadvantage is the price of the system, as the price of one of these tools with the two micron resolution needed was about $4,000. There was no way of managing the money needed to pay for the tool. The second main disadvantage of the device was that the tool needed a receiver positioned below the rollers. The receiver portion would be exposed to heat as well as other materials that could fall through the gap. This would disrupt the work that was done in the lab and could possibly be broken through heat or something falling onto it. These two thoughts were taken into consideration when choosing the final design for the no contact gap measurement.

Figure 2. An example of a laser micrometer from Micro-Epsilon.

2.2 Optics Based Technology

Another idea that was proposed throughout the course of the project was optical technology. This incorporated a few ideas into one but overall was determined to be looking at the gap with some sort of lens, snapping a picture of the gap, and then with the known zoom lens and distances, the gap width could be correctly determined. There are quite a few drawbacks to overcome when using optics to solve the problem at hand, including the focal length, necessary zoom levels, and photo processing and analysis software.

2.2.1 High Resolution Photography

The use of high resolution photography to image the gap involves of using an expensive camera to capture close up pictures of the gap. With these photos of the gap, the known zoom level, the distance to the actual gap, or some reference distance, the distance of the gap could be solved for using certain computer programs. The photo would be uploaded to the program and a measurement line would be overlain on the photo. The program would be able to correctly identify the width of the gap. The idea for high resolution photography came from a lab performed in previous years, during which students performed a Brinell hardness test in a Mechanics and Materials class. This test involved marking a material with a diamond indent and then looking at the indent through a microscope. The indent was imaged and analyzed using a computer program that allowed for the measurement of the size of the indentation from corner to corner.

The problems with this specific design came from being able to focus on something that small from approximately 30 centimeters away. This was a huge issue for the budget because the cameras that could meet the technical requirements necessary were out of the allotted budget. One thousand dollar cameras could not meet the technical requirements to focus on such as small gap at such a large distance.

An experiment was conducted by the team that led to the complete disregard for photography to determine the width of the gap. Dr. Gupta assisted the team by lending his DSLR camera for use in experimentation to determine if it was possible to image the gap with a camera. Several attempts at capturing a well-focused picture of the gap between the rollers resulted only in blurry, undistinguishable pictures. If focused properly however, the camera method would be used by photographing the gap and implementing a scale, as seen in Figure 3. Different zoom levels and lenses were experimented with and the conclusion that the gap width was far too small for this method was finalized.

Figure 3. One of the photos that was taken during the DSLR camera experimentation of a ruler that would be used for scale.

2.2.2 Long Distance Microscopy

The use of long distance microscopes was an attempt to maintain the advantages of high resolution photography while discarding the disadvantages. The main problem with cameras is the focal length. Cameras are made to capture an image that is large and shrink it to scale. For instance, a picture of a six foot tall person would come out to be only a couple of inches. This comes from the different focal length and the object being over twice the distance of the focal length. With microscopes, the focal length is very small and the object that is being observed is between the focal length and twice the focal length. This makes the object appear larger than its actual size. The goal with long distance microscopes was to acquire a microscope with a focal length of around 30 centimeters, or a decent distance from the heat of the rollers. With the long focal length, the object could then be magnified and seen more easily. Then, with the magnified image of the gap, a picture could be taken through the microscope and taken to the aforementioned software. The gap would then be determined through the program.

Problems concerning the microscopes involve the focal length again. The project focal length of 30 centimeters was not unheard of, but abnormal. There are not that many applications for a microscope that can only focus on something that far away. Because of this, the microscopes that could accomplish our task were far out of our price range, such as the Infinity K-1 Centrimax seen in Figure 4. The microscopes themselves broke the proposed budget of $2,000 by thousands of dollars, and the team would still need to purchase a separate camera to capture the image, and a program to measure the gap. After extensive research and budget analysis, it was decided that it was both a technically and financially unlikely solution.

Figure 4. An example of a long distance microscope that was considered. This particular model theoretically satisfied technical requirements, but was over $3,000.

2.3 Capacitance and Inductance Sensors

Capacitance and inductive sensors were the next step that was taken with this project. The two sensors are able to detect ferrous metals at small distances away with extremely small precision. These types of sensors are generally inexpensive, power efficient, and very reliable.

2.3.1 Capacitance Sensors

There are more than a few advantages to using capacitance sensors for sensing something with this small of resolution. The capacitance sensor works by creating capacitance with a ferrous material. The ferrous material does not have to be part of the sensor. The capacitance between the sensor and the ferrous material changes with tiny movements between them. The change in capacitance is measured and sent as a voltage to some input. The input could be a microcontroller for instance. The capacitance sensor comes in different types and can detect a number of different materials. There are even some capacitance sensors that can detect plastics.

Capacitance sensors come very inexpensive compared to the other options that were proposed. Most of them are well under two hundred dollars; however, measuring the distance between two rollers would be very difficult because the sensor would have to be mounted on one of the rotating rollers and would inevitably be crushed. Using this sensor would require some sort of arm or other protruding device be mounted on the rollers or something that the rollers are attached to.

2.3.2 Inductance Sensors

There are few differences in the applications between capacitance sensors and inductive sensors. They both are used for proximity sensing at miniscule distances. The way that an inductive sensor works is completely different from a capacitance sensor however. The inductive sensor works by creating a magnetic field in the proximity of the sensor. The magnetic field in return produces a certain electric current. The electric current changes by what material is inside of the electric field. The change in current is what the sensor reads and sends to the input of some other device. Both of these sensors could work properly and efficiently in the application of measuring something with the resolution of two microns.

Inductive sensors are also very cheap compared to the other options. The sensors cost about the same as a capacitance sensor at under two hundred dollars. The problem with these sensors again lies in the installation. The inductive sensors need to be rigidly attached to something that does not move for accurate readings. Research was conducted into the technical specifications needed and those available on the market, and the Keyence EX-422V inductive proximity sensor was selected, as it offered a working distance of 10 mm, and a resolution of 2 microns. A stock image of what a Keyence inductive sensor looks like when run into a microcontroller and display screen is seen in Figure 5.

Figure 5. Keyence EX-422V inductive proximity sensors that satisfy all requirements.

3. Methodology

With all of the background research at hand, it was important to select a design that will be able to meet the project's requirements. In order to select a design concept that will be best suited for the project, a decision matrix was utilized and can be seen in Table 1.

		Design Concepts				
Design Requirements	Weight	Laser Technology	Optics Technology	Inductance and Capacitance Sensors		
Accuracy	4	5	3	4		Key
Durabilty	1	4	2	4		5 - Best relationship
Easy to Use	2	4	2	3		0 - Worst Relationship
Price	3	0	2	5		
	Score = Σ (Weight * Rating)	32	24	41		
	Rank	2	3	1		

Table 1. Decision matrix that was created to determine the most efficient design.

The decision matrix is useful in the design process because it helps relate the potential design concepts to the requirements. The weight scale was configured by determining which design requirement was more important than the other. Accuracy was the highest weighted and this is because the project requires very precise and accurate measurement as the gap will be in microns. Price is the second highest weighted requirement and this is because our design concept has to fit into the budget allowed for the project. After the scores were calculated it was simple to see which design concept was the best to move forward. Laser Technology was a very accurate and easy to use design, but it was very expensive and most products were extremely over budget. This is why this concept received a zero in the price category. Optics scored the lowest in the matrix. Optics were somewhat accurate, but it difficult to use in some instances and also can be quite expensive as well. Inductance and capacitance sensors scored the highest in the matrix. These sensors are capable of the accuracy the project requires and are easy to use. The price for these sensors are well within our budget as well. The design concept selected is working with these sensors as indicated by the decision matrix. The next step was to make a design to implement the use of these sensors to measure the gap between the rollers.

The final design methodology revolves around establishing and measuring a representative gap that is directly related to the gap between the rollers. As the main constraint for the project is "non-contact," the representative gap has to be created in a way that does not come in contact with the rollers or interfere with the operation of the machine. This representative gap is created by rigidly mounting aluminum arms to the roller positioning blocks, as seen in Figure 6.

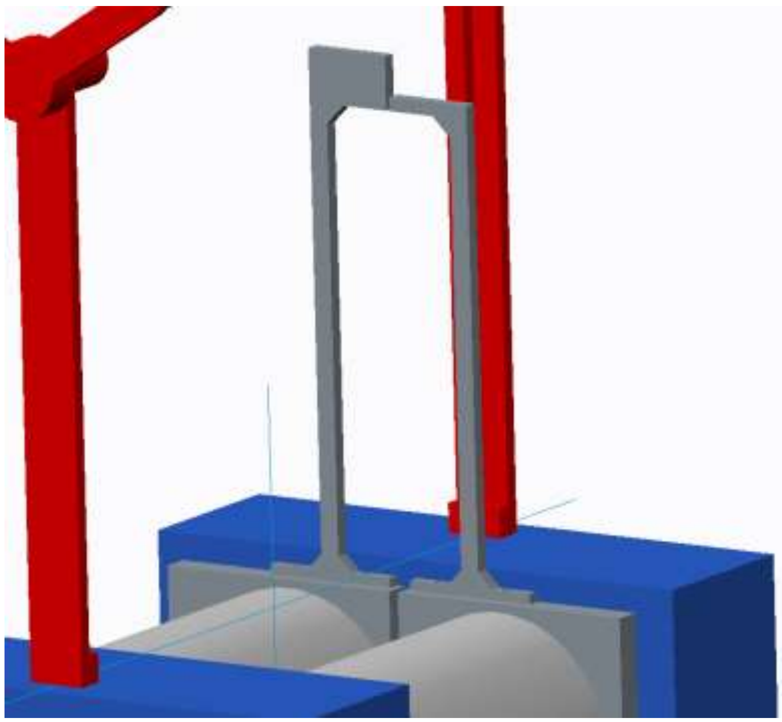

Figure 6. The aluminum arms rigidly mounted to the roller positioning blocks to create a representative gap.

This design allows the gap between the two arms to be linearly related to the gap between the rollers, so that when the gap between the rollers is varied, the gap between the arms will be varied as well. This structure places the representative gap 12 inches away from the rollers to be both non-intrusive in machine operation and unaffected by the heat transfer from the rollers. Finite Element Analysis was employed to study how heat transfer affected the air temperature above the rollers. Comsol Multiphysics was the program used to simulate a model of the air space above the rollers, with boundary conditions of 300°C for each of the rollers, and 20°C for the ambient room temperature. The resulting cross section of the air space can be seen in Figure 7.

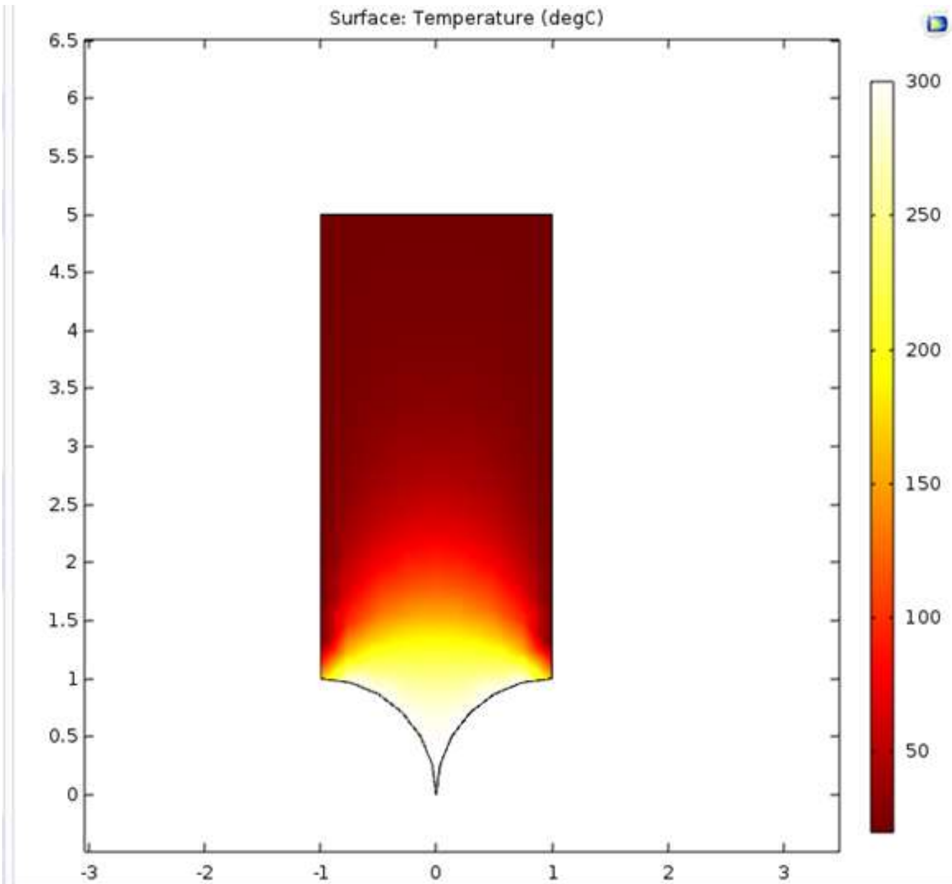

Figure 7. Comsol model of heat transfer in the air above the rollers.

The model is designed so that a unit length is the radius of the rollers, and the resulting image of the heat transfer shows that the change in air temperature is nearly negligible at the distance of one diameter away from the rollers. The arms extend two diameters above the rollers as a safety factor, so that theoretically, the sensors mounted on top of the arms will not be at risk of being damaged from incident heat.

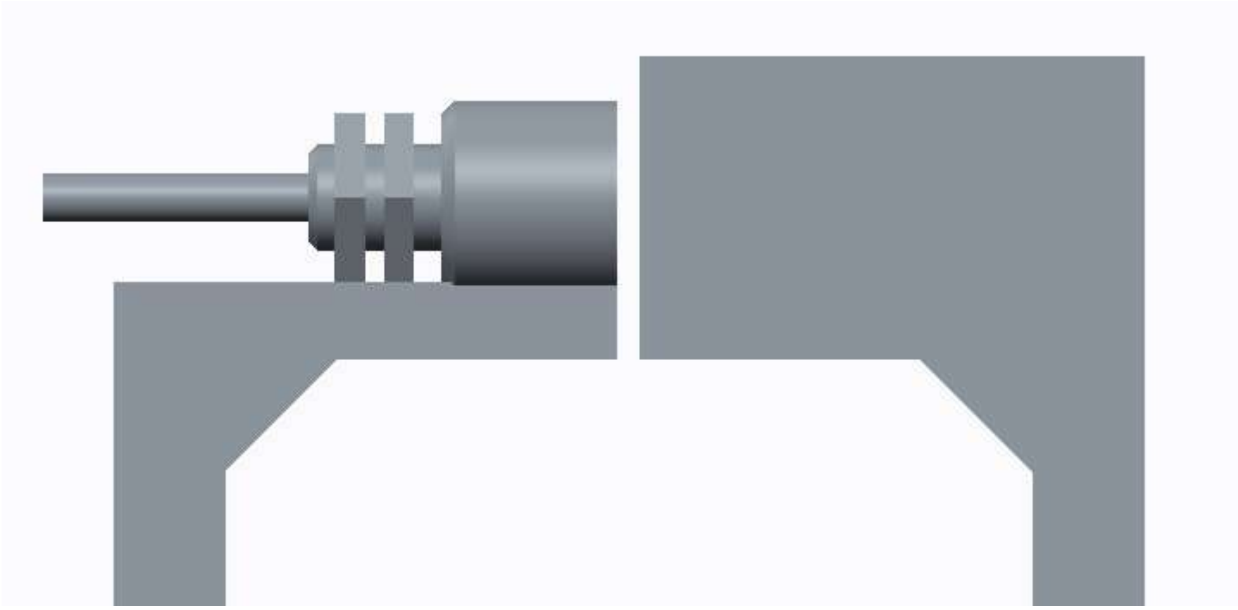

Figure 8. A close up of the inductance sensor placed on top of the shorter arm.

The inductance sensors will be mounted on top of the shorter arms and positioned so that they output the gap between the two arms as seen in Figure 8. These inductance sensors will be wired to the Arduino Uno microcontrollers mentioned previously, in order to linearly relate this representative gap to the actual gap between the rollers. Calibrating the microcontroller to relay the correct gap distance will require experimental data that relates the sensor readings to the thickness of the materials being rolled. The lab technicians currently use digital micrometers to measure the rolled film thickness, so the measured thickness can be compared to the approximated gap from the feeler gages, and the microcontroller can be calibrated to these readings. The microcontroller will have three inputs, two distance readings from the inductance sensors and one keypad input that will be used to input the temperature that rollers are set to. This input will assist in calibration as it will be used to determine the thermal expansion of the rollers. The current approximation used in the lab to account for thermal expansion is about 10µm per 100°C, so this factor will be programmed into the microcontroller. The microcontroller outputs will be displayed onto a LED display screen, and the outputs will include the gaps measured on both ends of the rollers as well as a calculated average gap between the rollers. A dimensioned schematic of the final design can be seen in Figure 9.

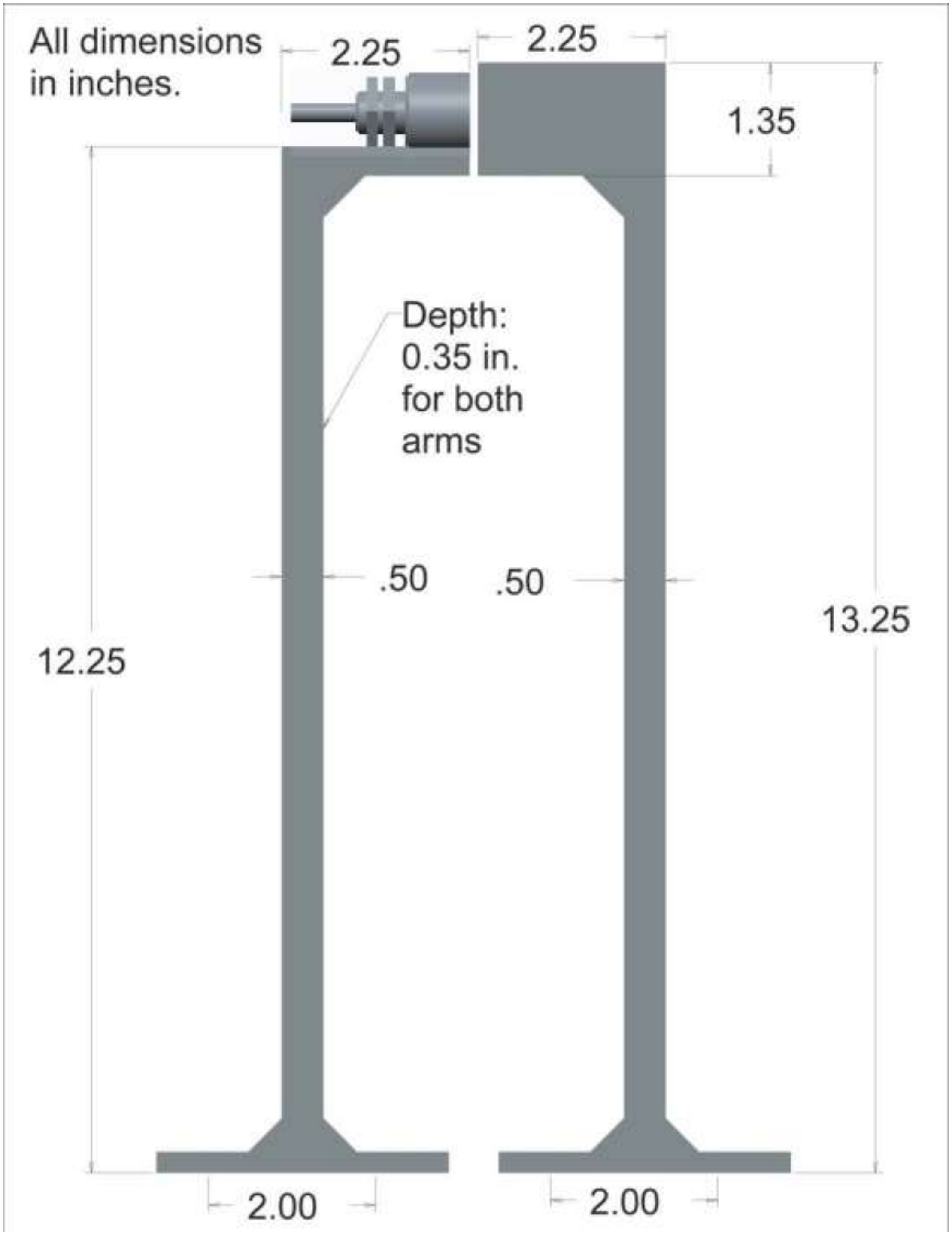

Figure 9. A full photo of the arms that will be mounted on the machine. The chamfered edges can clearly be seen and the sensor can be seen on the top of the model.

4. Results

Finite element analysis helped to determine that the high temperature of the rollers resulted in the arms needing to be a few diameters away from the rollers. This would ensure the safety of the sensors from the heat. The arm material of aluminum was compared to other materials with price and efficiency compared. The thermal expansion was compared between steel and aluminum. Aluminum has a higher thermal expansion than steel, but is still within the applicable range for the arms. The aluminum bars need to be completely rigid and strong enough to undergo any plastic deformation with small forces such as accidentally running into them with your hand in the lab. Any plastic deformation that occurs will invalidate the calibration of the sensors. Since the gap between the bars is only linearly correlated to the gap between the rollers, and not the same distance, the sensors need to be calibrated to be able to read the correct value and any deviations will destroy the precision. To help with the rigidity of the bars, the chamfer edges can be seen at every joint of the arms, as seen in Figure 9. Also, because the inductive sensors need a very smooth surface to view, the other arm will need to be polished. Any bumps or ridges that are over 2 microns in height will affect the measurement of the gap. Another problem that has to be assessed is the location of the wires and the microcontroller. These have to be far enough away to not be affected by any heat and cannot draw any power from the machine. These have to run on some sort of outside power source or connected to a wall outlet. Accessing the power source of the rolling machine would be too intense and any mishaps could destroy the machine. The microcontroller and the LCD display could rest on the machine but it would have to be one of the cooled portions on the machine. Finally, since our design will incorporate two sensors on both sides of the rollers, one of the wires from the sensors will have to run across the red safety bars above. The main concern is to be able to keep the wires out of range of the operators and not affect the operation of the safety feature.

5. Conclusion

The design that was chosen to be the most appropriate for the measurement of the gap between two rollers is the extruded aluminum arms measured with inductive proximity sensors. This design proves to be reliably accurate and precise, cost effective, and user friendly for operators. The sensor readings will be displayed on the microcontroller's LCD screen. The LCD screen will display the two sensor readings along with the extrapolated center gap width and the temperature of the rollers. The only problem that was not overcome with this design was that the gap width cannot be measured at every point laterally on the rollers. This problem was taken to our sponsor to discuss and was concluded that it would not be applicable within the budget constraint. It was concluded that aluminum is a more appropriate material than steel or another composite because its thermal expansion, price, and machinability were the most practical for the project. The Arduino Uno was chosen as the microcontroller as it has enough processing power to be able to handle the calculations and the necessary ports to be effective in this application. An outside LCD screen and number pad will be purchased and are easily programmed and usable.

Because of the reaction times of the chosen sensors, the measurements will practically be real time. For every distance that the rollers are manually moved, the sensors and displays will be able to provide feedback on the gap measurement almost instantaneously without interrupting the machine function or increasing difficulty of operation.

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Biography

Samuel Giaquinto is a mechanical engineering undergraduate at Florida State University's college of engineering. Currently pursuing the dynamics track, Samuel is interested in design work using CAD software. Expecting graduation in May of 2016, he is pursuing work in the automotive field.

Matt Nagy is a mechanical engineering undergraduate at Florida State University's college of engineering where he is currently pursuing the thermal fluids track. He is on pace to graduate in May of 2016, and hopes to work in sustainable energy.

Forrest Parker is a mechanical engineering undergraduate at Florida State University's college of engineering. Project management, website design, and computer programing are his strengths and interests. He plans on going into construction management as an assistant project manager after graduation.