Global Health: Prevention of Diabetic Foot Ulceration and Amputation

BME 301
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Abstract

Diabetic patients often suffer from ulceration in their feet which can result in amputation of the foot. In order to detect ulceration, others have employed a thermal imaging system paired with image processing software in order to detect statistically significant changes in temperature due to ulcer development. The team has been tasked with designing an imaging system that includes a thermal camera, image processing software, and a repetitive method to measure these thermal changes. The device proposed is a custom thermal imaging device that uses a microcontroller to send data via wifi to a database that communicates with a mobile application. The custom imaging device will mainly be composed of a MLX90640 thermal camera and a Raspberry Pi. Image processing will occur on a mobile application and the system will reside in an insulated box that is foldable, comfortable for the patient, and easy to use. Future work will consist of machine learning software that interprets the collected thermal data.

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I. Introduction

Motivation

Diabetes is a major epidemic in India; it is often referred to as the diabetic capital of the world, as over 60 million in the population suffer from the disease [1]. As many lack access to proper treatment, there are additional complications that arise that many do not typically associate with diabetes. Of those who suffer from diabetes, up to 25% go on to develop foot ulcers, which may go on to become infected, and ultimately end in the amputation of the foot [2]. For this reason, it is desirable to create a device for early-stage detection. The ability to screen large volumes of patients to determine the risk level of ulceration will allow for physicians to better determine who is most in danger of ulceration. With better knowledge about the progression of a patient's ulcer, physicians will better be able to advise their patients on successful preventative care measures. This likely means the patients staying off of their feet to allow for recovery, however, it may vary based on the severity of a specific patient's case [3]. Early detection of ulcer formation will lead to better preventative care measures and thus reduce the prevalence of diabetic foot ulceration and amputation.

Competing Designs

Others have done similar work in this area. Thermal imaging devices as well as image processing programs have been fabricated and shown to have success. The use of asymmetric analysis has allowed others to compare heatmaps of either foot in order to locate hotspots [4]. Asymmetric analysis utilizes computational methods to detect the borders of a patient's feet and then superimpose them on each other for comparison. The downfall to using asymmetric analysis is that if a foot has been amputated a comparison between the patients feet cannot be made; additionally, if there are hotspots forming in the same location on either foot, they will not be detected using this method. Additionally, many of the imaging systems which have been designed to reduce outside heat sources are large, bulky, and expensive, as seen in Figure 1. These designs are not tailored for low resource settings, where the device may need to be transported throughout the hospital. Some have also performed case studies that analyze the success of their devices; these case studies have helped to identify diagnostic markers associated with ulceration [5]. However, there has been a lack of data supporting competing designs coming from clinical trials. Case studies, while identifying some diagnostic markers, have failed to provide a holistic approach to diabetic foot ulcer detection. As our client has approval to continue clinical trials in India, as well as prospects for running clinical trials at the Veterans Affairs Hospital in Madison, this sets us apart from other similar designs. A large set of patient data will help to identify more holistic markers for detection, and will aid in the development of additional computational methods for ulcer detection. There is also much greater funding in competing projects, and so expensive and high-tech systems have been designed; the team seeks to maximize cost efficiency and create an ulcer detection device for low-resource settings.

Outside of utilizing thermal imaging systems, American companies have developed products targeting at home monitoring of diabetic foot ulceration. One example is continuous temperature monitoring socks (*patent number US20170188841A1*), which alert patients when certain areas of the feet reach temperature thresholds [6]. The at home availability of this device is enticing, although it is not entirely feasible as our client has expressed that many people in India do not utilize footwear, instead commuting barefoot. Our client previously worked on developing a similar footwear device that monitored pressures instead of temperatures, as increased shear forces can be indicative ulceration. This design alternative was abandoned as it was not feasible for low resource settings.

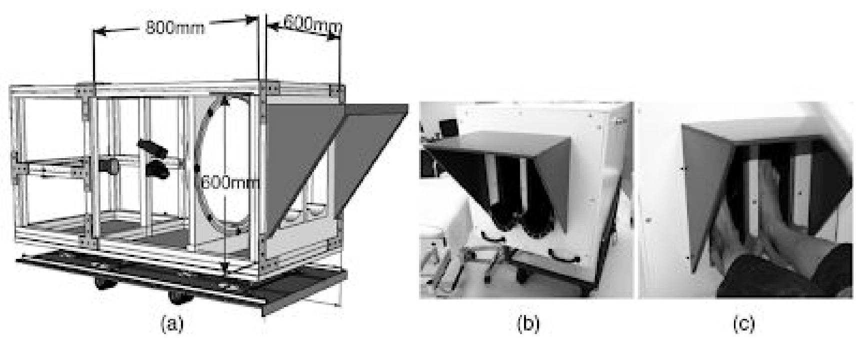


Figure 1. *competing design from [5]. This design consists of a large imaging box constructed for consistent imaging of the feet. Careful considerations were taken into account to reduce noise from outside heat sources. The major downfall to this design is it is large and expensive - not tailored for use in low resource settings.*

Problem Statement

Thermal imaging has proven to be an effective technique in early-stage ulcer detection in diabetic patients. However, a gap exists in the acquisition and analysis of thermal images by computation in order to streamline the process of ulcer detection and in design for low resource settings. The team has been tasked with creating a thermal image acquisition device to collect a large data set with future hopes of developing a machine learning algorithm to analyze thermal images of diabetic feet.

II. Background

Biology and Physiology

Diabetes mellitus is a disease that affects the regulation of glucose in the blood; it is split up into two categories based on how it is developed and treated. Type 1 diabetes is caused by the destruction of pancreatic cells which produce insulin. It is typically treated by administering synthesized insulin, a protein used in the regulation of blood-glucose levels. Type 2 diabetes, however, results from desensitized insulin receptors caused from over-exposure to glucose, therefore treating with insulin injections is not a viable treatment; the best way to treat Type 2 diabetes is through diet and exercise.

A common side effect that many diabetics suffer from is peripheral neuropathy, in which the individual loses sensation in their feet. This has detrimental effects, as the patient is unable to adjust their gaite to distribute mechanical pressures on their foot. Repeated shear forces acting on tissue over time can cause inflammation and tissue damage, regardless of the magnitude of the force being minimal [7]. Without the ability to sense the pain associated with inflammation and tissue damage, a diabetic individual may then experience the formation of an ulcer without noticing it. Left untreated, ulcers can easily become infected, and often require the amputation of a part of the limb. As inflammation is associated with increased blood flow and therefore heat, temperature measurement has proven to be an accurate marker of ulcer development. It has been found that an increase of 2.2 ℃ is associated with the beginning of ulceration [8]. This threshold provides a basepoint for analysis of risk through thermal imaging.

Thermal Imaging Technology

Thermal imaging cameras that are relatively low cost and non cooled, thus relevant to this project, can be split into two main categories: thermopile detectors and microbolometers. Thermopile technology, such as what is used in the MLX90640 thermal camera, functions on changes in thermal electromotive force proportional to infrared light energy. Thermopile detectors use an array of thermocouples that have two different thermoelectric metals. The two metals allow for calculations of the difference in changes in electromotive force that can be translated into a temperature. Microbolometers function on changes in resistance of a thermoresistive material based on the amount of infrared light that enters the device. Each pixel detects individually making these microbolometers very effective in measuring thermal data.

Client Information

Ms. Kayla Huemer is a recent graduate of the Biomedical Engineering Department at UW - Madison. After graduation she spent time in India on a Fulbright fellowship working on early-stage ulcer detection. She was able to collect about 250 images with the device that she created, and is now asking us to help with the continuation of the given project. She has an interest in bioinformatics and global health.

III. Preliminary Designs

Thermal Image Acquisition System

The thermal image acquisition system designs should include a mechanism to capture thermal data from the bottom of a patient's feet in addition to analyzing and running the data through predictive algorithms. The designs should also provide some way to gather repetitive and consistent measurements of the thermal data as well as collecting the data in a way that is comfortable for the patient. All designs should be easy to operate and ergonomic for an Indian hospital setting and should be realistic and able to be fabricated.

Design 1 – FLIR One Pro Camera + Phone

Figure 2. *Image of the first design, the FLIR One Pro Camera coupled with a smartphone. The FLIR provides good quality thermal images, but is expensive and makes image processing difficult.*

The FLIR camera was used by our client while she collected preliminary data on her Fulbright Fellowship. It attaches directly to the user's phone and provides high quality thermal images. The camera has a resolution of 160 x 120 and a tolerance of +/- 1 degree Celsius. Temperatures between -20 and 40 ℃ can be detected which is well within the physiological range needed for imaging of the foot. The FLIR is easily the highest quality thermal camera of those that we have considered, however, it is significantly lacking in some areas. The camera has a battery life of only an hour; for data collection purposes, this is very inefficient as the user would need to stop collecting data and recharge the camera at each hour. Additionally, the cost of the FLIR is $399 which is not desirable considering we are designing for a low-resource setting. Finally, the FLIR camera interfaces with the FLIR mobile application. This application does not interface well with other devices, however, making data analysis on a computer difficult. In prior work, we have had to convert the images to grayscale and go through tedious steps to move pictures onto a computer. This is inefficient and takes away the raw temperature data, which is of value for data analysis.

Design 2 – AMG8833 + Microcontroller

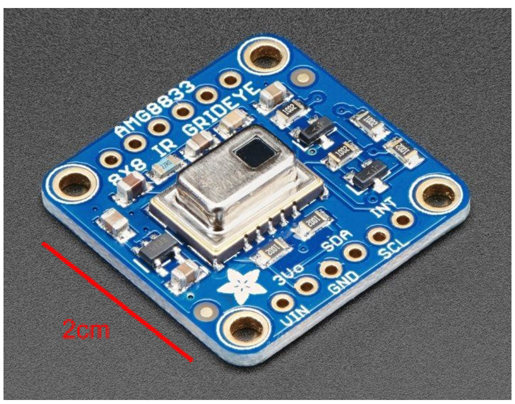


Figure 3. *Image of the AMG8833 thermal camera. A good option for low resource design, but some image quality is sacrificed.*

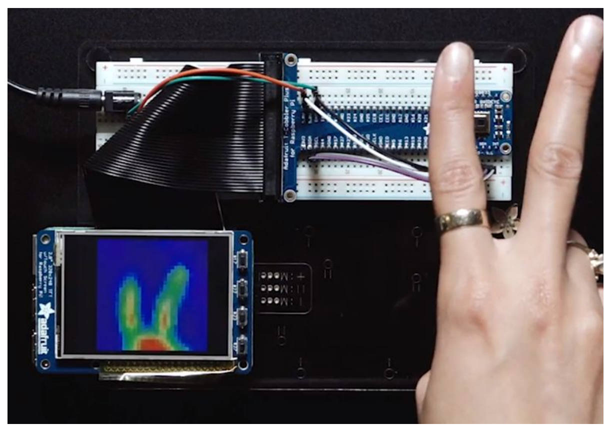


Figure 4. *Camera view showing the AMG8833 thermal camera display. Camera is hooked up to an arduino microcontroller via breadboard as seen.*

The second design, the AMG8833 thermal camera, allows for coupling with a microcontroller for thermal image capture. This imaging option is intriguing in terms of cost effectiveness relative to the FLIR Camera. This particular device, when connected to a microcontroller for image capture outputs an array of 64 IR readings, which can be interpolated to provide a better estimate of the heatmap. Additionally, the camera allows for thermal imaging of objects between 0 - 80 ℃ which includes our working physiological range. With this design cost is kept quite low at only $40 but this is reflected in the thermal specificity of +/- 2.5 ℃ which is not adequate for detecting the 2.2 ℃ temperature differences our algorithm requires.

Design 3 – MLX90640 + Raspberry Pi

Figure 5. *Image of the MLX90640 thermal camera. This camera provides better image quality for a price not significantly more than that of the AMG8833*

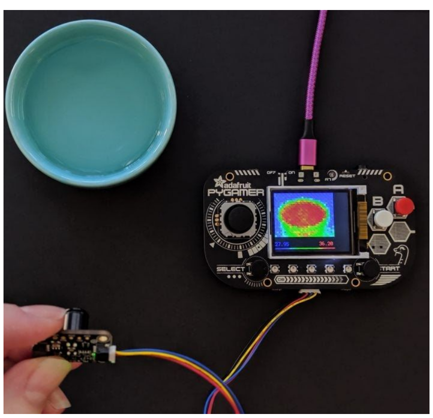


Figure 6. *Image of the MLX906040 thermal camera coupled with a microcontroller. Pictured is a thermal image of a cup of water.*

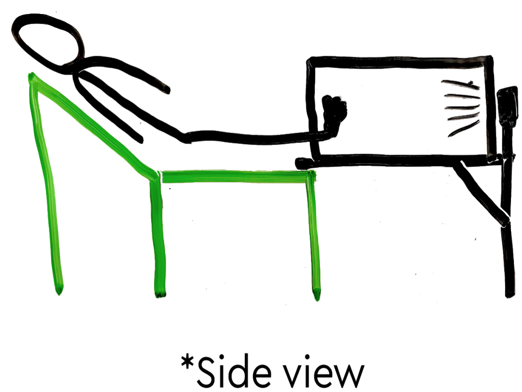


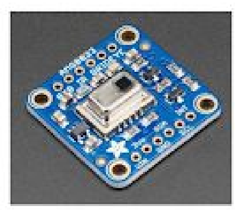
Figure 7. *Side view sketch of the camera coupled with our imaging box. The box will help to provide consistent image quality while being transportable.*

The third design is the MLX90640 thermal camera that can be coupled with Raspberry Pi microcontroller. The camera itself has an IR resolution of 32x24 pixels. Despite having much lower resolution than the FLIR camera, this imaging option is worth considering given its low price, which is about $60. It can output temperatures ranging from -40ºC to 300ºC with an accuracy of +/- 0.5-1 ℃ when operated within 0-50 ºC ambient temperature. Therefore, even though this camera is more expensive than the AMG8833, it provides accuracy that is adequate for detecting the 2.2ºC temperature difference and allows for an effective image analysis.

IV. Preliminary Design Evaluation

Design Matrix

Table 1. *Design Matrix Evaluation of various thermal devices to be used for image capture. Each design was graded in each category on a scale of 1 (worst) to 5 (best), and was evaluated with weighted categories. Total points displayed at bottom out of 100.*

Criteria	Weight (Design)	FLIR ONE Pro 		Adafruit AMG8833 		Adafruit MLX90640 	
Accuracy	(15)	5/5	**15**	3/5	9	4/5	12
Resolution	(30)	5/5	**30**	3/5	18	4/5	24
Battery life	(20)	1/5	4	4/5	**16**	4/5	**16**
Cost	(30)	1/5	6	5/5	**30**	4/5	**24**
Ease of Fabrication	(5)	4/5	**5**	4/5	**4**	4/5	**3**
Totals	**(100)**	60		**77**		**79**	

Accuracy

Accuracy is defined by how close the temperature readings taken by the camera are to the actual temperature of the feet. It was given a weight of 15 as it is important for effective image analysis, however, it was not one of the main categories that we are aiming to approve upon.

Resolution

Resolution is defined as the number of pixels the camera produces when capturing an image, or in other words how defined the picture is. This was given a weight of 30 as low resolution would not allow to distinguish between any "hot spots" on the foot, preventing the development of any effective data analysis tools.

Battery Life

Battery life is defined as the amount of time the battery can provide power after being fully charged. This was given a weight of 20 as it is very important that the device is able to go a full day (or at the very least the majority of the day) without needing charging.

Cost

Cost was defined as how much the camera cost, as well as how much it would cost to purchase additional necessary parts (microcontroller etc). It was given a weight of 30 because our product is being designed for use in low-income hospitals in India, keeping cost low is crucial.

Ease of Fabrication

Ease of fabrication was defined as how much additional work would be required to make the thermal camera into a functionable imaging option (coupling with microcontroller etc). Ease of fabrication was given a small weight, 5, because fabrication should be brief and a one-time commitment.

Proposed Final Design

Thermal Image Acquisition System

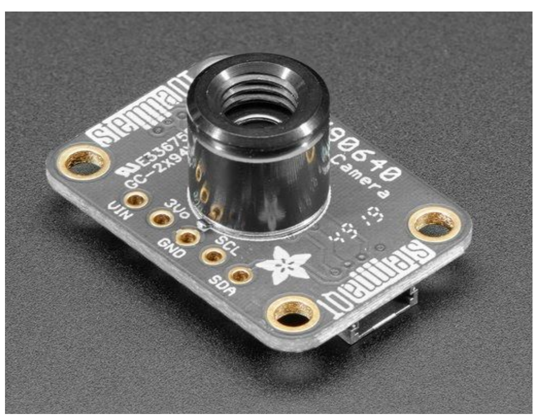


Figure 8. *Image of the MLX90640 thermal camera. This camera provided the best imaging quality for a price that fell within our Budget.*

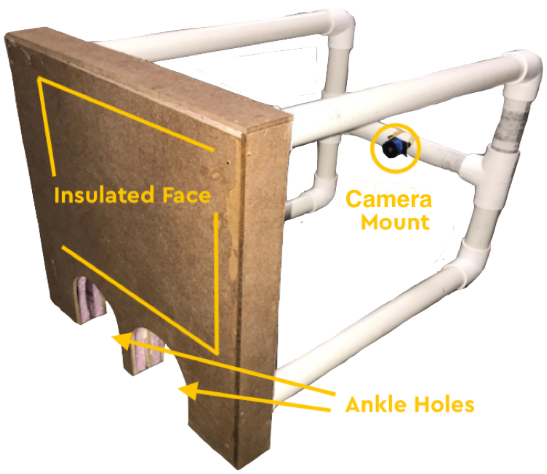


Figure 9. *Image of the standardized imaging box that the thermal camera and microcontroller will be coupled with. Imaging box will help to provide consistent thermal images.*

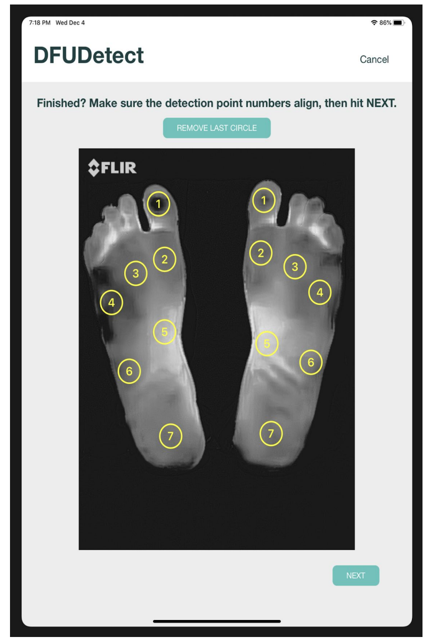


Figure 10. *Screenshot of our mobile application interface. Images from the MLX90640 will be coming here. Extracted data can then be stored in a database after analysis.*

The proposed final design is Design 3: the MLX90640 thermal camera paired with a Raspberry Pi microcontroller. This device proved to maximize the quality of thermal sensor while not sacrificing other important qualities. The FLIR, while possessing the highest quality thermal sensor, sacrificed far too much in terms of price, battery life, and ease of utilizing for image processing (the FLIR application makes further image processing difficult, as previously mentioned). Additionally, the accuracy of the MLX90640 thermal sensor is quite similar to that of the FLIR while operating at room temperature; as we expect the device to typically be operating at room temperature, this further qualifies the MLX90640. The AMG8833 on the other hand sacrificed far too much image quality without a significant price difference to be justifiable. The final design should provide adequate image quality and be easy to utilize for further image processing as it is powered by a microcontroller.

V. Fabrication/Development Process

Materials

Image capture: As mentioned, the MLX90640 camera was purchased as well as the Raspberry Pi. A USB-C power supply will be purchased for the Raspberry Pi. A Qwiic adapter and breadboard jumper will be used for microcontroller pinouts. A casing for the camera, microcontroller, and battery pack will be made from polylactic acid.

Imaging studio (previously constructed): We used ¼" particle board for the face of our box. Using polymer construction adhesive, half-inch polystyrene foam was sandwiched in between the particle board to provide insulation, allowing us to get more accurate thermal imaging of the feet. We purchased two 1.25" x 10' PVC pipes with elbow fittings. The use of PVC pipes allows our box to be dismantled for portability. We purchased screw tab caps to connect the PVC pipes to the face of the box.

Methods

Imaging studio (previously constructed): We used a handheld circular saw as well as a bandsaw to cut two 18" x 18" sections of ¼" particle board, which we smoothed with sandpaper. With the bandsaw, we cut two 4.5" diameter circles into each section of the particle board to serve as footholes. With a knife, we cut the polystyrene foam to fit between the two sections of the particle board. Using construction adhesive, we glued the two faces together with the insulating foam sandwiched between the two. We cut scrap pieces of particle board, which we glued between the faces to cover up the insulating foam and make the box more visually appealing. We screwed tab caps to the four corners of the box, which were fitted to connect with the 1.25" PVP pipes. We then cut the PVC pipes into four 20" tubes and three 16" tubes, using elbow fittings to construct a frame. Edges of the board were sanded so that they were all even; pieces were then cut to size and secured with wood glue and nails.

Software was first developed using MATLAB (see Appendix C) in which a user was able to grayscale an image, select points on this image to estimate foot height, then select multiple detection points and calculate the average pixel value within the circle. The underlying code structure was then implemented in Swift 5 to make an IOS application which had all of these features and additionally allowed the user to enter patient information, score the data, and save the results to a database. Scores were calculated based on multiple different parameters including a 2.2 ºC difference between corresponding points, the average temperature of the foot, and other measurements identified by our client to be indicative of ulceration risk based upon prior research and data she has collected previously.

Assembling the electronics will first involve connecting the MLX90640 with the Raspberry Pi. The team will use the I^2C communication protocol with the Raspberry Pi being the master and the thermal camera being the slave in this situation. This communication protocol will allow for multiple other electronic components in the future to be interfaced very easily as well as provide a simple way of transferring image data from the thermal camera to the microcontroller with minimal soldering and wiring. The next step will be to perform initial communication and preliminary processing on the Raspberry Pi with Python being the preferred choice for software. Python is advantageous as it will provide a smooth process for the next step: connecting the Raspberry Pi to our pre-programmed database (Firebase) via wifi. Once a connection is made to the database, that data can be retrieved using the pre-programmed IOS application (see Appendix B) to display images and perform higher level image analysis. A backwards software connection will then be made between the IOS application and the thermal camera, using the database and the Raspberry Pi, to control the camera from the mobile application as well as other electronic processes. With time allowing, additional electronic components including a battery pack, battery charger, ultrasonic distance sensor, and LCD display will be interfaced to further improve the portability, ease of use, and increase the amount of data collected.

Final Prototype

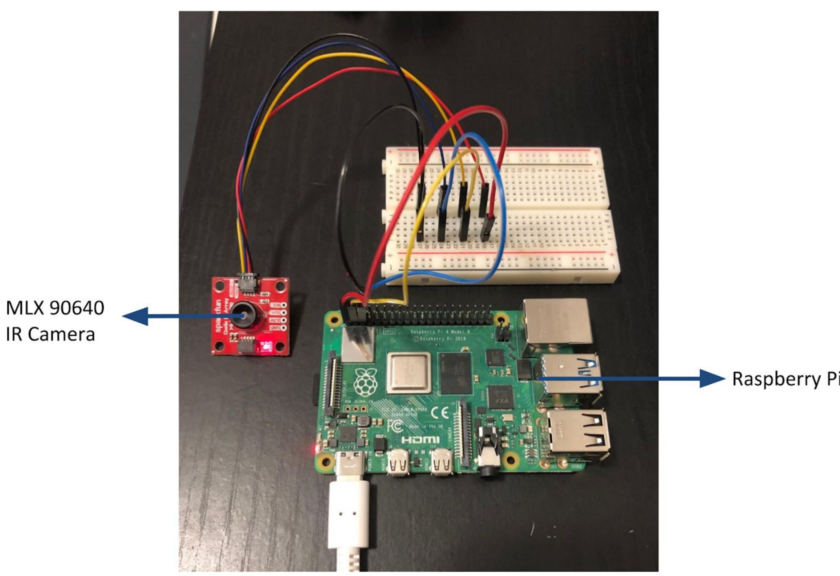


Figure 11. *Configuration of the MLX90640. A Raspberry Pi microcontroller was used to power the camera and receive inputs from the camera to send to a computer.*

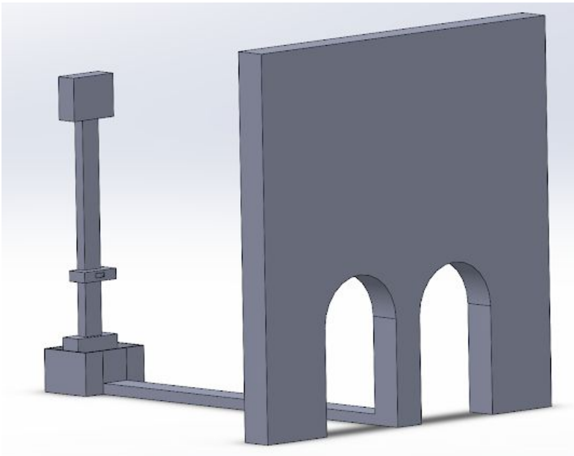


Figure 12. *SolidWorks was used to create a CAD model of the imaging system we hoped to design. A stepper motor would be used to control the camera in order to take multiple images of the patient's feet and stitch them together to improve camera resolution.*

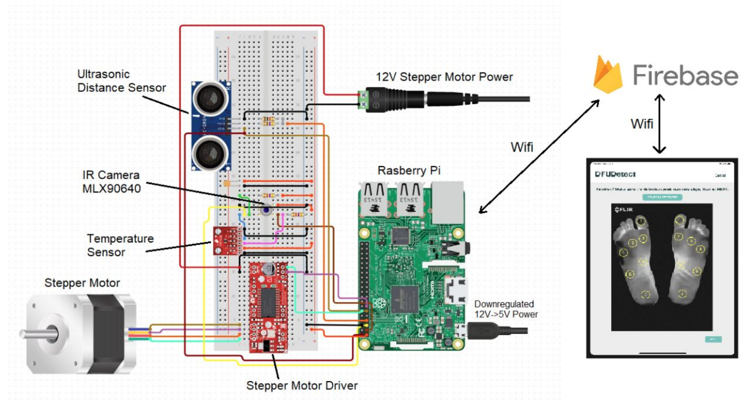


Figure 13. *Circuit Schematic of the Intended Imaging System. A temperature sensor, an ultrasonic distance sensor, a stepper motor, and a stepper motor driver are connected to the Raspberry Pi*

Apart from the MLX 90640 thermal sensor, several other sensors and motors that function to improve the quality of the thermal image are also added to the system. The complete circuit schematic can be seen in Figure 13. A stepper motor that is attached to a GT2 belt is programmed by the Raspberry Pi to move the camera along a vertical linear rail. This can further enhance the output resolution by stitching multiple images together. Another additional component is an ultrasonic distance sensor to input the distance between the camera and the feet to allow for precise image capturing. The acquired pictures and packaged data will then be sent using WiFi connection from the Raspberry Pi to the database, and finally to the mobile application for further processing.

The imaging system consisting of the electronic components will eventually be coupled with the imaging box that was previously constructed. The purpose of the box is to provide insulation and prevent heat from the rest of the patient's body from interfering with the images taken. The box is attached to a linear slider, which allows it to be extended or retracted when focusing the camera. A CAD model displaying the whole imaging system can be seen in Figure 12.

Testing

To determine whether the MLX90640 camera would provide adequate image quality for the purposes of our project, we attempted to perform tests to compare to a gold standard camera used as a baseline. The gold standard camera we used was the FLIR E5 provided to us by the UW -

Madison BME Department. This camera served as the control due to the high quality thermal images it provides. The microbolometer technology present in the FLIR E5 is the industry standard for high precision handheld thermal imaging devices. This is in part because of the repeated calibration for each image, this feature controls ambient temperature, reflection, and emissivity better than cheaper cameras. The FLIR E5 has a 160 x120 pixel display, providing a high spatial resolution; having good spatial resolution is crucial for being able to detect the location of specific hotspots indicative of an ulcer. It also has good thermal sensitivity (< 0.1 ℃ / < 100 mK) and thermal resolution (+/- 2% for ambient temperatures 10-35 ℃ and object temperatures above 0 ℃). These specifications for the FLIR E5 camera were outlined in the camera specifications datasheet; however, we also tested these metrics of the FLIR E5 in order to have experimental data to compare to that of the MLX90640 camera.

To test thermal resolution a heat dissipation curve was created, with this test we hoped to see a smooth linear curve denoting that the cameras were capable of recognizing small changes in temperature. A poor test result would resemble a stepwise function with rather discontinuous jumps in temperature. This test was conducted by heating a glass of water to approximately 49 ℃ validated by a simple meat thermometer. The water was then left unaltered to slowly cool. Each respective camera was used to capture thermal images of the cooling water every 15 seconds for the first five minutes and every 60 seconds for the next five minutes. Temperature analysis of these images for each camera was then used to create a heat dissipation curve, the curves were then compared to test the temperature resolution of the MLX90640 camera against the gold standard FLIR E5 thermal camera.

To test spatial resolution, ulcers were simulated on a subject's foot by pressing a warm coin against the foot, removing it and then imaging the foot. This experiment allowed us to analyze each camera's ability to detect a temperature difference of at least 2.2 ℃in the simulated hot spot. To simulate foot ulcers, we conducted nine unique trials. The coin was heated in 49 degree Celsius water for either 1, 3, or 5 minutes. Following heating, the coin was pressed on one of the three most common locations of foot ulcers: the first metatarsal, the 5th metatarsal, or the heel. Each combination of these two experimental conditions yielded the nine unique trials.

VI. Results

While the MLX90640 was previously working during preliminary setup and showing thermal data changes, upon further setup the camera stopped outputting data. Further troubleshooting and research found that the I^2C communication protocol was impaired and the board could not output data to the Raspberry Pi. It was found that others who bought the camera board experienced a problem with the SDA pin on the MLX90640 when the board reached a certain temperature after continued use. When testing the I^2C communication, “i^2Cdetect” can be used to show the address for any devices currently connected. This is done by letting the SDA pin float high and any device on the communication protocol will pull the pin low ultimately detecting the device. When we used “i^2Cdetect” all addresses were shown to be connected meaning that the SDA pin was always pulled low indicative of a short in the breakout board.

This problem was irreversible and as a result of this failure, we were not able to perform the testing protocol on the MLX90640 camera. Qualitative measurements during preliminary setup showed the ability to pick up hand movement and display realistic body temperatures, but the data is obviously not definitive.

Although comparison was not possible, gold standard experimental data for accuracy, resolution, and spatial resolution were determined. A linear heat dissipation curve was constructed with the FLIR E5 showing a root mean squared value of .88. The smallest temperature change that was recorded by the FLIR E5 in this test was .1204 degrees Celsius. In terms of spatial resolution, the FLIR E5 was able to detect temperature differences of at least 2.2 degrees Celsius between the two feet in all 9 simulated ulcer trials. The average temperature difference found was 2.89 +/- .76 degrees Celsius.

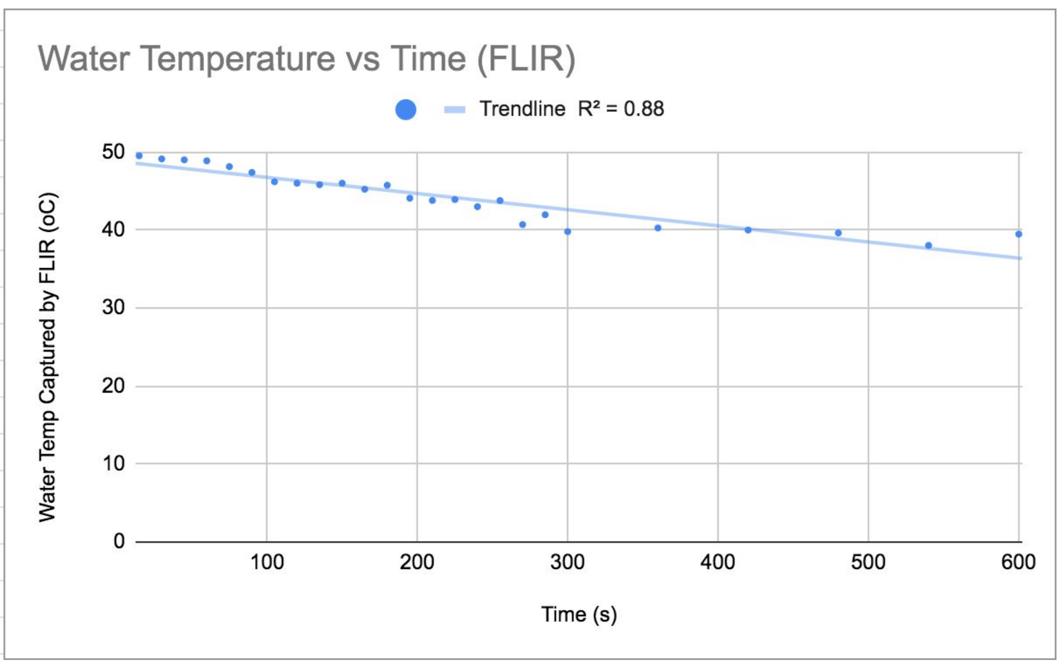


Figure 14. *Plot of heat dissipation with regression curve. Data shown is for FLIR E5. The thermal resolution of this camera is very good as expected, showing the ability to detect minute changes in temperature.*

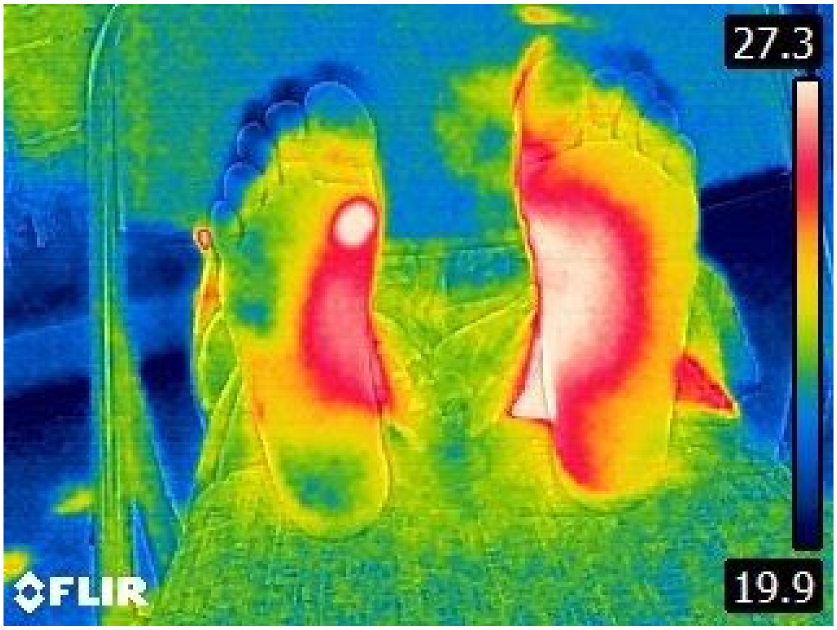


Figure 15. *Image taken from the ulcer simulation test. The FLIR E5 displayed very good spatial resolution. The simulated ulcer can very clearly be seen on the right first metatarsal. The average temperature difference found was 2.89 +/- 0.76 ℃.*

VII. Discussion

The FLIR E5 proved to be successful in acting as the gold standard for which to compare the MLX90640 camera. The heat dissipation curve yielded a linear regression with a mean-squared value of 0.88, therefore demonstrating very good thermal resolution. Additionally, a temperature change of 0.1204 ℃ was detected, demonstrating the ability of the camera to detect small changes in temperature. In the spatial resolution test where mock ulcers were created, the FLIR E5 was able to detect an average difference in temperature of 2.89 ℃ with a standard deviation of +/- 0.76 over the nine images captured. This proved the FLIR E5 provides very good spatial resolution, certainly good enough for the purposes of this project.

There are certainly some sources of error that could come about during the tests. Particularly, as such small temperature differences must be able to be detected, it would be best to test both cameras at the same time, taking an image on each one as the tests are performed; the consistency in images being taken between the two cameras would make for the best comparison. This did not happen as different members of the team were performing tests with each camera and were geographically separated, forcing them to have to reproduce identical testing parameters to the best of their ability. To best minimize error in this regard, protocol was carefully recorded while testing the FLIR E5 so that it could be repeated with the MLX90640 to yield the best possible results. Still, it is likely that there were some errors in testing parameters due to temperature differences. Additionally, there was debate over what to treat as the “real” temperatures. Initially, a meat thermometer was going to be used to detect the real temperature, and the accuracy of the FLIR E5 and MLX90640 would be determined based on that. It was later decided, however, that the meat thermometer may not provide the best accuracy and would introduce an additional variable. The temperature readings of the FLIR E5, then, would serve as the “real” temperature. These are also not completely accurate as the accuracy of the FLIR is +/- 2 ℃, but it was adequate for the purposes of this project, as accuracy is not necessarily the most important quality of the camera.

VIII. Conclusion/Future Directions

Although the team was not able to collect all of the necessary testing data to arrive at a definite conclusion as to whether the MLX90640 camera was a viable substitute for its predecessor, the FLIR One camera, we believe the MLX should continue to be developed in the future. Preliminary qualitative measurements made before complications arose while developing the software for the MLX showed at least the ability for the MLX to pick up hand motion and temperature changes that were expected of surface skin temperatures. While this is far from definitive, no data collected negatively impacted the outlook on the MLX. Board complications were found to be localized to the specific retailer and breakout board that was chosen, therefore we do not expect this will significantly hinder any future development. Subsequent iterations of the MLX design will still need to be compared to a gold standard thermal camera like the FLIR E5. Additionally, more controlled analysis comparing our ulcer detection scoring algorithm with the MLX and the FLIR E5 will need to be performed in a simulated and ultimately a clinical IRB setting to test viability for real clinical applications. Based on this semester, we suggest future project iterations to focus on creating more controlled testing protocols not achievable this semester in a virtual setting as well as focus on future categories laid out below.

MLX90640 Enhancements

A large segment that this semester's team was not able to focus on was enhancing the capabilities of the MLX90640 beyond single image capture. An image stitching system was proposed where the MLX camera would be panned vertically along both feet with images taken at multiple points via a linear actuator system. Camera movement would be controlled via a stepper motor attached to a GT2 belt with camera position ultimately controlled through the Raspberry Pi (RP) by moving the camera along a vertical linear rail. Image stitching would be performed post image capture with the RP using either position calibration via stepper motor feedback and/or physical feature extraction with an RGB camera for alignment. The ultimate goal for image stitching would be to increase the output resolution from 32 x 24 (px) with single image capture. From preliminary analysis we believe an increased spatial resolution will allow for increased spatial accuracy and precision of the MLX camera in detecting hotspots on the foot. This is due in part from the ability to pick up on more localized heat differences on the foot and by more effectively centering the ulcerated foot in the camera's field of view which would be the more thermal sensitive region of the camera. Another possible future enhancement includes the use of a distance sensor and modular box assembly to allow for a precise and repeatable camera distance from the foot. The MLX has a manual focus making the distance between the camera and subject important for most accurate results. A distance sensor could output to the mobile application to notify the physician to extend or retract the imaging box to reach the required distance for optimal focus.

Software Improvements

Currently there are four main categories for software in this project: 1) control of the movement and electronic components, 2) post image processing and data packaging occurring on the RP, 3) subsequent transfer of data to the mobile application via WiFi, and finally 4) image analysis and machine learning to output a diagnosis relating to ulceration risk and displaying the data in a digestible manner on mobile. We expect the RP post image processing and packaging (2) and image analysis (4) to be among the most daunting of the previous tasks and a major focus for future projects. Post image processing will include image stitching as mentioned previously and possibly color image overlay for increased visual acuity for diagnosis. Data packaging will be another hurdle to send data quickly and will include a tradeoff for processing time on the RP versus on mobile. Image analysis began last semester with grayscale transformation with average temperatures extracted from common ulceration regions that were manually selected on mobile. The paired locations on the feet were compared on both feet and scored for ulceration risk based on literature values discussed previously. A more effective algorithm should be developed to extract and isolate foot thermal data from background which may include but not limited to, K-means clustering, support vector machines, and histogram methods. Automation of temperature region selection is crucial in removing human error from manual selections. It will also be beneficial in including temperature data from the entire foot and not just common ulceration regions. More advanced deep learning and machine learning pathways are promising possibilities for more accurately classifying ulceration risk after data extraction but more training and testing data will be needed from an IRB clinical study to effectively apply these methods.

IX. References

[1] S. Kaveeshwar, “The current state of diabetes mellitus in India,” *Australasian Medical Journal*, vol. 7, no. 1, pp. 45–48, 2014.

[2] “The global burden of diabetic foot disease - ScienceDirect.” [Online]. Available: https://www-sciencedirect-com.ezproxy.library.wisc.edu/science/article/pii/S0140673605676982 . [Accessed: 09-Dec-2019].

[3] I. Kruse and S. Edelman, “Evaluation and Treatment of Diabetic Foot Ulcers,” *Clinical Diabetes*, 01-Apr-2006. [Online]. Available: https://clinical.diabetesjournals.org/content/24/2/91. [Accessed: 29-Apr-2020].

[4] C. Liu, J. J. V. Netten, J. G. V. Baal, S. A. Bus, and F. V. D. Heijden, “Automatic detection of diabetic foot complications with infrared thermography by asymmetric analysis,” *Journal of Biomedical Optics*, vol. 20, no. 2, p. 026003, Nov. 2015.

[5] C. Liu, F. V. D. Heijden, M. E. Klein, J. G. V. Baal, S. A. Bus, and J. J. V. Netten, “Infrared dermal thermography on diabetic feet soles to predict ulcerations: a case study,” *Advanced Biomedical and Clinical Diagnostic Systems XI*, 2013.

[6] L. Fraiwan, M. Alkhodari, J. Ninan, B. Mustafa, A. Saleh, and M. Ghazal, “Diabetic foot ulcer mobile detection system using smart phone thermal camera: a feasibility study,” *BioMedical Engineering OnLine*, vol. 16, no. 1, Mar. 2017.

[7] BRAND PW (1989). Repetitive stress in the development of diabetic foot ulcers. The diabetic foot./4th edition./edited by ME Levin, LW O'Neal p83-90.

[8] Reyzelman AM, Koelewyn K, Murphy M, Shen X, Yu E, Pillai R, Fu J, Scholten HJ, Ma R “Continuous Temperature-Monitoring Socks for Home Use in Patients With Diabetes: Observational Study”, 2018.

X. Appendices

A. Product Design Specifications

Title: Development of a diagnostic device and mobile app for the early detection of ulcer formation in the diabetic foot

Team Members: Jarett Jones, Thor Larson, Carson Gehl, Tamarin Tandra

Function: Our client has provided us with an IR camera (FLIR $315) that she previously used to take images of 250+ feet in India, all somewhere on the spectrum towards ulceration. We are tasked with developing an artificial intelligence program based on these images that has the ability to discern patients at low high risk for ulceration from those at high risk. A mobile application should also be developed for easy patient access. Additionally, a camera-mounting prototype needs to be designed and fabricated to allow for consistent measurement of patients' feet.

Client requirements:
- Mobile application to score thermal images for likelihood of ulcer formation
- Application should automate image analysis
- Apparatus to standardize thermal imaging
- Low-cost use in rural Indian hospital (<$150)
- Utilize variables such as typical ulcer location, typical ulcer size, temperature location etc to improve accuracy
- Crowded hospitals require portability of the imaging device (easily carried with 2 hands)

Design requirements:
- Imaging device: ~$150 to be implemented in a rural hospital where cost is a main concern. May be achieved with validation of low-cost thermal camera in comparison to $315 gold standard (FLIR).
- The device needs to be able to travel overseas to India.
- Device needs prioritize sensitivity over specificity in detecting patients early-stage diabetic foot ulcers.

1. Physical and Operational Characteristics

a. Performance requirements: As diabetes is an epidemic in India, this device will be used very frequently throughout a typical day, therefore it should have a battery life that lasts at least one day. It will be exposed to hot temperatures, which it needs to be able to withstand while still providing accurate measurements and data outputs.

b. Safety: Patients falling may be a concern if a patient is made to stand on top of an imaging device. Many patients who are at greatest risk for ulceration are elderly. Thus the device should allow for pictures to easily be taken either from a sitting (wheelchair) or lying down position (hospital bed). No safety concerns aside from typical electrical hazards from IR camera and telephone. Radiation is at a low enough wavelength (~750-1000 nm) to not be of concern.

c. Accuracy and Reliability: Our analysis of thermal foot images should precisely detect temperature differences of 2.2 ℃. It is not necessary for the temperature readings to be particularly accurate, but they must be precise. A component of our project is to reduce cost and experiment with lower quality thermal cameras that will test the necessary bounds of precision for our device to accurately identify ulcers. Therefore, the required temperature precision is to be determined.

d. Life in Service: The hospital device will be used 30+ times per day and needs to last several months to years. The physical components of our project include a portable phone rig, phone, and thermal camera attachment. Each of these components need to last at least a day without charge and withstand regular to heavy use. Longer battery life would be desired, but a single day allows for time to charge overnight.

e. Shelf Life: Life-time warranty. The IR-camera is equipped with a rechargeable battery giving it longevity in terms of shelf-life.

f. Operating Environment: The device will be used primarily in the hospital where temperature and humidity are relatively constant (~20 C, ~50%). There may be times during its transportation in which the device will be exposed to a hot and dry environment with possible accumulation of dust as well as significant noise levels. Temperature ranges in India regularly are between 25-50 C, or 77-122 F.

g. Ergonomics: The device should include a position for the patients' feet to stabilize for the imaging device while the patient is either seated or lying down in a hospital bed. Creating a consistent background (via a wet cloth or other material) needs to be inherently part of the design.

h. Size: The device needs to be portable to move quickly around the hospital. Small enough to be carried by hand, possibly foldable or retractable, and able to either be shipped in a suitcase or built upon arrival. Currently, the client uses box holder which has 2 degrees of freedom for taking photos. Sizing this down to make it more portable would be of interest.

i. Weight: The end goal is for patients to be able to self-monitor their disease from home. For this reason, nothing should be too heavy or bulky, as patients have varying health and physical strength, and it is necessary to be inclusive to all patients regardless of this. We will limit the weight to 35 lbs.

j. Materials: In the design of the “photo booth” device, there should be no heat-emitting materials as this would significantly affect the images being taken. All materials should be durable to aid in expanding the lifetime of the product. No particular materials have been determined or ruled out.

k. Aesthetics, Appearance, and Finish: As this is an application to be taken to a third world country in which healthcare does not receive the funding that it does in the United States, we are solely concerned about functionality, and not about aesthetics. The mobile application should be user friendly.

2. Production Characteristics
a. Quantity: We have been asked for just one device, although producing numerous products after the original has been tested may be of interest.

b. Target Product Cost: Our team would like to keep total product cost under $150 for use in hospital, and eventually reducing the cost to under $50 for in-home use. This figure does not include the thermal camera that has been provided to us. Most of our team’s expenditures will be materials costs for the fabrication of the box.

3. Miscellaneous
a. Standards and Specifications: Our client has IRB permission through the Christian Medical Hospital in India that was used to obtain preliminary study images. Currently, in collaboration with our client we are seeking IRB approval through the Veterans Administration hospital in Madison WI, to image diabetic feet locally.

b. Customer: The main priority is to minimize patients time in-clinic, as their livelihood depends on daily income and missing even a day of work produces a great burden for the patients. Shoe or sock related devices are viewed as ineffective in India as most of the population does not wear shoes.

c. Patient-related concerns: Patient data will be stored on the mobile device for use in clinical trials. The patients information is not linked to the images being taken, and the patients will not be identifiable from the images alone. Additionally, client has gotten IRB approval to collect images from patients.

d. Competition: There are many products that are nearly identical to the product we have been asked to develop. The main improvement our client is hoping for us to achieve is the implementation of a clinical trial to test the validity and viability of the AI algorithm and product.

B. DFUDetect Swift 5 IOS Application

The IOS application we will be using to that will ultimately take the thermal data and make it into a visual image for analysis. The application currently has the ability to analyze uploaded images and connect to a database. Multiple important functions were included, excluding any user interface functions. The function “touches began” calculates the positions of the circles based off of the user input and displays them to the user. The function “averagePixelValueInRadius” iterates through pixels within the radius specified and at the origin of the circle selected and stores the data into an array. The “calculate” function separates and scores the right and left foot data based off the multiple threshold values and parameters described in the comments. Additional important parts of the software include calculating the circle radius based upon foot height and uploading the patient info and results to a database.

```
override func touchesBegan(_ touches: Set<UITouch>, with event: UIEvent?) {

        for touch in touches {

            if let image = analysisImageView.image {

                let adjRect = AVMakeRect(aspectRatio: analysisImageView.image!.size,
                insideRect: analysisImageView.bounds)
                let adjLocation = CGPoint(x: (touch.location(in: view).x - analysisImageView.frame.minX),
                y: (touch.location(in: view).y - analysisImageView.frame.minY))
                if !adjRect.contains(adjLocation) {return}

                let circleCenter = touch.location(in: view)
                let circleDiameter = CGFloat(diameter)
                let originX = circleCenter.x - circleDiameter/2
                let originY = circleCenter.y - circleDiameter/2

                let adjFrame = adjRect.insetBy(dx: circleDiameter/2, dy: circleDiameter/2)
                if !adjFrame.contains(adjLocation) {return}

                let circleView = CircleView(frame: CGRect(x: originX, y: originY,
                width: circleDiameter, height: circleDiameter))


                if circles.count > 13 {
                    return
                } else if circles.count > 6  {
                    circleView.numberLabel.text = String(circles.count - 6)
                } else {
                    circleView.numberLabel.text = String(circles.count + 1)
                }

                view.addSubview(circleView)
                circles.append(circleView)

                checkDirections()

                let scaledX = Float(adjLocation.x - adjRect.origin.x) *
                Float((image.size.width)/(adjRect.width))
                let scaledY = Float(adjLocation.y - adjRect.origin.y) * Float((image.size.height)/(adjRect.height))
                let scaledRadius = Float(circleDiameter/2) * Float((image.size.width)/(adjRect.width))

                let pixelValue = averagePixelValueInRadius(radius: Int(scaledRadius), centerX: Int(scaledX),
                centerY: Int(scaledY), image: analysisImageView.image!)
                let tempValue = ((pixelValue/Float(255)) * Float(maxTemp - minTemp)) + Float(minTemp)

                tempValues.append(tempValue)

                print(tempValues)
            }
```

```
        }
    }

    func averagePixelValueInRadius(radius: Int, centerX: Int, centerY: Int, image: UIImage) -> Float {

        let rgba = RGBAImage(image: image)

        let rStart = centerY - radius
        let rEnd = centerY + radius

        var rgbArr: [UInt8] = []

        for r in rStart...rEnd {
            for c in 0...rgba!.width {
                let diff = pow(Decimal(radius), 2) - (pow((Decimal(centerX - c)), 2) + pow((Decimal(centerY - r)), 2))
                if diff > 0 || diff == 0 {
                    rgbArr.append((rgba!.pixel(x: c, r)!.rValue))
                }
            }
        }

        var total: Float = 0

        for pixelValue in rgbArr {
            total = total + Float(pixelValue)
        }

        let averagePixelValue = total / Float(rgbArr.count)

        return averagePixelValue
    }

   func calculate() {

        var score = 0

        var rightData = [Float]()
        var leftData = [Float]()
        var diffData = [Float]()

        for i in 0...6 {
            rightData.append(tempValues[i])
            leftData.append(tempValues[i + 7])
        }

        // Calculate difference, if greater than 2.2, +1 score

        for i in 0...6 {
            diffData.append(abs(rightData[i] - leftData[i]))
            if diffData[i] > 2.2 {
                score += 1
            }
        }

        // Calculate average temp of each foot, if greater than 34, +1 score

        var sumRight: Float = 0.0
        var sumLeft: Float = 0.0

        for temp in rightData { sumRight = sumRight + temp }
        for temp in leftData { sumLeft = sumLeft + temp  }

        if (sumRight/7) > 34 { score += 1 }
        if (sumLeft/7) > 34 { score += 1 }
```

```
        // Calculate standard deviation of each data, if greater than 1.55, +1 score

        if std(arr: rightData) > 1.55 { score += 1}
        if std(arr: leftData) > 1.55 { score += 1}

        // Calculate absolute value of the difference in standard deviations
        // if greater than 0.3, +1 score

        if abs(std(arr: rightData) - std(arr: leftData)) > 0.3 { score += 1}

        // Calculate average difference data, if greater than 0.7, +1 score

        var sumDiff: Float = 0.0
        for diff in diffData { sumDiff = sumDiff + diff }
        if (sumDiff/7) > 0.7 { score += 1 }

        // Calculate average std difference data, if greater than 0.7, +1 score

        if std(arr: diffData) / 7 > 0.7 { score += 1 }

    }
```

C. Preliminary DFUDetect MATLAB Application

The first iteration of the software consisted of the MATLAB application below that had the ability to grayscale an image uploaded, select circles on the uploaded image, and record the average pixel value and the temperature inside the circle and store this data. Our final application built upon the principles of the MATLAB application with the goal of making it quicker, more efficient, and easier to use.

```
close all
clear all

lowTemp = input('What is the min temperature? \n');
highTemp = input('What is the max temperature? \n');
deltaTemp = highTemp - lowTemp;
pixleRange = 255;
collect = true;
circleCount = 1;
regionTemp = 0;
tempArray = strings(2,14);
tempArray(1,1) = 'Click on the Right Toe' ;
tempArray(1,2) ='Click on the 1st Right Metatarsal' ;
tempArray(1,3) = 'Click on the 3rd Right Metatarsal' ;
tempArray(1,4) = 'Click on the 5th Right Metatarsal' ;
tempArray(1,5) = ['Click on the Right Foot' char(39) 's side'];
tempArray(1,6) = 'Click on the 1st Left Metatarsal' ;
tempArray(1,7) = 'Click in the middle of the Right Heel' ;
tempArray(1,8) = 'Click on the Left Toe' ;
tempArray(1,9) = 'Click on the 1st Left Metatarsal';
tempArray(1,10) = 'Click on the 3rd Left Metatarsal';
tempArray(1,11) = 'Click on the 5th Left Metatarsal' ;
tempArray(1,12) = ['Click on the Right Foot' char(39) 's side'];
tempArray(1,13) = 'LArch' ;
```

```
tempArray(1,14) = 'Click in the middle of the Left Heel';

normalRead = imread('Copy of 32.jpg');
normalFile = rgb2gray(normalRead);
imshow(normalFile);
title('Click 2 points on the foot to estimate its height')
[ROWS COLUMNS] = size(normalFile);
normal3Dimension  = repmat(normalFile,1,1,3);

% Gather a line to estimate foot length -> collection size
title('Click once on the top of a big toe')
[x1 y1] = ginput(1);
title ('Click on bottom of the heel of the same foot')
[x2 y2] = ginput(1);
lengthLine = sqrt((x2-x1)^2 + ((y2-y1)^2));
circleDiameter = lengthLine / 10;

%click where you want to take the measurement from
while(collect)
    close all
    %change to temp version of photo incase want to throw away measurement
    tempPhoto = normal3Dimension;
    %display image and title instructions
    imshow(tempPhoto, []);
    title(['Measuring with a circle diameter = ' sprintf('%.1f', circleDiameter) ' pixels. Click the middle of the
Right Toe'])
    if circleCount > 1
        title(['Measure next: ' string(tempArray(1, circleCount))]);
    end

    %Collect the center of the circle
    [r c] = ginput(1);
    n=1;i=0;j=0;
    for i = 1:ROWS
        for j = 1:COLUMNS
            % if a pixel lies within the circle surrounding the dot
            if (sqrt((r-j)^2+(c-i)^2) < 0.5*circleDiameter)
                %add the pixel to the circle matrix for calculation
                circle(n) = normalFile(i,j);
                %change that pixel to RED
                tempPhoto(i,j,:)= [255, 0, 0];
                %increment the circle pixel index number
                n = n+1;
            end
        end
    end


    %check to see if user wants to keep this measurement
    imshow(tempPhoto, []);
    title('Keep this circle? 1 = YES 0 = NO');
    %keyboard input
    keep = input('Keep this circle? 1 - YES, 0 = NO \n');
    if (keep == 1)
        %increment number of circles collected
        normal3Dimension = tempPhoto;
        % calculate the temperature of that region
        regionTemp = (mean(circle)/pixleRange*deltaTemp)+lowTemp;
        %add it to the array of temperatures
        tempArray(2,circleCount) = regionTemp;
        %increment the circle number to be created next
        circleCount = circleCount + 1;
    end

    if circleCount > 14
```

```
        collect = false;
        title('Snag the completed temp data from tempArray variable');

    end

end

score = 0;

r_data = [tempArray(2), tempArray(4), tempArray(6), tempArray(8), tempArray(10), tempArray(12), tempArray(14)];
l_data = [tempArray(16), tempArray(18), tempArray(20), tempArray(22), tempArray(24), tempArray(26), tempArray(28)];

r_data_int = [];
l_data_int = [];

for ind = 1:7
    r_data_int(ind) = str2num(r_data(ind));
    l_data_int(ind) = str2num(l_data(ind));
end
```