Measurement Devices for Custom Shoe Manufacturing

by

Dragos Besliu

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The majority of North Americans suffer from foot problems at some point in their lives. These foot problems can be divided into three domains ranging from mismatch on healthy feet, to small injuries and deformities and extreme sensitivity and deformities. A solution to these problems is the development of corrective shoes. The design of corrective shoes involves three steps: first, the measurement or digitization of the foot to create a model; second, the manipulation of the model and last creation; third, constructing the shoe with the last. This work focuses on developing a foot digitization system or scanner for each of the three problem domains. A good digitization paves the way for development of foot manipulation algorithms and last manufacturing techniques that can be applied to develop well fitting comfortable shoes.

Three scanning methods were investigated in this work. The first was designed for scanning near normal feet and automatically building a 3D approximation of the plantar surface of the foot. This digitizer was successfully built and demonstrated. The second scanner was designed to scan the entire 3D surface of the foot. This scanner was built and used to extract data for building complete 3D models of the foot. The last scanner was designed to measure and modify the pressure distribution of the loaded foot on a controllable surface. This scanner is more capable in creating an optimal corrective shoe, but is more expensive. A pin matrix design was selected and subsystem prototypes were successfully produced and tested.

The first two developed designs provide low cost solutions for modeling feet, for the purposes of corrective shoe and insole creation. The third design explores a method of measuring foot pressure and distributing it via control of a 3D surface upon which the foot is supported.

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Chapter 1

Introduction and Background

The research presented in this thesis is focused on applying and improving existing technology for the purpose of creating better fitting and more comfortable shoes. Shoe making has always been a highly skilled and specific profession; however it has not quickly adopted many of the technological benefits available in the manufacturing sector today. The following introductory sections describe the traditional shoe making process, how it has evolved in modern manufacturing, and the problems faced by customers today.

1.1 Traditional Shoe Manufacturing

In the early days of shoe making, the trade was the forte of skilled shoemakers who ran their own business or apprenticed in larger guilds. Shoes were custom made by hand to fit any customer. This process began by meeting with the customer and taking measurements and tracings of their feet. Next the shoe maker would either modify an existing last or in the case of more expensive service, create a new last for the individual customer. A last is a physical representation of the customer’s foot as shown in Figure 1.

Figure 1: Plastic Last Turned on CNC Lathe

Notice that this is a modern last machined on a CNC lathe, out of plastic stock. It is not yet finished as it still has the turning centers attached. These features would be removed manually to complete the last. Typically lasts were made from wood and amended or modified with cork and leather pieces. The objective of making the last is to create a scale representation of the shape of the customer's foot. The more skilled and experienced the shoemaker the better their capability in making a good last. Once the last was made, measurements would be retaken and tuning would be done to bring it even closer to the measured shape. Upon satisfactory creation of a last, the shoe maker would begin creating the shoe. This is a complex process that will not be described as it is not pertinent to this research focus. The key factor pertaining to this research is that during assembly and construction of the shoe, the aforementioned last is used as the building block upon which the sole and uppers of the shoe are laid out and then joined. Upon finishing the shoe the last is removed from inside. Most lasts have an internal hinge mechanism that makes their removal easy upon shoe completion. Building the shoe around the custom last ensures the closest possible shape to the customer's foot. The customer would then be fitted with the shoes and form, fit and function would be verified by the shoemaker with customer feedback. Some break in period would be expected with most shoes, as time is needed for the leather to stretch and expand to the matching foot shape. This process results in a custom shoe, as it was made for a specific customer, which is well fitting and comfortable.

The process described above is time consuming and requires skill obtained over many years of apprenticeship and training. This resulted in shoes being expensive and only available to the most affluent of society. Most people would have to make do with more primitive shoes or mismatched used shoes. With the advent of the industrial revolution, and large scale development of shoe manufacturing, more complex and better shoes became available to the general population. This was possible as in many other industries by standardization and breakdown of shoe manufacturing tasks into smaller lower skill subsections and incorporating automatic machines and processes for the making of shoe subcomponents.

1.2 Mass Market Shoe Manufacturing

In order to produce a large number of shoes, standardization and the implementation of a low skill workforce is essential. Standardization refers to the minimization of variations or differences amongst products. This means that a large shoe producer will create a series of shoe sizes and only make shoes in those sizes. This is a dramatic change from creating lasts for each customer, as now large industry only uses one set of lasts for all their shoe production. This set ranges in size from smallest to largest with one last for each size increment. The shoes are then made in batches with preset stamped cut parts to match each standard size, and assembled per size. This method of production creates a large mismatch between the population and their shoes. Several studies, referenced in chapter 2, have showed that finding a well fitting shoe is very difficult and most customers end up with poorly fitting shoes. This is due to the fact that feet are not standard and have a very large variation in size and form factor. The sizing systems still used today only correlate one or two linear measurements to size, without any regard for shape. Further complications arise from the many standards in shoe sizes and the variation from manufacturer to manufacturer. For instance a Nike [1] size 10 shoe will have a different shape than an Adidas [2] size 10 with variation in width allowance and instep or ankle girth. This is because these two different manufactures have a different set of lasts that they have created based on their market success and feedback. The result is a large percentage of the population wearing poor fitting shoes.

The use of poor fitting shoes will result in injury with prolonged exposure. These may be small blisters or large impairments; regardless the comfort and walking capability of the customer is highly impended. Several attempts to correct this were made by large industries with the sale and marketing of orthotics or special insoles. This is mostly recognition that mass market shoes are not performing their function and a possible solution for a subset of customers that may find a fitting orthotic. As with mass market shoes, any off shelf orthotic is made to fit a sizing standard that may or may not fit the customer’s foot. While most customers can find a shoe and/or an orthotic insert that fits them relatively well, a large market of dissatisfied customers exists and is growing. This problem becomes larger with age and sensitivity in the feet. This creates a group of customers with chronic foot problems caused by long exposure to poor fitting shoes, or injury, which are forced to seek custom shoes or custom orthotic inserts.

1.3 Custom Shoe Manufacturing & Corrective Shoes

If a customer does not have the good fortune of having feet that closely match an existing standard shoe size, they will seek out custom shoes sometime in their life. Hopefully, before extensive damage or impaired walking emerges. The creation of custom orthotics and shoes today returns to the traditional principles of shoe making, which are to create the best possible fit for the particular client based on their foot size and geometry. Methods in measuring a foot and forming a last are more advanced today and often use molding or impression techniques. This creates a highly accurate geometric model of the customer’s foot which can then be matched to a modified last. This would result in the creation of a custom shoe that would work well with a healthy foot. The customers seeking these shoes usually need more than a good fit, and thus corrective shoes are made. A corrective shoe is based off the measured or molded foot geometry but also adds support to the foot arches and twist or alignment features as needed. The exact corrective needs are determined case by case by an orthopedist that positions the foot in a corrected position and then takes its mold or impression. More modification iterations may be needed once the shoe is made such that pressure is well distributed across the plantar surface of the foot. The result is a custom well fitting shoe that positions the foot in a correctly supported load bearing structure that is comfortable.

To create the shoe described above as with traditional shoe making, an extremely high skill set is needed. This skill set has largely been diminishing in Canadian industry due to the transition of shoe manufacturing overseas. There are few clinics and few shoemakers with the capability of creating orthotic and corrective custom shoes. Furthermore education of new labor into this field is limited as demand for the trade has also diminished over time. The lack of supply and high work requirement places an initial pair of custom shoes at a price range of $2000-$4000 [8]. Subsequent pairs are less expensive if a custom last is reused, but are still around the $2000 range. Despite the high cost of these shoes the work required to create a pair, 50 hours or more, is reducing the profitability in this industry. This fact, along with the difficulties in bringing new labor to the trade is resulting in more out sourcing of work for custom shoes. The high cost of these corrective shoes is again limiting their market share to only the most affluent customers.

1.4 Purpose of Work Presented in this Thesis

The purpose of this research is to apply modern and available technology to the custom shoe manufacturing industry. In doing so reduce the cost and increase availability of well fitting and correctly supportive shoes.

For scope specification, three stages of creating a custom shoe are identified. Measurement of the customer's foot, production of a custom last, and manufacturing of the shoe. This thesis addresses the stage with most improvement potential, which is the measurement of the customer's foot. The production of a last can be highly automated with modern CNC technology once a digital model of the foot is available. The creation of a shoe, from a last, is a long known process that has well established best practices. Hence, improvements in automating shoe creation or improvement of last making were not investigated in this work.

The core focus is to apply modern technology that will produce an accurate digital model of a customer's foot. This model can then be used with automated machines to create a last that will be used to produce a well fitting, corrective and comfortable shoe without need for modification iterations. This model will be a meshed surface created from a set of points with coordinates in three dimensional (3D) space. Using a inter platform storage file system such as stereolithography (.stl) any computer aided manufacturing (CAM) software can be used to create tool paths and automatically machine the last. The model is not only beneficial to creation of custom shoes, it can also be used to obtain better sizing information and for diagnostic purposes. To create this model, three approaches into 3D digitization of the foot were explored.

An industry survey done in conjunction with Podopal Inc, conveyed the importance of low cost technology for successful integration into the industry. A high capital cost barrier has kept existing technology from entering the smaller businesses that work in making custom shoes. Hence the baseline research criteria was creating a good 3D model while minimizing apparatus cost. The cost constraint limits the application domain as more complex foot problems require more expensive measurement apparatus. To address three major domains of foot problems, as described in chapter 3, a division into three distinct digitizer prototypes was made. A digitizer is a device which creates a digital model of a physical object, in this case a foot. The first prototype is a two dimensional flat scanner designed to produce a 3D model of the plantar surface of the foot at a very low cost. The second is a three dimensional scanner designed to produce a 3D model of the entire foot surface. This device was designed to also lower the capital cost threshold to below $10,000 such that 3D scanning can become available to smaller clinics and shoemakers. The third is a 3D variable surface pressure sensor, designed to create the optimal geometric model by incorporating pressure measurement and distribution into the digitization process.

In Chapter 2 the status of the research relevant to the current work is reviewed and limitations of current work and commercially available products are identified. Chapter 3 presents the application domain of and an introduction to each digitizer prototype. Chapters 4, 5 and 6 describe each digitizer in detail.

Chapter 2

Review of Literature and Previous Work

The purpose of this chapter is to provide background information on the research field that this research builds on. This includes brief review of academic work done on foot scanning and pressure sensing as well as industrial technologies that are relevant to this application. As there is a large spread of academic work and industrial technology on the subject of orthotics and custom shoe manufacturing, this review cannot encompass all relevant material. The chapter will present a subset of research and industry products most relevant to this thesis work, and identify limitations in the current solutions. These limitations were used to refine the research objectives presented in chapter 3 and improve the capability and availability of the technology.

The focus of this thesis work is on the field of shoe manufacturing. More specifically, the measurement of a client’s foot for the purpose of creating a custom last. The accuracy of this measurement will be directly correlated to the fit and functionality of the shoe. Traditionally shoe makers would use manual tape measures to size up a client’s feet with flat foot tracings when needed. Shoe retailers today will have a Brannok device [3], which will quickly provide basic length and width information. This information is then used to try and select an appropriate sizing. This method, developed in 1927 is highly outdated. At the time of its initial use a men’s size 10 and women’s 8 was the maximum size for shoe fitting. Since then, improvements in population nutrition and lifestyle have allowed significant growth in foot size and more importantly in foot variation. To accommodate for this variation custom shoe makers will use costly molding and casting techniques to replicate a client’s foot. Mass market shoe producers have mostly scaled their set of lasts to incorporate larger sizes and sometimes a few more width divisions. The lack of a middle ground between basic linear size measurement and casting methods has created an opportunity for the application of modern measurement technology. This technology uses non contact optical measurement to obtain foot geometry. With the implementation of 2D scanning and more advanced 3D scanning, many researchers have applied optical measurement methods to improve and automate foot measurement and shoe or last production. The accuracy and capability of these systems is removing the need for manual measurement or casting even for custom footwear. Furthermore work done in the field of corrective shoes revealed the need for pressure measurement. This added parameter required development of new sensor platforms and brought insight to the correlation of pressure distribution and comfort. The overall goal is to digitize the foot and create a model useful for shoe making. The basic models can be accurate 2D contours while the more advanced models incorporate full 3D geometry and pressure modeling.

As this project incorporates knowledge from several fields of applied science, the sections below divide the review into different approaches to foot digitization and pressure measurement as well as auxiliary research done for better prototype development. The first section reviews studies that have thoroughly identified problems with off shelf shoes and the motivation to improve foot measurement and the subsequently created shoes.

2.1 Problems with Mass Market Shoes

In order to understand the need for the technology developed within this thesis, and by other researchers, the structural problems in the footwear industry that this work strives to resolve must be identified. The foremost problem is the large number of poorly fitting shoes amongst the population. This refers to the majority of customer's purchasing and using poorly fitting shoes. Several studies have confirmed this mismatch through statistical sampling and focus groups, Rossi [4], Collazza [5], and also have shed light on why this is such a predominant problem. The cause is two sided, firstly the manufactures that produce the shoes, and secondly the customers and salespersons who sell the shoes. Mass market shoe producers use several sets of standard lasts to create shoes. The sizing for these lasts is different amongst producers and the shoe sizing system varies from region to region. Since no feet are alike, a customer is forced to try and find a shoe that best fits their foot from the available selection. This is the start of the mismatch process, since at this point poor knowledge of shoe fitting can result in a purchase of unsuitable shoes. For instance three quarters of people have one foot longer than the other, either the left or the right [4]. Fitting a shoe to the smaller foot will then result in the larger foot having an improper fit. And since most customers do not know which of their feet is longer the choice is often arbitrary. Furthermore when full body weight is placed upon a shoe the foot will change in size up to a half size larger [4], thus if both feet were not checked under fully loaded conditions another poor fitting purchase can happen. The purchase of shoes made from traditional materials such as leather, require a breaking in period. What this means is that the misfit between the foot and the shoe will slowly diminish as the material stretches and deforms to accommodate the foot. Leather can stretch up to 40% in length. Unfortunately newer materials such as polyvinylchloride's and urethanes have strong material memory and will not stretch and break in permanently. Hence they will persistently aggravate the foot at areas of poor fit. Thus, a purchased poorly fitting shoe will not break in and remain poorly fitting if made from these materials. Approximately one third of shoes produced today use materials that will not stretch or accommodate misfit. Due to these difficulties in finding a well fitting shoe many customers are forced to make many shopping trips at various locations to try and find a good shoe [4]. This often results in much lost time and wasted product since a shoe that may initially feel like a good fit will create persistent aggravation due to its inability to break in, or an un-noticed poor fit. As there are many different fitting problems: tight fit 22%, narrow toes 19%, poor arch support 14% and sloppy fit 9%, Witana [6], a customer has no way to holistically verify shoe function in the small amount of time spent purchasing a shoe.

Further studies have shown that these predominant misfit problems are not mostly caused by a customer's inability to select a well fitting shoe, but more because there is no well fitting shoe available. Most shoe sizing systems use length as the primary fit indicator and give some divisions within each length for width constraints. This is not enough information to create a good fitting shoe. A study conducted in evaluation quality of footwear fit, Witana [6], showed that by breaking down the shoe into three regions, fore-foot, mid-foot, rear-foot it was easy to identify misfit locations in one or more of these regions. This means that even if a shoe fits well on length and width, it may have poor fit in the mid region or heel support that will result in discomfort or injury. The long term effect of wearing these poorly fitting shoes is injury, impaired walking and reduced walking capability, especially in the elder population. The common injuries can range from minor aggravations such as sores and bunions to more chronic conditions that can permanently distort walking and foot functionality. The medical repercussions and their treatment of these injuries are not the focus of this work, although creation of corrective shoes is a byproduct. Producing a good fitting shoe is the focus of this work. As described in the introduction the first stage in creating a custom shoe is measurement of the foot or the surface that must be fitted. The next sections describe the application of technology to foot measurement.

2.2 Application of 2D Scanning

Two dimensional (2D) scanning is the first approach used to improve the measurement of feet. This method is a good approach to replace manual techniques such as tracings. Often if a shoe was ordered, a shoemaker would take perimeter tracings of the foot, which would then be used to abstract sizing and contour information. The application of 2D scanning replaces this method and highly improves it by providing more accurate information and includes other visible landmarks which can be used in the creation of a better plantar shoe surface. With application of modern computing technology such as CAD and CAM, a 2D scan can be taken and then used to automatically create a model of an insole and automatically fabricate it on a CNC mill, Huang [7]. Previous work, this research builds on, applied this approach to create not only insoles but a fully custom orthotic sandal based on 2D scanned images.

The following is a quick review of previous 2D scanning application research done by Sam Lochner (MASc, Phd Candidate, University of Waterloo). This work was the basis of research done on accuracy enhancements and depth extrapolation for 2D scanning. The objective was to create a custom sandal from 2D scans. The sandal creation process is as follows: an off-shelf 2D scanner would be used to create a left and right side image scan for the plantar surface of the customer's foot as shown in Figure 2 below.

Figure 2: Left Foot 2D Scan

These images would then be uploaded to the processing server where several manual operations would be performed. These include an operator choosing points on an image to create lines for length and width of the foot as well as identifying key features such as the toe crest and ball joints. The automation of identifying landmarks on a foot is under development, however at this stage human input is still needed to identify more difficult landmarks such as the 1st and 5th metatarsal phalangeal joints. Also operator input is used to validate that automatic scripts have run correctly in creating the outline or contour of the foot. Figure 3 shows these landmarks mapped onto a foot scan.

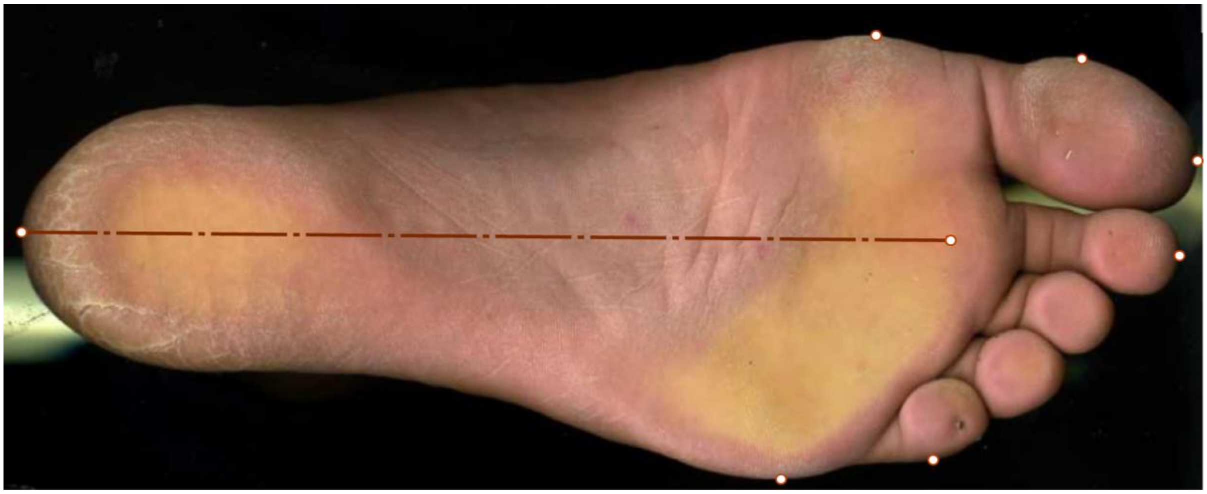


Figure 3: Scanned Foot with Selected Landmarks

Once the operator had finished selecting the landmarks, automatic contouring of the foot would begin and the image would be placed in 3D space where a custom orthotic surface would be extrapolated. This was done with custom scripts programmed into the Rhino CAD application program interface (API) that would take the 2D information and create an orthotic base with designated features such as heel and arch support and a toe crest. Figure 4 shows the progression and result of the extrapolation.

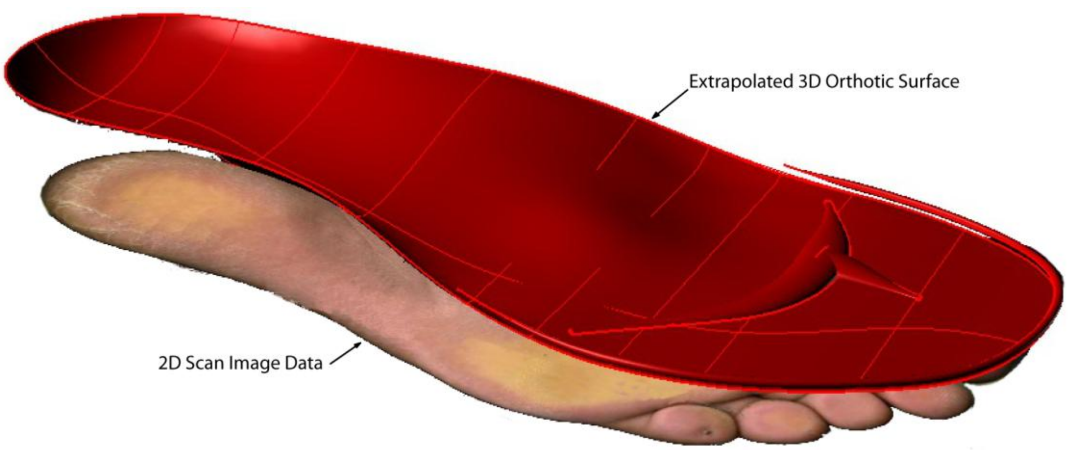


Figure 4: 3D Extrapolated Sandal Sole

This newly created 3D surface would be the sole of a custom orthotic shoe. Using the partnership with industry this technology was applied to create custom orthotic sandals for the summer season.

The sole was made using a CNC mill that cuts out the surface from layered stacks of ethylene vinyl acetate. This is then made into a sandal by adding the sole cover and upper straps. Figure 5 shows the produced sandal, courtesy of Podopal Inc.

Figure 5: Custom Orthotic Sandal

The sandal showed in Figure 5 is not only a custom fit to a client's foot but also has the built in comfort of an orthotic insole surface. Nevertheless, much of the heel height and arch support 3D surface information is an estimation based on standard sizing scaled to the correct foot contour and landmarks. This sandal is a large improvement to off shelf shoes as the outer contour of the foot is the first critical factor in establishing comfort, Tezera [8]. Creating a good contour will prevent any injuries from rubbing or tightness but it does not imply that the foot is supported at the correct heights. As accessibility to technology and computational power improved, academic research became focused on producing 3D models of the foot, and using them to create even better fitting shoes. The downside to this is increasing the complexity of the system and the capital cost in moving from a 2D scanner to a 3D scanner. The need for a low cost 3D model resulted in a research approach of creating 3D models from several 2D images, Luximon [9]. The approach in this work was to use low cost 2D images to create a reliable 3D model. This was done by using a group of 40 participants to create a scaling model that then would be applied on another group of 40 to validate its accuracy. These prediction algorithms provided models that fit within 0.052inches (1.3mm) of error. The downside to creating a scalable geometric model for feet is that there is so much variation which can cause the model to breakdown easily and hence it will work best with normal feet of low variation. Also as there are different sections of the foot that will be scaled differently from client to client, more 2D images would be required to obtain information in each section. The single camera sweeping scanner, such as those used to scan documents, avoids this issue but is still limited by not having any depth extrapolation. An important part of creating an orthotic surface is knowing the height needed for heel and arch support which is not available from current 2D scanners. Furthermore flat scanners have an inherent optical distortion that creates measurement error on surfaces that are farther away from the glass surface. This is problematic for foot scanning as the contour of the clients foot varies in height and what is needed is a true projection onto the glass surface. These limitations are the base for improvements to the 2D scanning platform described in chapter 4.

2.3 Application of 3D Scanning

With the research field shifting to more information and better accuracy, 3D scanning has quickly become the standard in capturing foot geometry. The mechanic for capturing 3D information is more complex than in the 2D scanner and hence several technological approaches are available. One approach is to use a single camera view angle with a projection of a grid or stripe pattern on the scan surface, Gartner [10]. The distortion in the projected grid can then be mapped to depth via geometric triangulation. This type of system is usually more vulnerable to ambient light variations and has lower resolution, due to the limited grid density, than systems that use a sweeping camera with structured light. As a foot scanner may be placed in variable lighting conditions at clinics or stores, it is important that external lighting conditions have a minimal effect on the scan result. Research into robust scanning systems has created designs that use multiple optical paths by incorporating a mirror and beam splitter, Blais [11]. This creates a highly resistant system to external optical disturbance. Many industrial providers of 3D foot scanners such as the Easy-Foot-Scan by Ortho Baltic [12] advertise the scanners ability to withstand direct light injection and still function correctly. Other industrial companies such as IDEAS [13] produce a series of different foot scanners, some using several fixed cameras or sweeping platforms. Often the mechanic of scanning is a projected structured grid or simple triangulation. Regardless of range finding technique the information provided by a 3D scanner is invaluable since it allows full customization of a shoe to fit any client’s foot.

The availability of 3D scanning technology does not immediately result in its application in foot measurement. This is because many less expensive manual methods already exist that have been used successfully to create custom shoe fits. These include foam boxes, and sock or suspension casting. Analysis into the capability of 3D scanning for foot modeling showed that 3D scans were very reliable and repeatable, Carroll [14]. Furthermore limitations and variations were identified with the casting processes due to the inconsistent bias from human input in the process. The 3D scan removes possible error created by operator interaction with the customer's foot and hence becomes a more reliable and more accurate measurement method. Also, 3D scanning is a better long term investment due to its minimal operational cost as it is faster and requires no consumable material unlike the molding methods. Given the accuracy and reliability of 3D scanning, CAD/CAM systems were extended to use 3D model input and automatically create custom lasts as shown in the work of Bao [15]. The reduction in manual work is extensive due to the removal of time consuming casting and manual adjustment of the foot.

The benefit of 3D scanning is not limited to making custom lasts, and has large scale applications such as providing insight into the measurement and specification of feet. Girth is one of the critical parameters in constructing the uppers of a shoe, and its measurement must be done by a skilled shoemaker. With the advent of available 3D models from 3D scanners, work was done to create algorithms that automatically measure the ankle-girth, short and long heel girth to within 0.175inch (4mm) accuracy, Zhao [16]. This again reduces the human factors error and ensures a more reliable foot measurement. Lastly the analysis of a large sample of 3D foot scans can be used to produce generic classification. Studies can be conducted that correlate foot factors with regards to region, age, gender, sports activity, and occupational work as shown by Grimmer [17]. This large scale statistical insight can help large producers of shoes to better tune their outputs and minimize waste product.

The downside of the aforementioned 3D systems is their relatively high cost and low integration accessibility due to proprietary knowledge and intellectual property held exclusively by the manufacturer. By working to create an affordable 3D scanner, low cost 3D models can be obtained much faster than with traditional manual techniques and made available to smaller shoemakers.

2.4 Application of Pressure Measurements

The availability of a precise 3D model is not a complete solution in creating the optimal shoe. Although a good geometric fit will remove any sizing or shape problems, the next stage of providing complete foot comfort is pressure distribution. The distribution of pressure along the plantar surface of the foot is dependent on the geometry of the surface the foot stands on. Pressure distribution is different on flat surfaces than on an orthotic insole. The pressure thresholds of a human foot, identified experimentally, Xiong [18], show that discomfort can result with the application of as little as 5lbs and pain within 10lbs of pressure. Thus any high pressure zones, even on a customer of average weight, can result in chronic discomfort. The problem is exaggerated on overweight individuals and highly exaggerated in individuals with sensitive feet as in the case of diabetic customers. To resolve this problem shoe makers use insoles and padded surfaces that are inserted along the plantar surface of the foot to distribute pressure and create a comfortable support structure. This method is based on trial and error and requires an experienced shoemaker and constant feedback from the client. To get a better understanding of the pressure distribution on a person's foot, several technologies were applied to create foot pressure sensors. This included initial methods of visualization of pressure with ink or photosensitive materials and then progressed to arrays of piezoelectric sensors and then to strain gauges and finally to less expensive resistive sensors, Frederick [19], Rosenbaum [20]. The two dimensional resolution of pressure distribution is increased by using optical measurement methods. However the downside is the low reliability caused by lower grade materials and high sensitivity to cleanliness, temperature and aging of material, Betts [21]. Maintaining an optical measurement platform under heavy use becomes expensive and impractical. Thus, strain gauge systems, although providing lower resolution, are a more reliable alternative. Some of these systems use a flat matrix assembly to create a pressure plate. Resistive sensors can be placed in a dense mat to obtain better resolution form such a pressure plate. Lower cost pressure sensing systems can be made by using a limited array of flexible fingers or with individual strain gauges as in the work of Teodoro [22]. These pressure pads are initial approaches to mapping pressure distribution but they are all based on a flat surface. Although this is useful for diagnostics and detection of collapsing arches, the pressure distribution obtained is not the same as compared to the foot placed in a shoe.

Since no shoe provides a flat sole surface, it is not very useful for shoe making to look at the pressure distribution on a flat surface. Hence several commercially available products such as the Pedar [23] and F-Scan [24] focus on creating thin membrane insoles that can be placed in a shoe on the surface contact area between the foot and the shoe surface or orthotic insole. These systems can provide dynamic pressure distribution information during walking or standing. This tool is highly effective at evaluating how well a shoe or orthotic surface distributes pressure.

As with 3D scanning, the information provided from measuring plantar pressure can also be used in creating models and correlating foot pressure and stresses to comfort Natali [25], Keijsers [26]. The pressure map data is used to identify foot deformity and high pressure zones that need to be mitigated.

The foremost limitation with available pressure sensors is that they either operate on a flat surface or require an already made shoe to test a 3D surface. Despite the availability of pressure sensing technology, its application is limited by the need to prefabricate the orthotic surface or shoe on which to then evaluate the pressure distribution. As each client requires a different surface the iterative nature of the pressure measurement process makes it very time consuming and often not practical as manual adjustment methods with customer feedback can attain a satisfactory result faster. Thus creating a controllable 3D surface that incorporates pressure measurement is the next step investigated in the development of foot pressure measurement technology.

Chapter 3

Digitizer Application Domains

This chapter describes the breakdown of the main research goal into three distinct areas of research. The main research goal is to create well fitting and well supporting footwear at a lower cost to the public. This will be done by improving the measurement and modeling stage of the shoe making process such that a well fitting and supporting shoe can be made faster. The incorporation of measurement technology will be used to obtain fast and superior measurement as opposed to manual measurement methods. This time reduction will allow the servicing of more clients and make corrective shoes available to more people.

There is however a complication in producing a cost effective, accurate and fast foot measurement device. This is due to the fact that different foot problems or corrective needs will require a different capability in the measurement device. That is to say the extent of correction for a custom shoe determines the needed capability of the measurement system used to produce a last for making set shoe. For instance, a client having problems with tight fitting shoes causing rubbing and blisters or soreness can have a well fitting shoe made by incorporating contour measurements of their foot from a 2D scanner or hand tracing. This will ensure the correct clearances and resolve the problem for this otherwise healthy foot. A client with extensive blistering or bunions will require more information as to the size and location of their injuries in order create needed clearances in the shoe. This will require a mold of their foot or a full 3D surface scan. If a customer has very sensitive feet or needs an alignment correction in their foot support, a pressure measurement system will be needed. Finally if a client has a mixture of problems including increased foot sensitivity, poor standing alignment and deformity of the foot, they will require a composite system that includes 3D surface measurement and pressure measurement. As the complexity of the measurement needed increases so does the cost. If the cost of the measurement device surpasses a given threshold it will not be accepted into the manufacturing sector and hence not meet the research objective. Thus the research presented in this thesis is divided in three categories based on their application domain. Figure 6 shows the domain of each focus based on the two identified application parameters. The horizontal axis represents the extent of correction or the complexity of the foot problem. The vertical axis shows the complexity or capability of the measurement device which is directly correlated with the cost of the device.

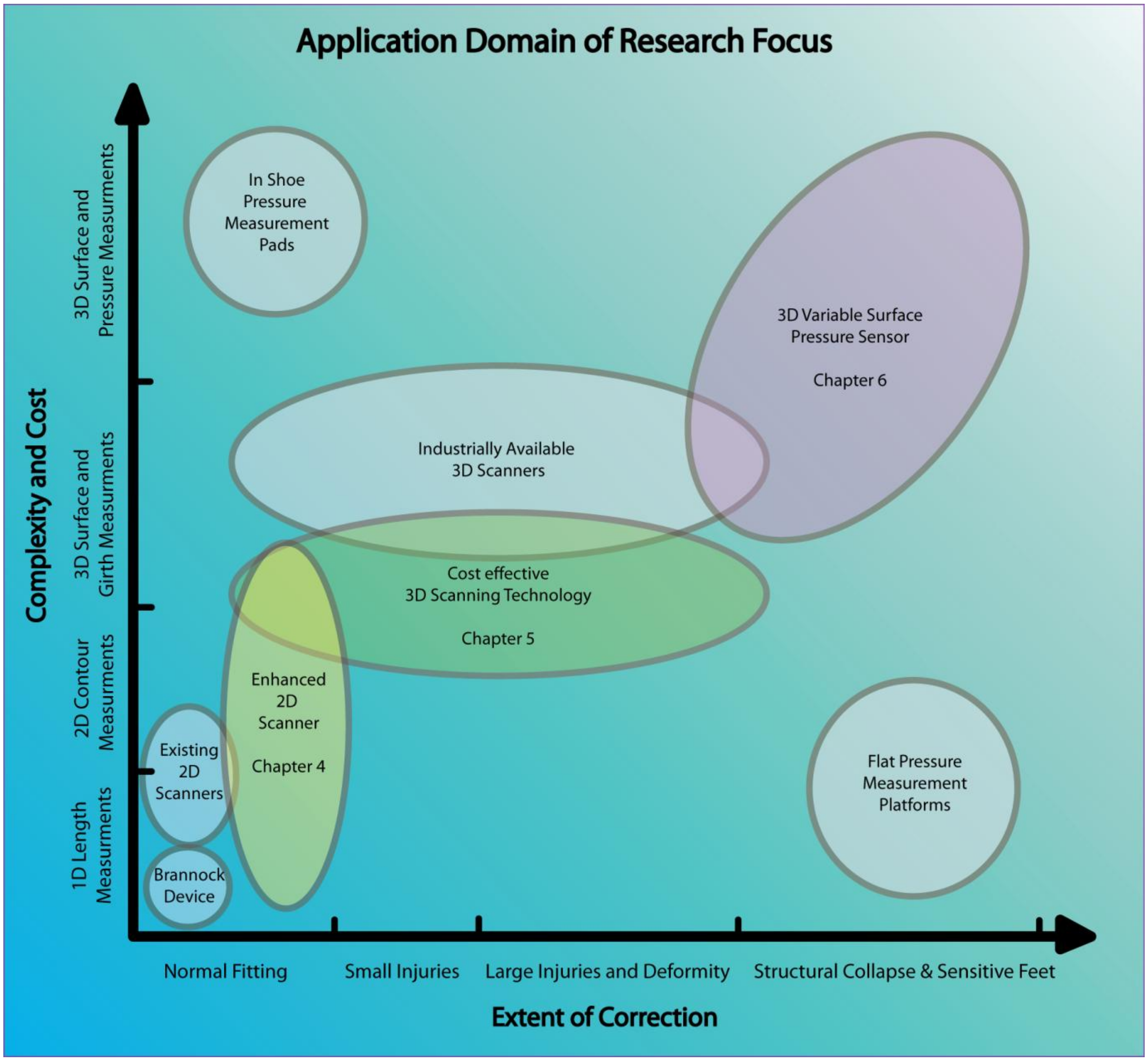


Figure 6: Application Domains

This thesis presents work in the following three domains: 2D scanning technology, 3D scanning technology and pressure measurement on a 3D variable surface. The next sections describe the application domain in detail and provide the research objectives.

3.1 2D Scanning

The first application domain is located within the normal fitting category. This means that this measurement technology will be focused on clients without any foot injuries or special corrective needs. This is a majority of the population that is in need of shoes to match their geometrical foot size and shape with no need of support compensation or injury adherence. As this scanner is intended for widespread use and does not require complex measurement it is the most cost effective solution. This is because the technology is readily available and affordable. The 2D scanning approach offers the benefit of applying a complex system that has already been engineered and refined to fast foot digitization. It is low cost and compatible with most computer systems. Also, as only a single image is produced, it can be transferred to a remote server that does post processing and analysis, removing the need to distribute software and updates.

As shown in Figure 6, the enhanced 2D scanner domain has been expanded to not only provide 1D and 2D contour information, but to also provide a 3D plantar surface of the foot. This is to address current limitations with 2D scanners that have visible depth in their scans up to one inch above the glass, but have not used this information to create a 3D surface. The objective of this research focus is to take an affordable document scanner that has depth of field capability, and use it to obtain an approximate 3D model of the plantar surface of the foot. The system will provide enhanced contour accuracy of the foot and identify key foot features. The research focus is a direct extension of the sandal manufacturing process reviewed in chapter 2. This enhanced 2D scanner can also be used for quickly obtaining sizing and geometric information of the customer's foot for purposes of finding a good shoe fit whether or not a custom shoe is made.

3.2 3D Scanning

The 3D scanning application domain spans from normal fitting to small injuries and then to larger problems such as deformity. It is not a complete solution for structural or sensitivity foot problems as it does not provide pressure information. The capability of 3D scanning greatly exceeds the 2D scanning method as it will provide a more accurate measurement of the entire 3D surface of the foot. As reviewed in chapter 2, many 3D scanning systems exist and are technologically adequate or often over capable in accuracy for the foot scanning application. The limitation that is addressed in this work is availability and accessibility to these scanners. Due to their large capital cost most foot clinics have not yet incorporated 3D scanning technology. Furthermore from a research perspective a purchased scanner will not allow low level access to its image filtering and processing methods that will then prevent accessibility to texture information. Thus the objective of this research focus is to design and prototype a complete 3D scanner within a budget of 10,000$CAD. The scanner does not require ultra high precision as some industrial scanners do and hence its accuracy constraint is +/-

0.01inch (0.25mm). Furthermore the open source design and construction of the hardware and software systems of this scanner will allow access to raw image data for texture mapping of the foot model. Mapping the foot texture to the scanned 3D model is a very useful technique for easily locating injuries and key foot features on the model. As this has not been fully investigated yet it is the secondary objective of the 3D scanner research focus. An additional secondary objective of the 3D scanner is to take the obtained models and manipulate them for the purpose of simulating the effect of support by an orthotic surface. This will allow a digital verification of the orthotic surface fit before it is manufactured.

As shown in Figure 6 the 3D scanning system developed in this thesis covers the same application domain as industrially available scanners and is lower in cost and complexity. This is achieved by using the basic triangulation approach and not incorporating costly and advanced range finding methods. The minimized cost of the system is achieved by using available consumer products such as CCD cameras and laser line generators in conjunction with affordable controls via hobby microcontrollers and motors. The reduction in cost and improvement in quality of electronics such as CCD cameras, microcontrollers and logic chips as well as motors and drivers have created this opportunity for low cost 3D scanning with sufficient accuracy for the foot measurement applications. As shoes are made of elastic materials and have clearances for dynamic motion the accuracy of a scanner to within 0.04inch (1mm) is more than what is needed for corrective shoes. The scanner created will exceed this accuracy specification while maintaining a low capital cost.

3.3 3D Variable Surface Pressure Sensor

The third research focus is the creation of a 3D Variable Surface Pressure Sensor. This is a new approach in the application of pressure measurements. So far pressure measurement can be done on a flat pressure pad or within an already created shoe via the use of an in shoe pad. This research focus aims to create a device that will have a pressure sensitive 3D surface which can adhere to the any programmable shape. The following is an introduction to this concept and the resulting research objectives.

Upon taking a 3D scan of a foot a geometric model is generated. This model is rigid, which means it does not deform. This is not true in reality as a foot will have a different shape based on what surface it steps on and how much weight is on the foot. The optimal objective in digitizing a foot is to have a geometric model of that foot, in the position of standing with full load, on a correct surface. This is to say that if a prefect shoe existed, this model would be the shape of the foot while standing within that shoe. This is a non trivial task as foot shape cannot be measured when it is within a shoe. To solve the problem, a new measurement mechanism is proposed. This is to create a 3D variable surface. This is a surface that can be programmed to any shape and it will attain set shape. Furthermore this surface is pressure sensitive, and will measure the contact pressure. Using a 3D scan on a flat surface as the starting point, the client can step on surface configured to their foot that will be similar to a flat plane. Upon reading pressure information the surface can now change shape in an intelligent manner. This results in added support or relief to the foot, based on minimizing high pressure zones. This process will distribute foot pressure and create a comfortable feel. The manipulation of the surface can be done manually or automatic once enough testing has been done to create algorithms that can distribute pressure. The result is the customer standing on a 3D surface with optimally distributed foot pressure. As the surface geometry is known, it can be converted to a shoe or insole. The 3D scanner developed on this project was designed in a modular fashion so that it can be used in conjunction with this device to also map the uppers and sides of the foot for full last construction. The result would then be a foot model, standing in the correctly loaded position, as confirmed by the customer during the pressure testing.

The application domain of this device is dealing with the most sensitive and problematic of feet. The sensor would provide a method to obtain optimal pressure distribution and therefore best comfort. The complexity of this device makes it very expensive and it would be used exclusively for research studies or clinics dealing with severe foot problems. As this is a very complex device the research objective in this section is to design a feasible system and test its functionality with the use of subsystem prototypes. The secondary objective is to review the capability of the system upon validation and asses the feasibility of producing a fully functional prototype.

The creation of a 3D variable surface pressure sensor presents some unique engineering challenges. Chapter 6 will briefly describes some explored concepts; however the final approach taken was to use an array of pins with controllable height to create the required surface. Research into industrial manufacturing methods revealed that the use of pin matrices is applied in Digitized Die Forming (DDF). This is the process of creating custom formed sheet metal parts by using dies comprised of an array of programmable height pins, Cai [27]. The pins can be individually positioned to create any surface that is then used to form the sheet metal. These devices are large and highly expensive industry tools. Actuation schemes for these pins vary from servo motors to hydraulic pistons, Walczyk [28]. Drive systems can include gears and clutches to minimize motor numbers or have direct screw drives with one motor per pin, Haas [29]. These devices are usually slow in chaining configuration and do not provide good geometric resolution due to the large pin size, starting at two inches or higher (square pin design). A survey of prior art on development of reconfigurable pin-type tooling found that several improvements are needed to make these tools more viable in industry, Munro [30]. These included increase in resolution to 1” square pin, reduction in cost, and individual pin actuation for rapid configuration changes. All of the above limitations are addressed in the work to design the 3D variable surface pressure sensor. The research focus begins by taking the pin matrix concepts from forming applications and scaling them down to a small enough form factor such that they can be used for foot pressure measurement. As this is a device that will work beneath a customer’s foot, independent pin actuation is a must for fast response in surface manipulation. This device is a novel application as pressure sensing has not yet been combined with a variable 3D surface support. Some commercial products such as the V-300 by Varifit Orthotics [31] use pin arrays to take castings and quickly prototype orthotic insoles. The fast turnaround of this device is very beneficial to shoe making, but at this stage no information on pressure distribution is coupled with the geometric data. Also alignment of the pins is still manually done by pressing the foot into the pin array. This limitation is addressed with the individual actuation of each pin.

Chapter 4

2D Scanning on a Flat Surface

This chapter describes the investigation into applications of two dimensional (2D) scanning and technological developments added to the 2D scanning approach.

4.1 Implementation of 2D Scanner

As identified in Chapter 2, the large occurrence of poorly fitting shoes result in wide spread foot problems. Although foot scanning devices are available, and can be used to build custom shoes that can correct some of these problems, they are expensive. The primary criterion for the first foot scanning method was to develop a low cost foot scanner that can be readily available to small shoe makers and foot clinics. Thus the goal was to produce a low cost system, which significantly improves the form and fit of custom shoes by incorporating information specific to a customer's foot into the design of the shoe.

The flat scanner is a complex electromechanical and optical system that requires in depth research and product development. This includes the electromechanical design of the optic system and motoring mechanics, as well as electronic drivers, sensor calibration, and image processing to create the final stitched image. Development of this system from scratch would be an entire research project on its own. Fortunately due to the wide spread application of the technology for document and image scanning, it has become readily available at prices below $100. This low cost and off shelf availability makes 2D scanning a very cost effective method to obtain digitized information of a person's foot. Thus the system can be created based on existing and well established technology. The additions and design modifications for this specific foot scanning approach are made in such a way that any off-shelf scanner can be incorporated based on the most economically available option. As a starting point, several off the shelf 2D scanning system produced by Epson [32] and Hewlett-Packard [33] were tested and selected based on open lid scan performance to be the starting point for this application's research.

The goal of the scanning device is to produce a 2D image of the plantar surface of the foot, seen though a glass layer on which the foot lies flat. At this point there would be no pressure applied from the foot to the surface or the foot is in the unloaded position. The leg would be gently placed on the glass layer, or supported via a sitting position with a thigh rest as shown in the work of Bao [15] on unloaded scanning. The method of flat scanning is a single line progression scan stitched together by traversing a camera over the length of the foot. This is the same technology developed for paper or document scanning. Unlike using a camera or series of cameras, as in the work of Luximon [9] to create a 3D image, these systems use a camera to capture only one line of pixels at each point of traversing across the length of the foot. This technology produces a 2D image that is the starting point of this research focus.

4.1.1 Additional Benefit of 2D Scanning

Aside from the cost effectiveness of using pre developed technology, there are several other benefits of 2D scanning from the applications perspective. First of all, the image capture, transmission and processing is embedded into the system and the final result is a small format colour image that shows the geometry, topography and texturing of the customers foot. This removes the need for localized processing and allows any generic windows computer to be coupled with the scanning system, without concern of overburdening or high computational load. Furthermore the captured images, of the left and right foot scans, can then be uploaded to a remote server that can run computationally intensive programs to obtain useful topographical information from the 2D scanned image. The remote upload of images from scanning stations abroad allows full control of client database, and produces a statistical base of information useful for the large scale manufacturing of shoes.

4.1.2 2D Scanning Objectives

The goal of the 2D scanner application is to create a 3D model of the plantar surface of the foot by improving available 2D scanning technology. Current 2D scanning technology allows the extraction of contour information and some landmarks. This section improves the contour detection by adding contrast to foot contour and identifying optical errors with 2D scanning that can be compensated. Furthermore depth information is extrapolated from the 2D image with the use of structured laser planes at specified intervals. The result is a close geometric approximation of the plantar surface of the scanned foot. This surface can then be use in conjunction with CNC milling to quickly and affordably produce better fitting custom sandals or shoe insoles with well matched plantar surface support.

4.2 Design of Modifications for the 2D Scanner

This section covers the investigation done into limitations and capability of 2D scanning and the improvements made to the 2D scanning platform. This includes supporting a fully loaded foot while scanning and extrapolating accurate depth as well as a more precise outside contour of the foot.

4.2.1 Load Bearing Platform Design

The first step in creating a robust scanning system was to design a variable height platform to support and protect the scanner from the weight of a client standing on the scanner. Needless to say an off shelf document scanner, such as the ones used for the 2D scanning application are not designed to have up to 200lbs of load on their glass cover. Hence to ensure that a full load bearing scan can be taken with individuals weighing up to 300lbs a custom transparent support platform was created with loading capability up to 300lbs. This ensures that if a heavier individual was to shift a larger portion of their weight onto the scanned foot, the platform could still support the load and allow a functional scan. Figure 7, shows the design of the support platform.

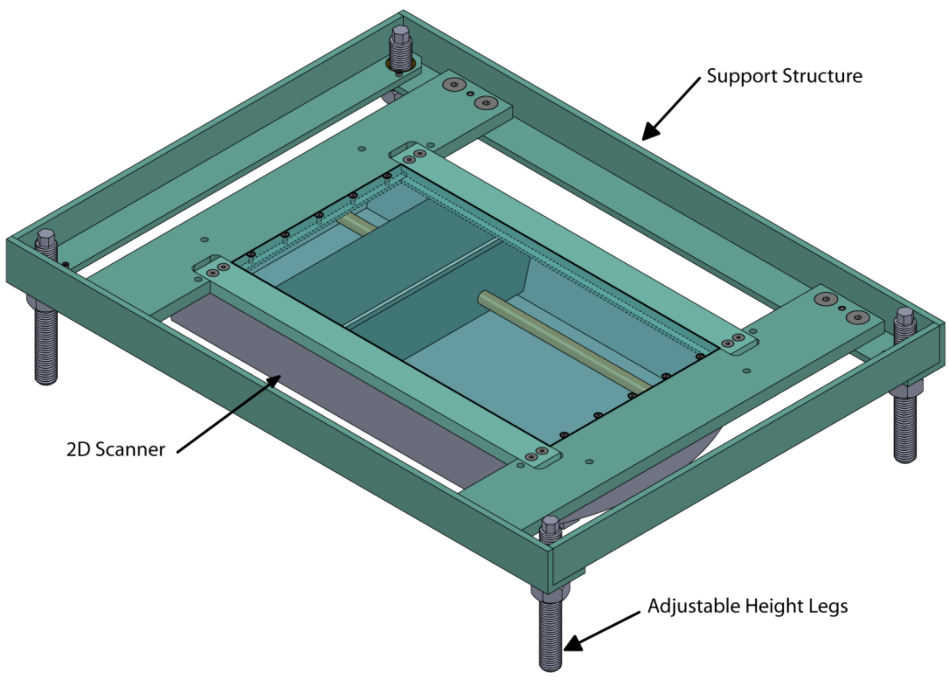


Figure 7: 2D Scanning Platform

The platform is made from an aluminium frame with internal cross members that hold the open scanning surface. Aluminium was chosen due to it being light weight, easy machineable, and more than sufficient in strength for supporting the weight of a customer. The overall width of the platform, 22inches (558mm) by 18inches (457mm) was specified such that it would accommodate sitting on top of larger legal size scanners such as the HP Scanjet 8300 series scanner. This also accommodates the added laser plane apparatus described later in the chapter that enhances the scanned image. Notice that the platform is supported on four riser screws. This adjustability is useful for this prototype platform since it can be fitted to the height of various scanners under test. The screws have locknuts that can be used to lock in the platform after it has been leveled and height adjusted. The Scan surface is 15inches (381mm) long by 8inches (203mm) wide which accounts for shoe sizes up to size 24 in the United States sizing system. A recessed lip approximately 0.125inch (3mm) thick all around, supports the scan surface material, the total shear area coupled with the yield strength of the material provides a loading capacity approximately 500lbs. This is much more than is needed, however the reason for overdesign in capacity was also to minimize bend across the length of the platform with a centralized load. Experimentally the deflection under 200lbs of load was measured to be 0.125inch (3mm). Hence the scanner platform is placed with a 0.2inch (5mm) buffer space above the scanner such that deflection will not interfere with the movement of the scanning head.

Two materials were experimented with for the transparent scanning surface. These were Lexan a Polycarbonate Plastic, and a Tempered Glass. Both of these materials satisfied the safety criteria of not being potentially dangerous if the surface was crushed or stomped on. Lexan is not brittle and would only deform under extreme load, however it is less sturdy and more likely to bend than glass. Tempered glass has the benefit of breaking into small and less hazardous pieces if smashed and also is stiffer than Lexan. During testing both materials were acceptable as the transparent scanning medium. The deciding factor would be based on the colour gradient. Lexan has a blue transparent tint, while the tempered glass has a green transparent tint. The choice was then left to the later stages of image analysis that would determine which material provided images that were easier to work with. As multiple scan tests resulted in no noticeable advantage from either material, tempered glass was chosen due to its superior surface hardness that does not allow easy scratching and wear of the scan surface. Throughout testing it was noticed that Lexan would scratch very easily if there were dust particulates dragged along its surface during stepping on and off of the scanner.

4.2.2 Cylindrical Optics and Side Light Additions

In this section the inherent cylindrical optic problem of scanning with a 2D scanner is explained.An improvement in contour edge detection is also shown. The 2D scanner technology used in testing is based on a CCD camera that traverses in a linear motion and captures a single line of pixels at each point of travel. The camera uses a lens that distorts the image by making things closer together at the focal point of the lens and farther apart as you move away from the center of the lens. To compensate for this several embedded algorithms are used, this creates a visible fan that goes out of the camera. To attain the needed scan width this fan passes through a mirror system that allows placing the camera much closer to the scan surface reducing the size of the scanner. The camera will only see the foot up to the point of tangency to its visible fan angle. This point is not the point of perpendicular tangency and will result in a smaller measurement. Figure 8 shows the optical layout.

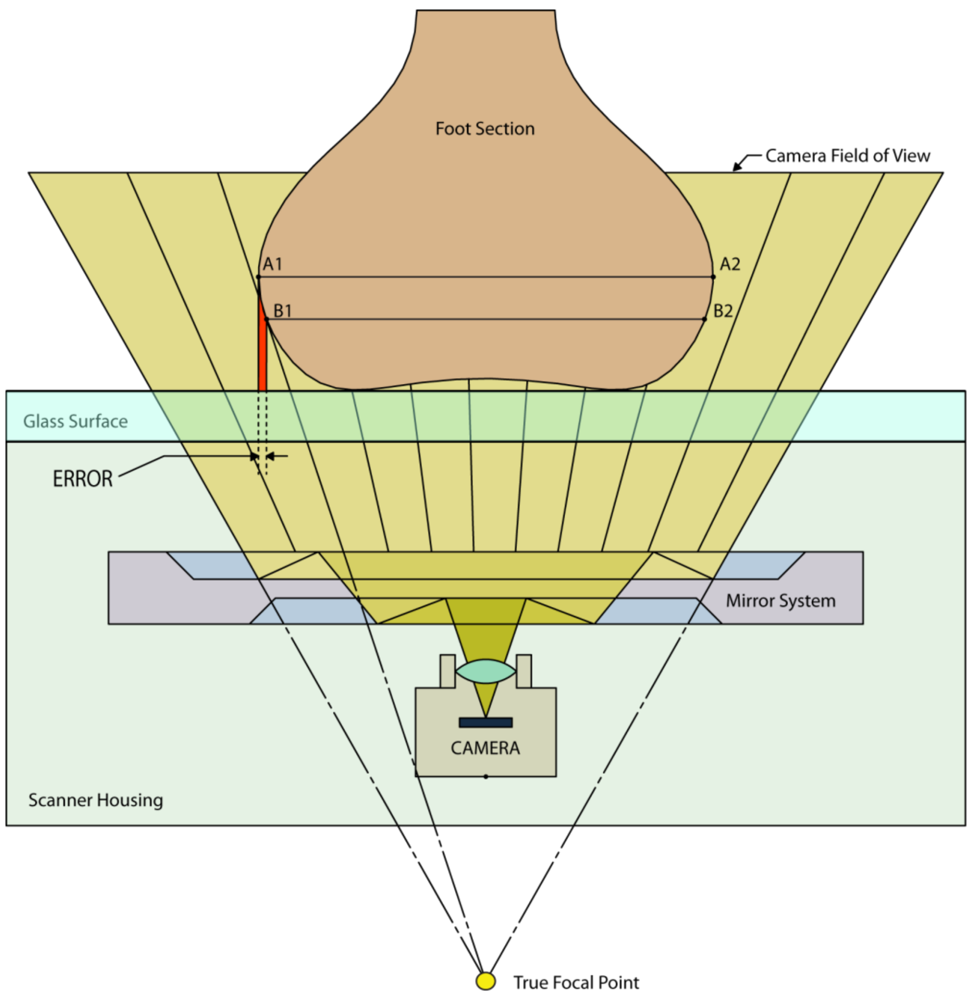


Figure 8: Diagram of Cylindrical Optic Distortion Error

Notice that the scanned width segment B1B2 is smaller than the actual width segment at vertical tangency of the foot edges A1A2. This error is usually 0.08inch (2mm) per side and increases with wider feet. The cylindrical distortion can be partially compensated if you can assume a value for depth at which the foot surface becomes perpendicular to the scanning. This is difficult because the 2D scan does not provide depth information and identifying the edge of the foot is subjective due to the low contrast between the edge and the infinite field of view background. Hence to better identify the visible edge, such that it can be compensated based on a calibration study, more contrast is needed on the peripherals of the foot.

To create larger contrast near the edge of the foot to the scan background, several neon lights were added on the scan surface contour. They were fixed to the non transparent aluminium frame such that no scatter light would go directly into the scan surface. The selected colour for the neon lights was blue, this is because there is usually very little blue content in a foot scan, and it would not interfere with the red and green laser colours used in extracting depth described in the next section. Figure 9, shows the higher contrast edge from a scanned foot with the added lighting. A single green laser contour is also visible, more on this in section 4.2.3.

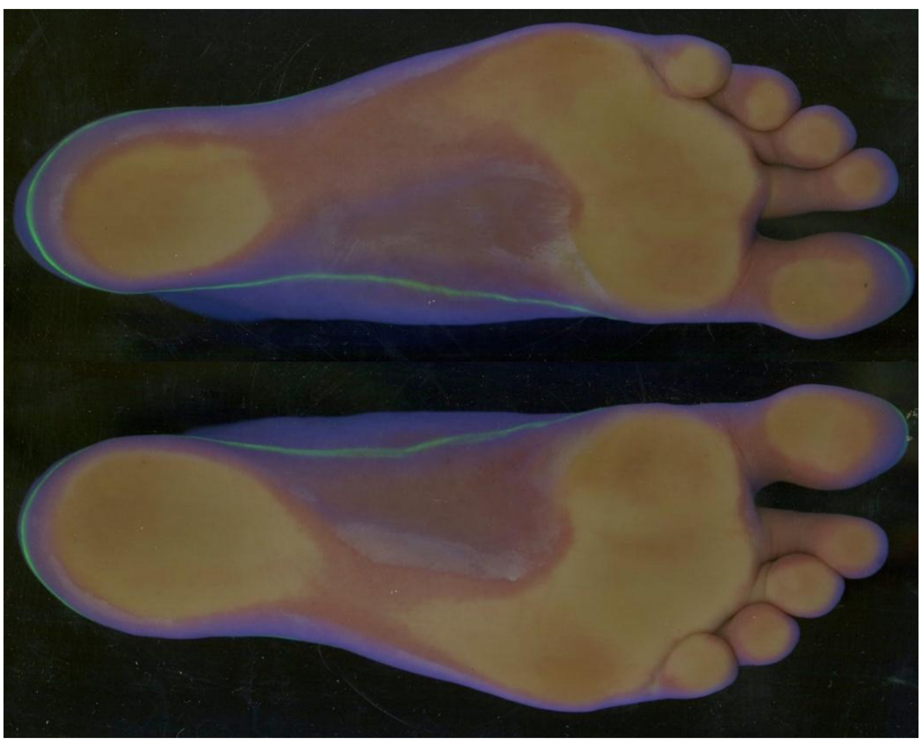


Figure 9:Left and Right Foot Scan with Side Lighting

As seen above the added blue volume of light makes the side edge highly recognizable and more easily detected and threshold mapped for automated image analysis purposes. The position of these neon lights surrounds the entire scan perimeter, with two small 6inch (152mm) lamps at the front and back of the area, and larger 12inch (305mm) lamps on the sides. This creates a blue contour around the entire foot which can be used to identify the outside contour of the foot under load. At this point a nominal guess for the foot height at the point of perpendicularity is used to compensate for cylindrical optic error. The outline produced after compensation is by far the most important parameter with respect to comfort of the shoe [8]. Once the outside contour is established, basic size and fit information can be mapped to an existing sizing system for selecting off shelf shoes. For custom shoes this is just the beginning. The next step is to extract depth from the 2D image to better map the plantar surface of the foot and create a more custom fit.

4.2.3 Laser Plane Concept

This section describes the application of structured light for the purpose of extrapolating depth from a 2D image. In order to create a well fitting concavity that matches a customer’s foot, depth or 3D information is needed. One of the most direct and reliable ways of extracting depth from a single camera is using structured light. For the 2D scanning case several methods were investigated for placing structured light on the foot, in the form of a grid or laser lines, such that depth could be extracted. These methods were not successful since the scanning head of off shelf scanners is often large and will occlude the needed angles to project the grid. Hence a new and unique concept was developed to extract depth from a 2D image. This is the laser plane concept.

The laser plane concept works by creating optical contours at given heights. Similar to a topographic map each laser contour would identify a cutout of the surface being mapped at a specific height. To illustrate the design Figure 10 shows a model foot with projected contours on it. For prototype construction and proof of concept testing two laser contour planes were used. One plane was a 535nm wavelength laser at 0.2inch (5mm) depth and the other a 650nm wavelength laser at 0.4inch (10mm) depth. This produced a green and red laser contour respectfully. The two different colours help simplify the image analysis and distinguish the two laser planes from each other in high slope areas where they can overlap. A fully loaded foot on a flat surface results in blood drain from contact areas that creates a paler skin colour, distinguishable from the parts of the foot not in contact with the glass.

These flat areas are used to generate additional contours at zero depth that will also be used to create the 3D plantar surface.

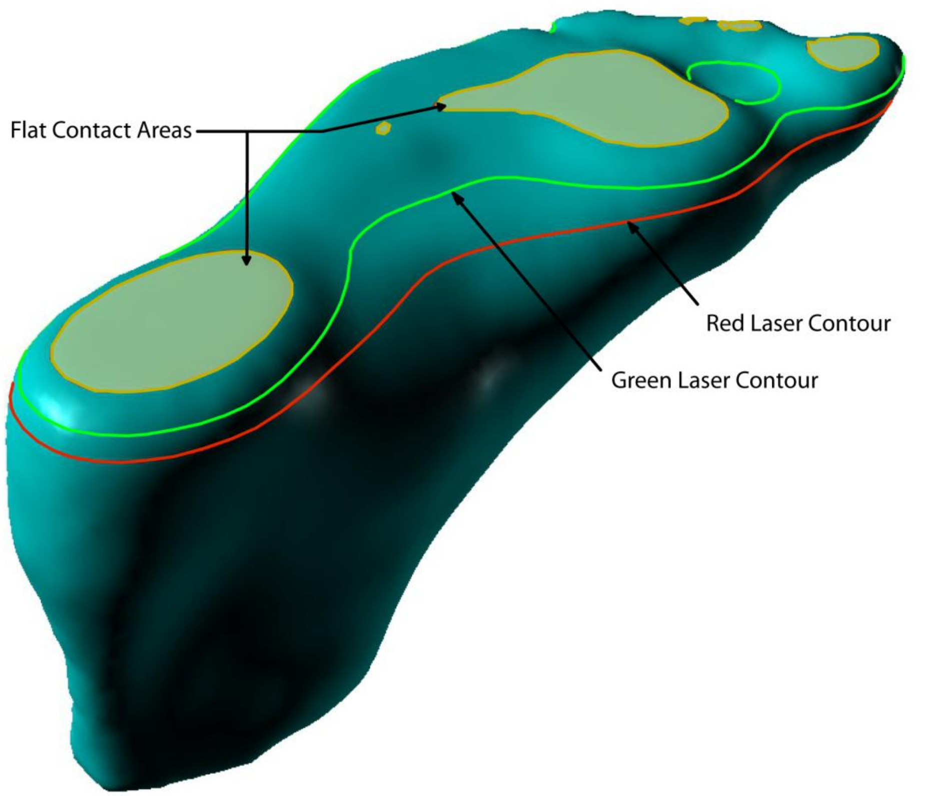


Figure 10: Foot Model with Laser Planes

To practically implement the laser planes, four laser diodes are used per plane, with a cylindrical splitting lens that creates a laser line from a point beam. They are placed in the corners of the scanning area and project a closed plane. Figure 11 shows the design of the apparatus for mounting and aligning the lasers, as well as resultant laser plane projection on calibration parts. The lasers used on the apparatus range from 5mW to 10mW power and hence are very safe even in the rare chance of temporary direct eye contact. As mentioned before the testing used planes set to 0.2inch (5mm) and 0.4inch (10mm) depth above the standing surface. This is adjustable on the apparatus; however time consuming calibration must be redone to re-align the laser diodes. As this prototype allows for continuous adjustability via screw clamping an epoxy would be used at the end of calibration as to avoid drift or recalibration needs over time. The scan image produced by this apparatus is shown in Figure 12.

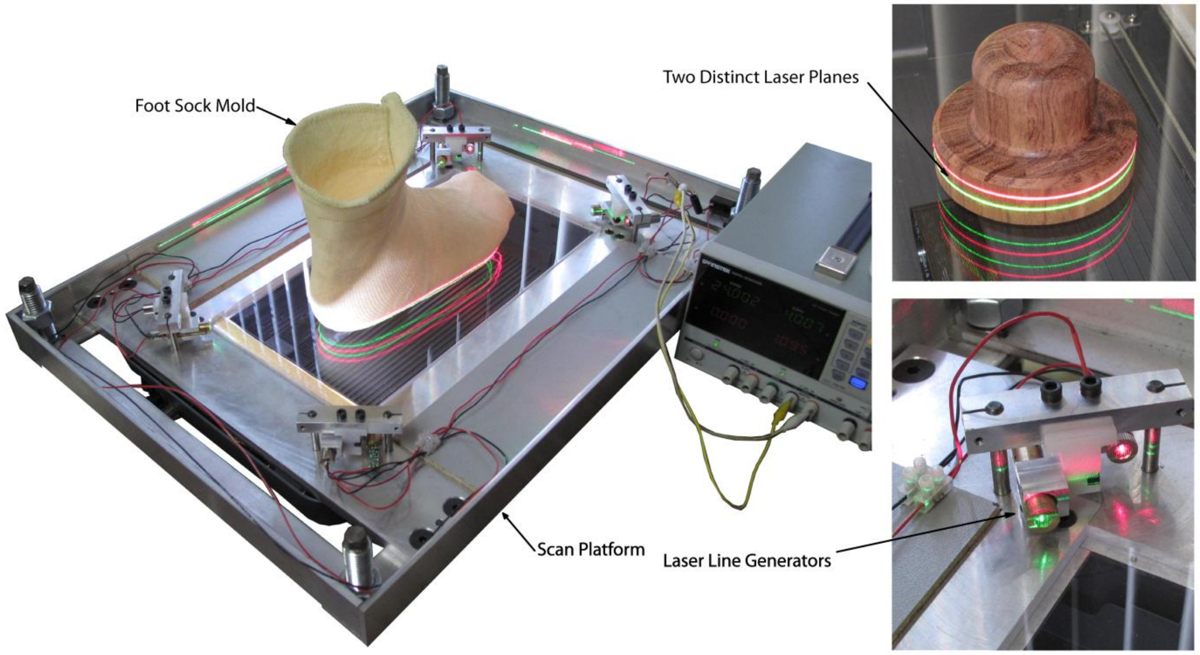


Figure 11: Laser Plane Apparatus

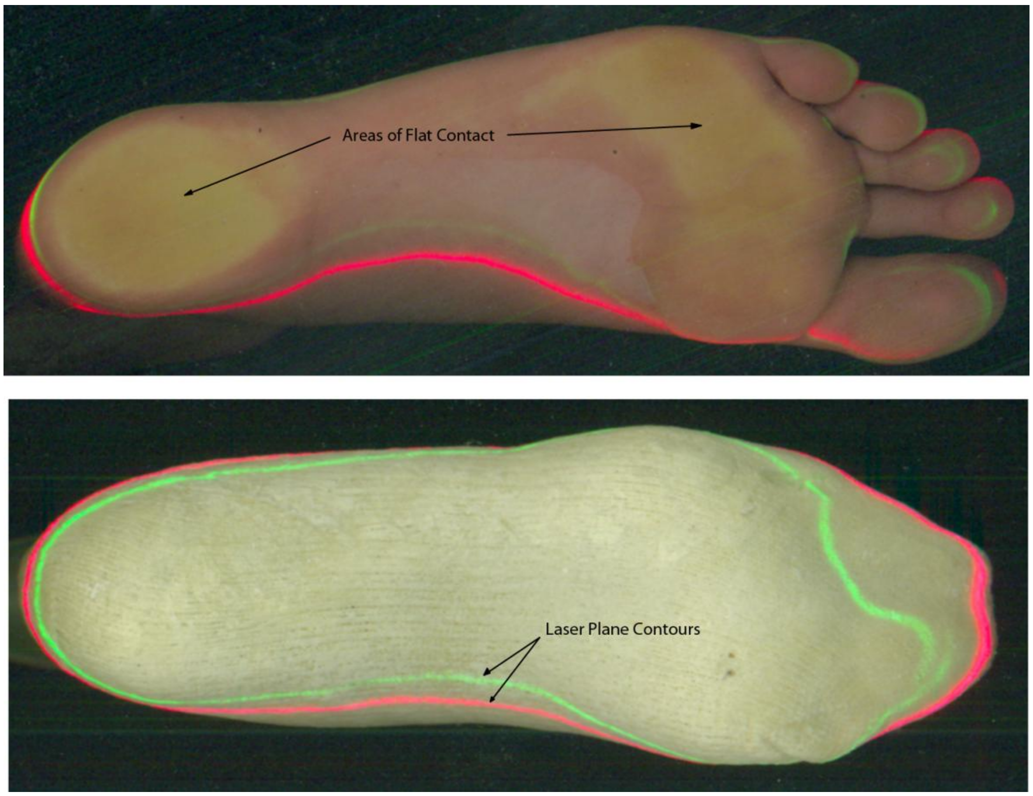


Figure 12: Foot and Sock Mold with Projected Laser Contours

Figure 12 above shows the two laser planes projected on a sock mold model of a foot, as well as on a real foot. Notice that depending on the shape of the foot there are breakpoints in the contours caused by optical occlusion. Also it became apparent that 0.2inch (5mm) and 0.4inch (10mm) spacing may be too high for smaller feet and the laser contour planes would have to be repositioned to provide useful information. A larger study with more test subjects would have to be done in order to identify the optimal placement in depth for the laser planes.

As mentioned before, it was observed that areas of foot contact where pressure is applied causes blood to temporarily drain and produces a paler surface. These zones are used to identify flat contact regions on the glass. Having 2D scans with the added laser contours, image analysis and parsing algorithms can be applied to map these contours into continuous curves. Once this is done a surface can be created by linking the cross section data points from these curves with splines. Figure 13 shows one example of a cross section segment containing points from the contour curves that would be connected with a spline.

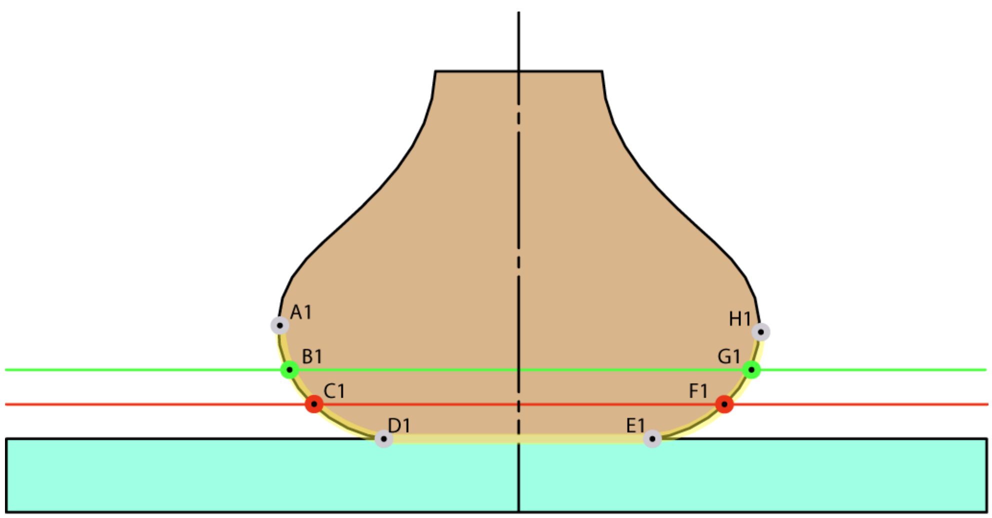


Figure 13: Cross Section Spline Mapping

As seen above a spline, highlighted in yellow, was matched to the corresponding points derived from the laser planes B1,G1,C1,F1; tangent surfaces of the outside of the foot A1,H1; and flat contact areas D1,E1. This is done on each line of the scanned image and then stitched into a surface to create a better depth representation of the plantar surface of the foot. Since the curve that maps the surface is based on at most six points and two tangencies a fairly smooth surface will be the result. Figure 14 shows the surface result that is created from a 2D scan. Note that for visualization only a few cross section spline paths at even intervals are shown with labels. In reality the surface would be created by a large number cross section splines fitted between the known points of the laser contours and flat areas of the foot. Notice that the spline crossover points are labeled in the same order as in Figure 13 to illustrate the depth information added to the XY position of each point. Many segments of this swept surface do not include points D1,E1 as fully flat contact does not occur on the arch areas of the foot.

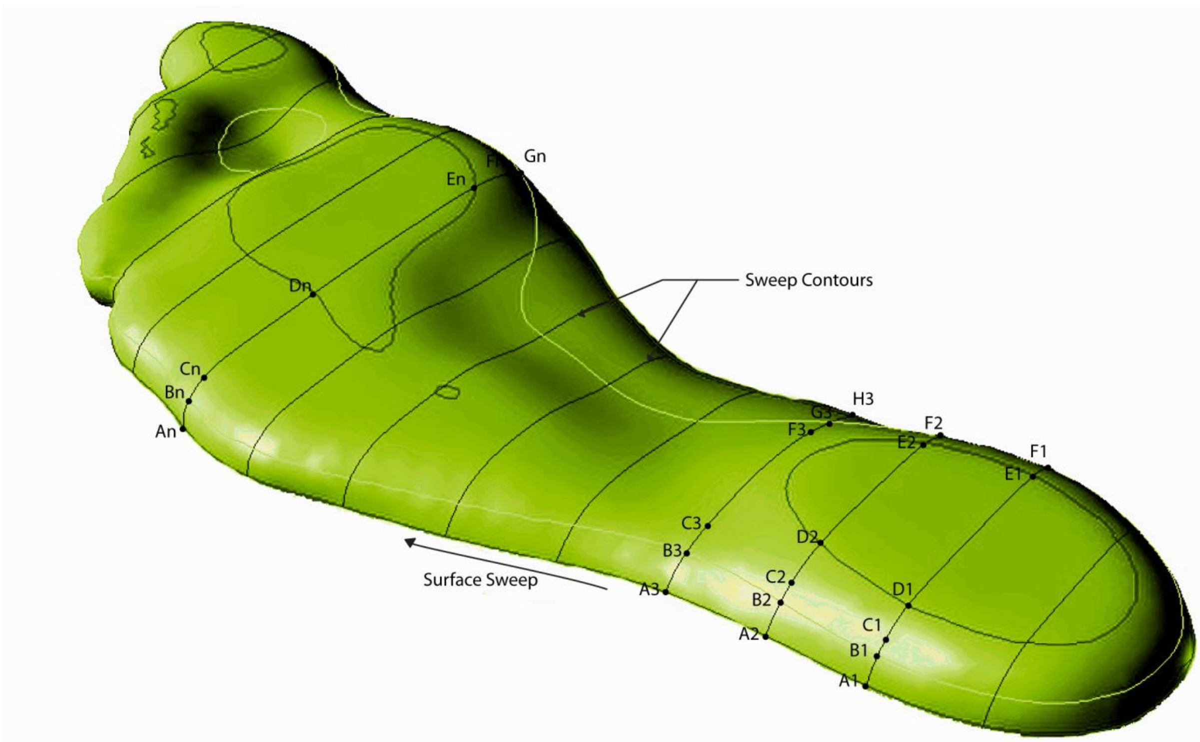


Figure 14: Approximate Surface from 2D Scan

The resulting surface shown in Figure 14 is a great improvement on previous work that used only 2D contour information and landmarks to create an approximate guess for a fitting orthotic surface. The incorporation of 3D depth information creates a surface that is much closer to the shape and form of the customers' foot. The next sections cover the limitations of this scanning technology and its applications.

4.3 Limitations of 2D Scanning

The 2D scanning technology is very cost effective as it makes uses of existing mass produced scanners. Furthermore the additions to better extract foot contour and depth information do not add greatly to the cost of the product. The performance however is limited by the difference of intended application, and this modified use of the scanner. Most document scanners produced today are highly optimized for scanning flat paper or images. Scanners that advertise depth can only go as far as 1.2 inches (30mm) before losing focus. Since scanning a foot requires the entire scan surface to be fully exposed, a great deal of external noise is introduced into the image. For instance Figure 15 shows samples of introduced noise or artifacts into the image.

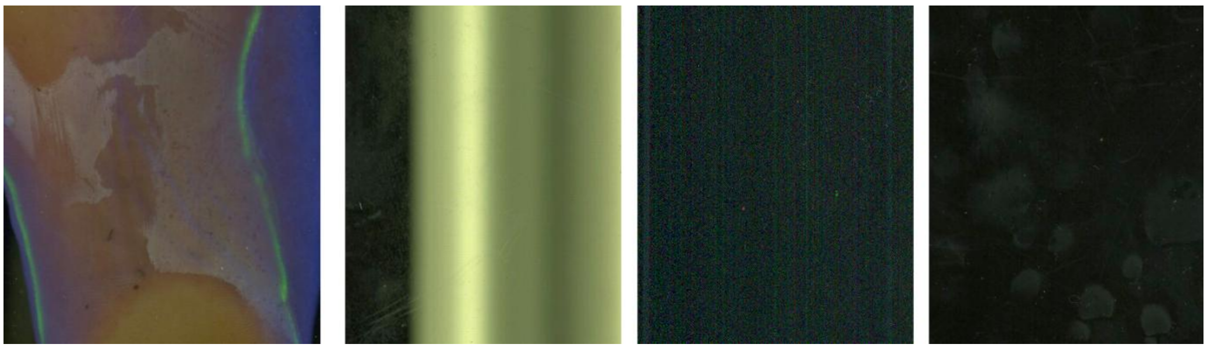


Figure 15: Noise in 2D scans: Humidity, Backlight, Background Noise and Debris

The first segment shows a very common problem of humidity and condensation on the scanning surface. This is difficult to remove since the customer's foot and scanner have to be wiped down immediately prior to scanning. Sometimes several attempts are needed and if most of the humidity is not removed a poor quality image is produced. The second distortion is caused by a florescent light on the ceiling that was in the field of view of the scanner. The third image shows sharp noise in the infinite depth field of view caused by lack of ambient light in the room. The fourth segment shows accumulation of debris and damage to the scanning transparent material that occurs over extended use. The above limitations make automating the image analysis algorithms difficult. More specific filtering and parsing is needed to remove the various sources of added noise. Thus far human interaction is still needed to adjust the results of the program scripts to ensure a good result is obtained. Furthermore, human feedback is essential at verifying that the scanned images are of high quality before being sent for processing. If a low quality image is processed the result could be unexpected or cause a breakdown in processing.

Another limitation arises from the depth extrapolation via laser planes. The resulting surfaces are built on no more than four contours: flat contact, laser plane 1, laser plane 2, side tangency. This creates a very smooth curve fit as there are not enough data points to map a more uneven surface. This surface will suffice as an approximation for persons without any foot problems or defects such as bunions, sores, or deformities. If any more complex and non typical geometry exists, it will be missed by this system.

4.4 Applications of 2D Scanning

Despite the above limitations, 2D scanning has been successfully implemented in creation of custom orthotic sandals. The new capability of abstracting a 3D plantar surface as well as 2D contours will further increase the comfort and surface matching to each client's foot. The application market is for customers without major foot problems that have difficulty finding shoes due to sizing mismatch. As indicated in the works of Rossi W.A [4] and Collazza [5] this is a very common and wide spread problem that can be minimized by the application of 2D scanning. Thus for generic orthotics and mass market shoes, 2D scanning can offer valuable insight into sizing distributions and better estimation of the population shoe size requirements. The scan shapes and sizing produced from 2D scanning are especially useful in sports and athletic shoes that have far more flexibility and adjustability of tightness that compensates for any scan inaccuracies created by limitations discussed in section 4.3.

The low cost of this scanning system and its broad application domain will make it very applicable to either orthotic making or general sizing. It can be used as a higher level tool with advanced algorithms for surface matching or as a lower level tool available for use in shoe retail stores. By distributing this type of scanner into the shoe retail markets, fast and accurate client foot information can be obtained and then sent abroad for custom shoe manufacturing. As most mass market shoes are made overseas and automatic and standard scanning platform can bridge the gap between measurement and shoe making. This provides an opportunity for many new custom shoe makers to sell their products remotely by receiving orders along with a plantar surface scan. This is conducive to the overall goal of this thesis which is to increase the availability of well fitting shoes to more people.

Chapter 5

3D Scanning on a Flat Surface

This chapter describes the conceptualization, needs assessment, and design of a 3D scanner for foot digitization. The 3D scanner will be a complete digitizing solution that will produce a point cloud representing a person's foot. A point cloud is a list of points in space with X,Y,Z coordinates. All of the points will be located on the surface of the scanned foot. These point clouds can be stitched together with surface mapping in CAD software to create a surface model of the foot. This model is the starting point for creating corrective shoes and custom orthotics based on individual customer needs. Thus the primary difference from the output of the 3D scanner compared to the 2D scanner is that it provides a full high resolution model of the customer's foot instead of an approximation of the plantar surface alone. Figure 16 shows a 3D surface model of a foot with a subset of its point cloud highlighted. Showing the full point cloud would result in a very dense mesh hence the point number is reduced for visualization purposes. This is the expected output of the 3D scanner.

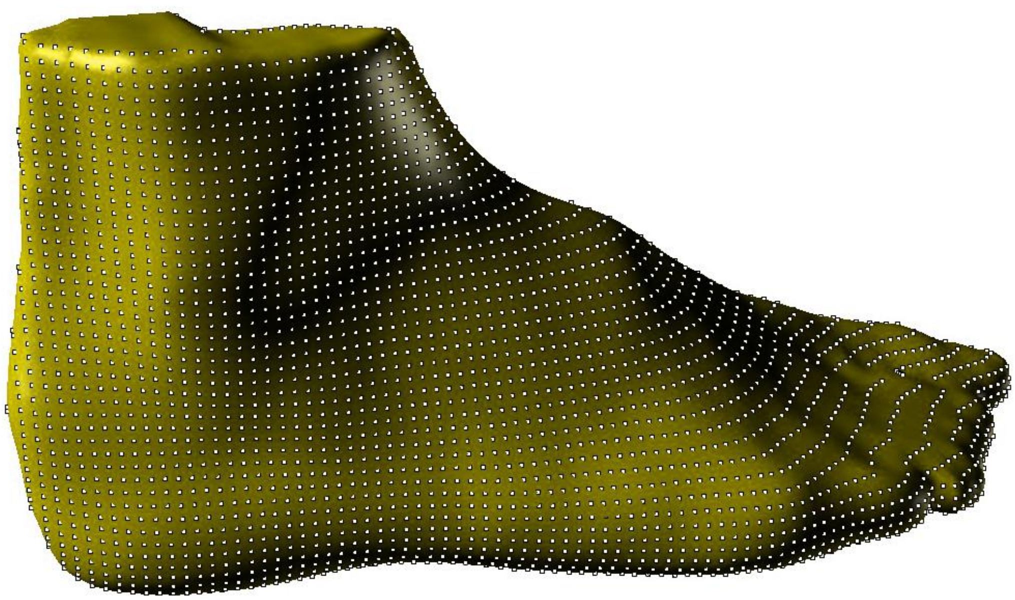


Figure 16: Surface and Point Cloud Foot Model

5.1 Need for a 3D Scanner

The foot problems experienced by the majority of the population can be categorized into two types. Posture and sizing problems that can be resolved by using a well fitting shoe and medical problems that require detailed correction of a whole custom shoe. The 3D scanner is intended for the second type of problems as corrective shoes cannot be made from a simplified 3D plantar surface extrapolation, obtained from a 2D image. This is due to the limited information and depth resolution of the 2D scan. Feet have very large variations in size, width, volume, proportionality and support structure. This variation prompts the need for more information to correctly digitize a foot. Furthermore, medical problems such as deformity, injury, or abnormality on a foot cannot be accommodated with the 2D scanning.

The 3D scanning technology is available in the industrial markets as shown in chapter 2, several researchers and companies have applied it for the purpose of foot scanning. These applications however are exclusive to their work, or their packaged product. Furthermore, industrial grade 3D scanners are very expensive and are often designed for reverse engineering of products with very high resolution in the range of 0.001inch (0.025mm). These systems vary in price from 25,000$CAD to 75,000$CAD. The use of these scanners is limited by their packaging and intended purpose so they cannot be easily streamlined to the foot scanning application. These barriers along with the reduction of cost the main reasons for developing a 3D scanning platform to address the needs of shoe making. The availability of low cost sensors such as CCD cameras as well as structured light make the development of a 3D scanner feasible without requiring large resources. From the perspective of cost, the 3D scanner prototype was developed and constructed with a budget of approximately $7,500. This cost can be further reduced by using more economical manufacturing techniques as opposed to mostly CNC machining used for the production of the current prototype.

5.1.1 Benefits of a 3D Scanner

The primary benefit of the 3D scanner is that it will provide a higher resolution model that can be used on all feet regardless of deformity, abnormality or variation in foot shape. The high resolution refers to the design specification of depth and stroke resolution of +/- 0.010inch (0.25mm). The scan time is slower than that of 2D scanning ranging from 30 seconds to 2minutes. Note that faster scans can be done if lower resolution is acceptable, which may be the case for generic foot scanning purposes. The 3D scanner also provides information of the upper parts of the foot including ankle shape and location as well as girth measurements. As seen in the works of Zhao [16] the extrapolation of girth measurement from a 3D model is important in making restrictive and less flexible shoes fit comfortably. Finally, the capability of the system due to its higher resolution allows small defects or injuries on a foot to be recognized and accommodated for in the designed shoe. For example if someone has several bunions in various locations on their foot, these can be identified and cavities can be created in the corrective shoe to not aggravate the condition and allow for healing and effective treatment.

5.2 Design of a 3D Scanner

This section covers the mechanical and electrical design of the 3D scanner with a brief introduction to the software design and image analysis.

5.2.1 3D Scanner Criteria

Since the design and prototyping of a 3D scanner is an involved project, the following list of criteria and specifications were developed to be the baseline of work and thought process throughout the design stages.

- **Cost**: Cost is one of the primary criteria of the scanner. The main benefit of developing a scanner in-house is not purchasing expensive industrial system. This influenced design decisions to choose manufacturing methods readily available at the University of Waterloo and to focus on simple construction with the use of off shelf components, and nominal material sizing where ever possible. Hence this initial prototype is built from machined stock materials and does not have more expensive components such as molded, cast or stamped parts that could be implemented on a revised design.

- **Accessibility & Modularity**: This is a criterion that makes the design very open and easy to assemble and disassemble. The modularity criterion refers to creating three scanning modules. One for the plantar surface and two for the left and right sides or uppers of the foot.

- **Size, Form Factor, and resolution:** This refers to some initial engineering specifications, developed in collaboration with industry sponsors that specify what would be acceptable as basic parameters of the scanner. These include having resolution of less than one 0.04inch

(1mm); having a scanning volume of 5.5x4.5x15inches (140x114x380); having a maximum distance of 12inches (305mm) from foot to foot when standing on the scanning platform. Other specs also include keeping the scanner low to the ground, within 6inches (152mm), such that customers do not have to step up to a high platform to be scanned. More specifications will be described as necessary in the next sections.

5.2.2 Mechanical Design

The following sections cover the mechanical and optical design of the 3D scanner.

5.2.2.1 Introduction to 3D Scanning

Before describing the specific features of the mechanical design of the proposed scanner, a brief explanation of how the scanner works is needed. The scanner uses the structured light approach and triangulation to determine the depth of an object. Figure 17 shows the basic layout sketch of a single camera and laser. Notice that the camera is placed at a known angle from the laser. If an object was to be placed in the field of view, the camera would see the laser dot at a certain pixel number in one of its pixels rows. Since the camera and laser form a right angle triangle, trigonometry is used to extract the depth of the object by correlating pixel number to depth. For instance if the camera has a row of 480 pixels and a laser line is identified at the middle of pixel 240, the depth would correspond to the middle point of the depth of field. The other pixels would then be mapped to correlated depth. Since the camera is on an angle it is important to notice that there will be more pixels per unit of depth, or more resolution at the start of the field, and less at the end of the field. This relationship can be mapped with a lookup table or mathematical functions. For simplicity Figure 17 shows a camera with a row of eight pixels, in reality many more pixels are in use and the selected laser point will often be disturbed across several pixels. The exact center can be found by using a histogram template of intensity that is matched to each row of the image.

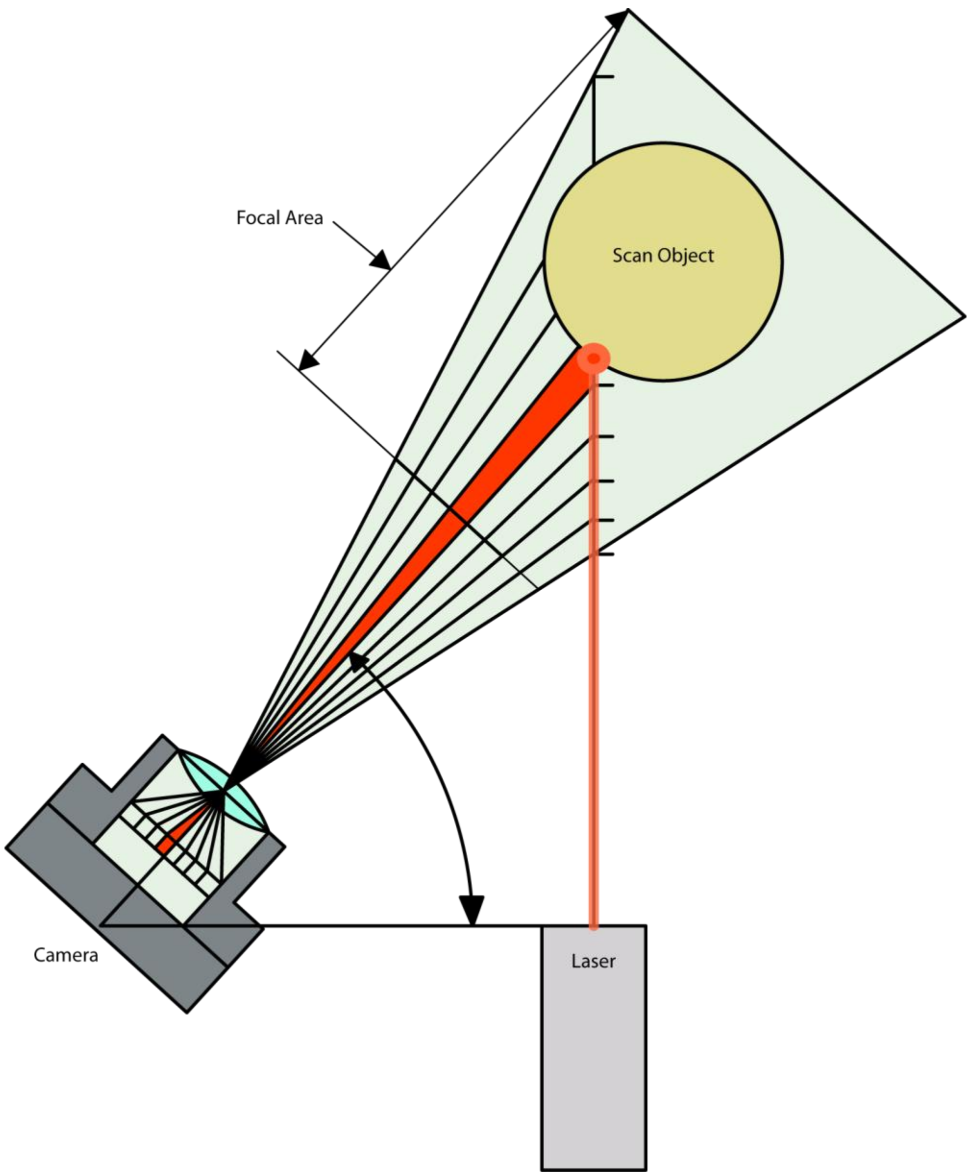


Figure 17: Range Finding with Structured Light

The depth value provides a single measurement of depth at a point, however since the cameras selected have an array of 640x480 pixels and the laser is split into a beam, an entire line of depth is obtained that corresponds to a two dimensional slice of the object being scanned. To obtain the third dimension, the entire apparatus is then moved across the object and each new line produces another contour in the third dimension. This method of scanning was chosen due to its high reliability in variable lighting conditions. Since a higher power (50mW) red laser is used, it creates a very high contrast line on the object being scanned. This allows easy image parsing to filter the depth line from the entire image information. The downside of this system is it requires actuation and coordinated movement, unlike stereoscopic multi camera approaches. Nevertheless this system can be built in a modular setup and needs relatively simpler software algorithms to work. Once one camera is calibrated the same code can be applied to the others since the optical setup is the same on all cameras.

To create the scanner several design stages are undertaken. The first is the Optical layout. In this stage key parameters such as the number of cameras needed and their geometric positioning is specified. This creates the visible field of view in which a foot can be scanned. Second is the design of the motion platforms that actuate the scan heads. Finally the scanner support structure that supports the client's body weight and connects the motion platforms is designed.

5.2.2.2 Optical Layout

The goal of the optical layout is to create a scan field of required size to fully digitize a client's foot. This design ensures that the required volume of 5.5inches (140mm) width by 4.5inches (114mm) height by 15inches (380mm) depth is satisfied such that there is no occlusion and maximal coverage during the scan of convex or concave features of various sizes. Figure 18 shows how convex and concave geometry can cause occlusion or lack of continuous scan data if only one camera is in use.

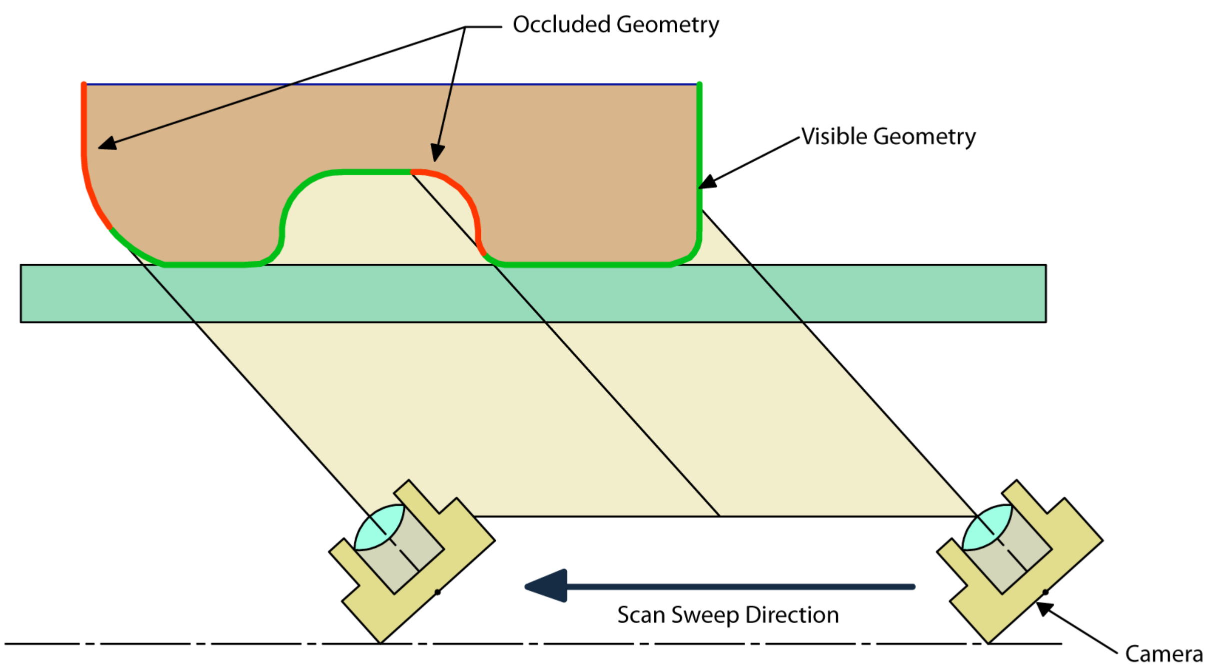


Figure 18: Optical Occlusion with Single Camera

This creates a requirement to have two cameras with each laser, one on the front and one on the back side to ensure no features of the scanned foot are being occluded. This conjugate camera pair is especially critical in areas of large convexity such as the heel and toe area of the foot. The next stage is to ensure that 360 degree coverage is given to the foot. This first requires an established depth of field. Depth of field is the mapped area where depth information can be read. Its size is dependent on the camera view angle and relative positioning to the laser line. The projected plane of the laser line on the camera field of view will create the measurable depth of field.

To create a suitable depth of field, a camera must be selected such that it's viewing angle and focal depth is known. For this application a cost efficient mass produced CCD web camera was chosen. This was the Compact 1.3MP PC USB 2.0 Webcam, it fits the application well due to its small and rectangular form factor, as well as having large enough resolution to meet the accuracy specification. This camera also has an adjustable focus length that allows close range measurement of 3inches (76mm) and thus minimizes the size of the scanner. In order to meet the desired resolution of 0.01 inches (0.25mm), a depth of field area of 3.5inches (89mm) visible depth, is selected. Since the column resolution on the image is mapped to depth, 480 pixels over 3.5inches (89mm) creates a max resolution of 0.007inch (0.17mm) which is within the specification. Note that the resolution approaches 0.010inch (0.25mm) per pixel in the farther range of the depth field and 0.005inch (0.13mm) per pixel in the near range of the depth field. With the specified 3.5 inches (89mm) depth of field, the camera and laser layout was designed in CAD. Figure 19 shows the cad model and outline sketch with the identified field of view. This is a modular scanning head that is used on all the scan modules. The exact tilt angle of 42 degrees was verified experimentally, to ensure good focus at small distance to the scan object. This is also allowed verification that a sharp image is produced from the start to the end of the field of view. As the field of view is an optical preset that will not change, the camera support plates are formed on a bending press to the exact angle needed. A die was created to ensure repeatability in the forming process which also limits variation in orientation from camera to camera and reduces calibration work.

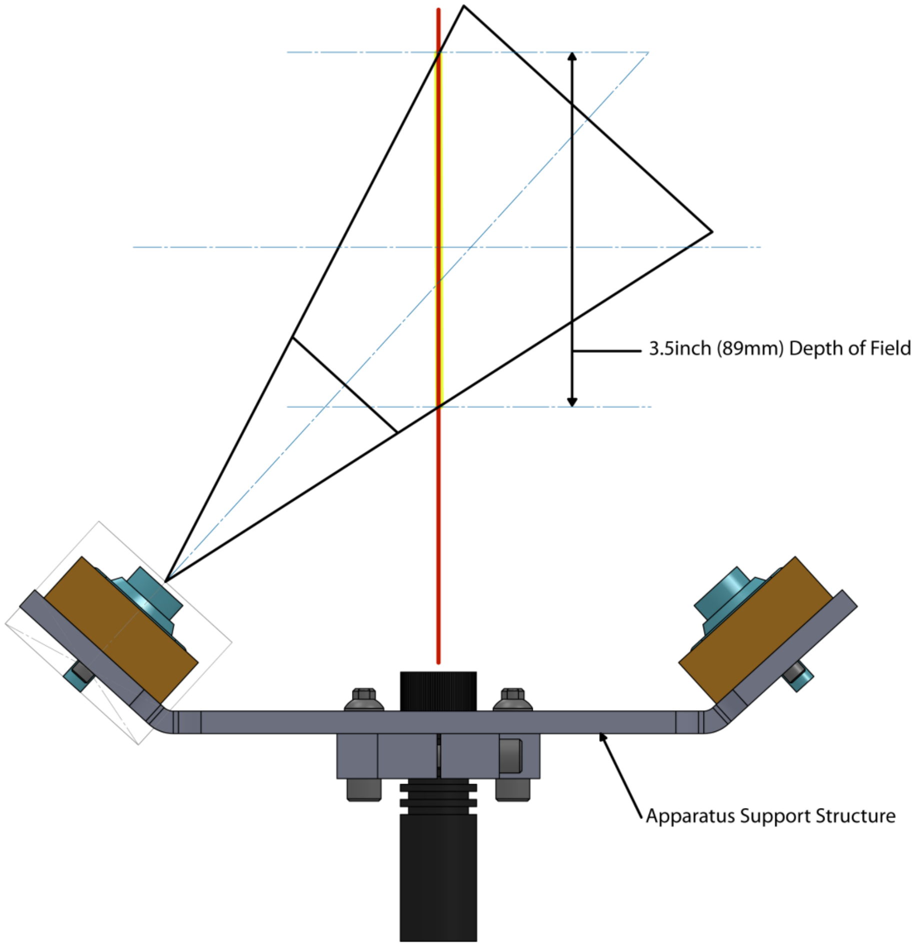


Figure 19: Camera and Laser Layout

Notice that the camera view angle is 30 degrees and this parameter as well as the focal depth requirement result in the orientation angle of 42 degrees between the laser and camera. This 30 degree view field corresponds to the columns of the CCD array that are 480 pixels long. The projected field of view of the in 3D space is shown in Figure 20. The width of the CCD array is 640 pixels and has a 40 degree view angle. This creates a projected area onto the laser plane produced by the laser line generator. The laser line generators used on the scanner have an 80 degree fan angle; hence they are not a limiting factor in coverage of the foot.

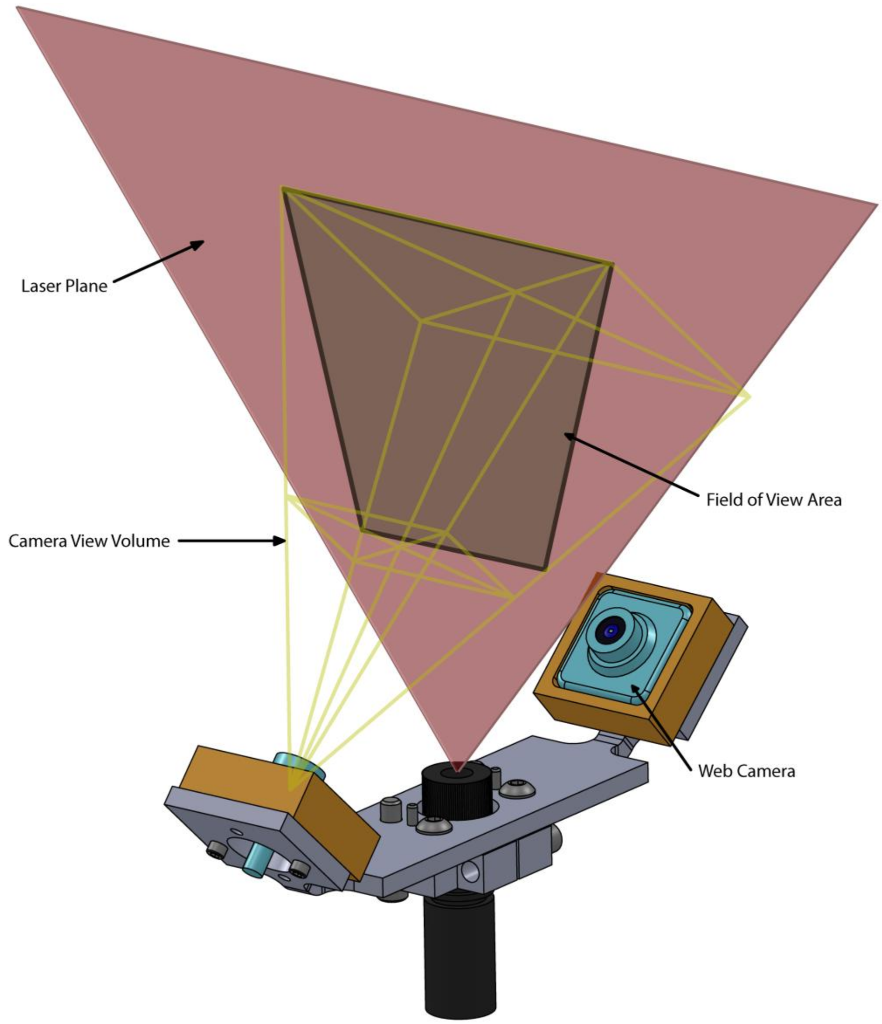


Figure 20: Projected Field of View

The field of view area shown above is where cross section depth information of any 3D object can be measured. If the object is not contained within this field of view area it cannot be measured by the scanner. Thus to ensure full coverage of the foot several scanning heads are needed which are arranged with slight overlaps in field of view areas. In total four pairs of scanning heads are needed to completely surround the volume chosen that is large enough to fit a customer's foot. Two scanning heads will cover the left and right side of the plantar surface underneath the foot, and two more cover the upper left and right sides of the foot. The complete optical layout of the scan area is shown in Figure 21. This cross sectional area will scan across the full depth of the scanner to create the scan volume with a length of 15.5inches (394mm).

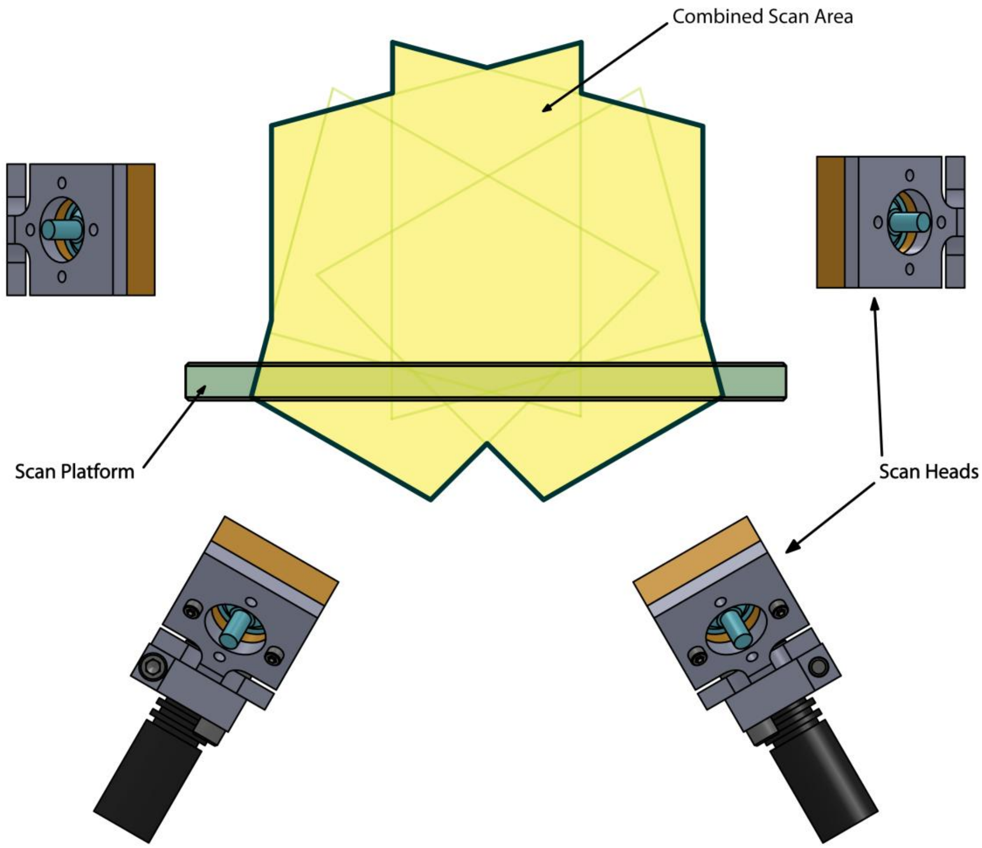


Figure 21: Cross Section Scan Area

Notice that there is significant overlap in the field of views from the four scanning heads. This overlap is designed to minimize any occluded geometry that would occur if there were blind spots between the scan areas. At this design stage the heads are positioned in space without support. The structure and drive modules will be constructed to fit this orientation. A total of four lasers are used to fully encircle the foot, only the bottom two are shown in this figure. With this established scan area, via geometrical position of the four scan heads, the electromechanical system that supports the heads and actuates them can be developed. This scan area moves along the length of the foot to create discrete contour slices that are then stitched together to form a complete model.

5.2.2.3 Modular Assembly

One of the initial requirements of the 3D scanner was modular construction. This means that fully functional scanning heads can be detached from the scanner and attached for future projects and reconfiguration of scanning parameters. To achieve this, the scanner is comprised of three modular motion platforms. They are identical platforms that support the scan heads. Two platforms hold a single scan head for the top left and right side views and one platform holds two scanning heads for the bottom or plantar surface scan. This system is also beneficial when only 3D plantar surface scans are needed, without the upper geometry of the foot. This allows the side scanning modules to be used independently on the 3D surface pressure sensor described in chapter 6. The design of a module is shown in Figure 22. Notice that this motion platform runs on a single precision ground ball bearing rail that can be loaded in any direction. This allows functionality with module orientated in any position as well as a smooth and rigid motion path. The module is equipped with a cable tray that will route the instrument wiring safely during motion, and again allow the use of the platform in rotated or inverted orientations.

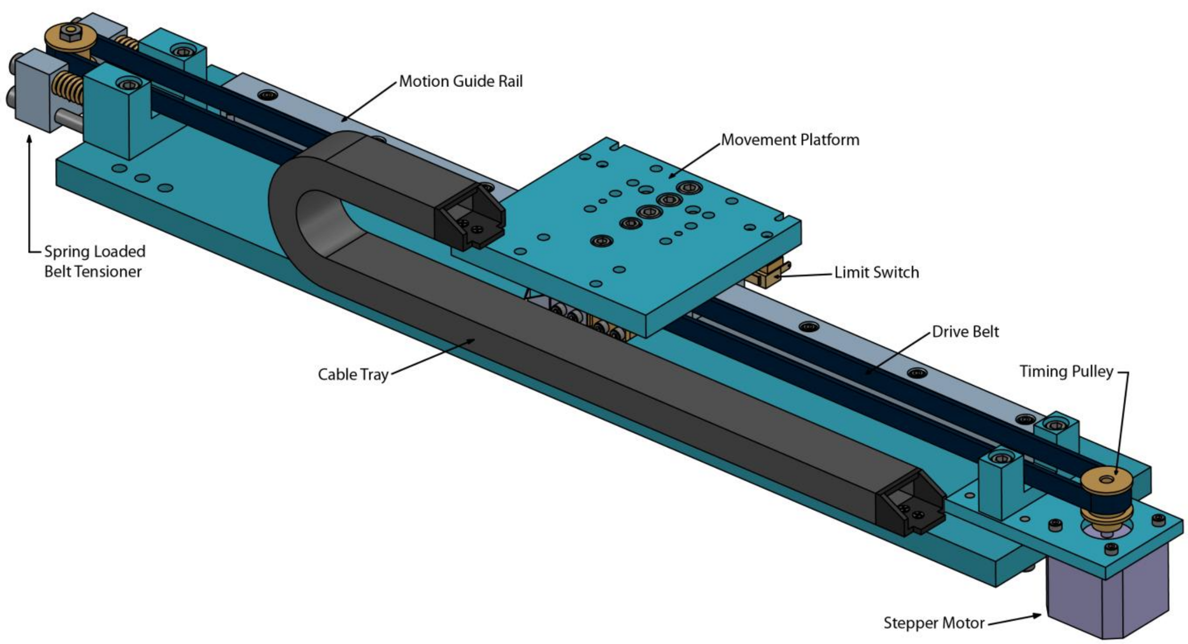


Figure 22: Motion Platform Module

The platform that slides on the guide rail is actuated via belt drive from a stepper motor located at the end of each module. The belt is guided by support blocks at both sides of the module that ensure good pulley engagement and also act as limit stop triggers. To keep constant tension on the belt, the follower pulley is on a sliding block that is preloaded by compression springs. This also ensures a smoother travel motion and absorbs jerks at motion start or during a sudden stop. Additional benefits to using a belt drive system are its lower cost and lower manufacturing precision requirements than using drive screws. Furthermore a belt drive system runs quieter than a mechanical drive screw unless high end ball screw designs are used, which would significantly increased the cost of the scanner.

The stepper motor was chosen as the mechanical driver based on cost and simplicity. Using a stepper motor offers precise open loop position and velocity control. It also simplifies the electronics of the system significantly since no closed loop encoder, or variable power amplifier is needed. This added simplicity makes the electrical system easier to implement, and requires less powerful microcontroller due to a smaller computational load. To match the depth resolution requirement, a drive pulley motor of pitch diameter 0.637inch (16mm) was chosen. This creates a travel per revolution of 2.0inches (50.8mm) and when coupled with a 200 step motor, a step increment of 0.01inch (0.25mm) is obtained.

5.2.2.4 Vibration & Deflection

One downside to the use of the stepper motor is the added vibration caused by individual steps instead of a continuous motion as in a servo motor. To minimize the effect of vibration on the sensors, several parts were overdesigned to be more bulky and rigid. These include the camera mounts and their thicker support bracket. Although the scanner is mostly made of aluminium, the belt coupler under the moving platform is a larger and heavier steel part. This helps by adding more inertia and keeping a smoother motion under constant velocity operation. The scanner is also placed on vibration mounts such that there is more dampening available from the structure to the floor. To ensure that more vibration dampening is not needed, the prototype platforms were instrumented with a precision indicator and ran at speed with the indicator measuring deflection along the camera mounting plate. Close to the center connection point no deflection could be seen, and as the indicator moved out towards the cameras a small oscillation was observed +/-0.0005inch (0.013mm) which was within the smallest resolution segment on the indicator. Since this deflection is far too small to cause any accuracy errors in scanning, no further damping was added. With regard to extending the lifetime of this type of scanner more damping or isolation of the cameras may be needed, however this is a non issue for the shorter lifespan of the experimental prototype.

Indicator testing was also used on stop tests for repeatability of the system. The module was programmed to go to specific points and the step size was confirmed to reliably be 0.010inch (0.25mm). Running the module to and from an indicator stop resulted in positional repeatability of +/-

0.0004inch (0.01mm), non cumulative. That is means that regardless of repetitions there was no drift in steps and the error bracket remained the same. Note that the above testing requires a fully working electronics system that is described in the next section 5.2.3.

5.2.2.5 Structural Setup

After completing the design of the scanning heads and motion platforms, a support platform is needed to fit the optical layout and withstand the weight of a standing client. This was done through geometric placement in CAD, followed by development of a structure to support the foot. Figure 23 shows the final design of the 3D scanner. Additionally a cover was made from painted lexan polycarbonate that protects the apparatus from dust debris and shields out lots of external lighting. See appendix A for pictures form the 3D scanner prototyping process.

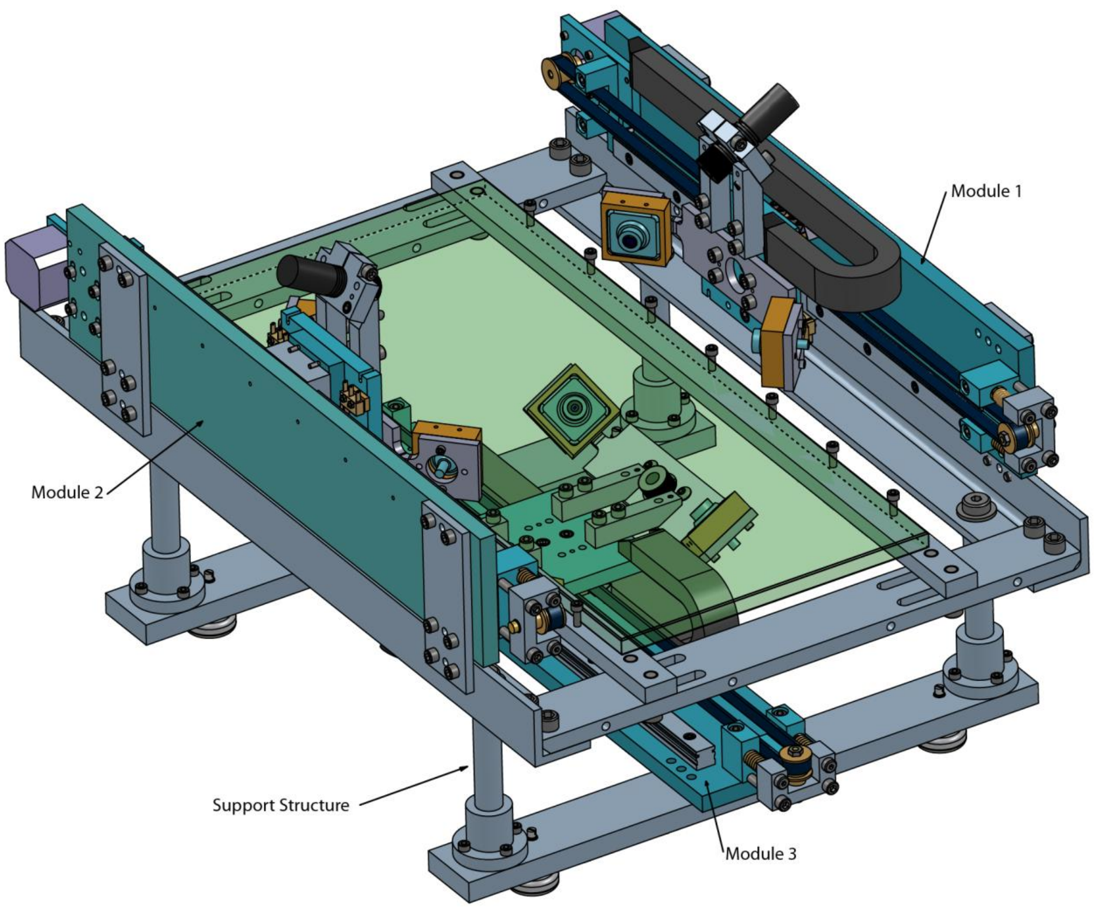


Figure 23: 3D Scanner Prototype

As seen above, the 3D scanner support structure follows closely the platform design principles for the 2D scanning platform. A series of stock aluminum plates and extruded segments are fastened together with machine screws to position the modules in the correct orientation. To maintain high alignment accuracy on the scanning heads, dowel pins are used as part of the locating connection from component to component. Tight machining tolerances will keep locating pins in position within +/- 0.001inch (0.025mm) and there is a maximum stack tolerance offset of +/-0.005inch (0.12mm) based on there being less than five components that can stack with increasing error. Once the cover is placed, rigid handles are attached to the front and back of the structure such that the scanner can be easily transported. The approximate weight of the scanner is 50lbs so one person can carry it, but it is recommended that two individuals are used to move it for safety purposes and convenience as the scanner is large.

5.2.3 Electronics Design

This section includes the design of the electrical drive system, the controls and interfaces to this system and the low level embedded software that runs the system.

5.2.3.1 Motor Control

As mentioned above a stepper motor is used to actuate the motion platforms. The motor is operated in the bipolar method with two coil architecture. By chaining the polarity of a single coil at a time the motor moves one rotational step. The sequence of steps is as follows: 00,01,11,10 where 0 and 1 represent opposite current flow and the each digit is a coil. The rotation direction is simply controlled by running the sequence forward or backwards. The most economical way to drive the stepper motors was to build a custom drive circuit with logic chips and solid state relays. The actuation circuit is shown in Figure 24, and is used on each module. The step sequence output is provided by the microcontroller to create the needed motion. The microcontroller will keep track of the step each motor is on and increment this as the motor moves. The most common move function is to run at a specific speed that suits the image capture rate. The speed is achieved by outputting a continuous step sequence at the corresponding frequency. Increasing or decreasing this frequency can be done until an optimal speed is discovered. As stepper motor control is open loop there is no feedback as to the position of the platform which may drift over time. To remove this potential failure two micro switches are mounted on the moving platform which trigger at each end of motion travel. This prevents the motor from hitting any hard stops at the end of travel and missing steps.

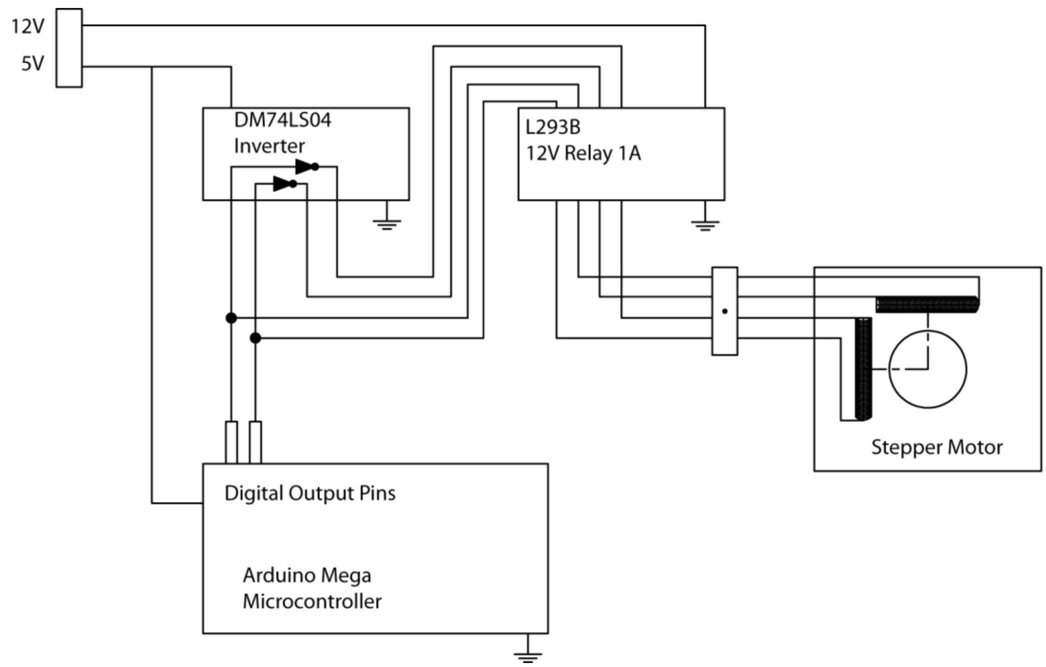


Figure 24: Motor Drive Circuit

Although the motor has more toque than is needed to move the platform, there is always a chance of missed steps over time. Hence before every scan, one of the limit switches is used to home the motor and re-zero its position within accuracy of one step. This also allows exact alignment of the laser line generators to be set at calibration and re-achieved based on the home reference switches.

5.2.3.2 Microcontroller and Drive Circuitry

To actuate the motors with the drive circuit described in the previous section a microcontroller is needed. This will be the brain of the electromechanical system that runs the low level functions. These functions include controlling the motors, interfacing with a hand held device, and interfacing with a computer. The image capture electronics and image analysis is described in the software section. The microcontroller chosen to run the system is the Arduino Mega [34]. This controller meets the required number of digital input/output (I/O) and analog I/O channels needed to run the motors, the manual control pendant, and is readily equipped with a USB 2.0 interface that is used to connect to a computer. Furthermore the Arduino architecture comes with a high level software interface that allows object orientated programming in C++ of the microcontroller. This reduces the complexity of low level programming and speeds up development time. Figure 25 shows the completed setup of the drive electronics. See the appendix for internal of the control box.

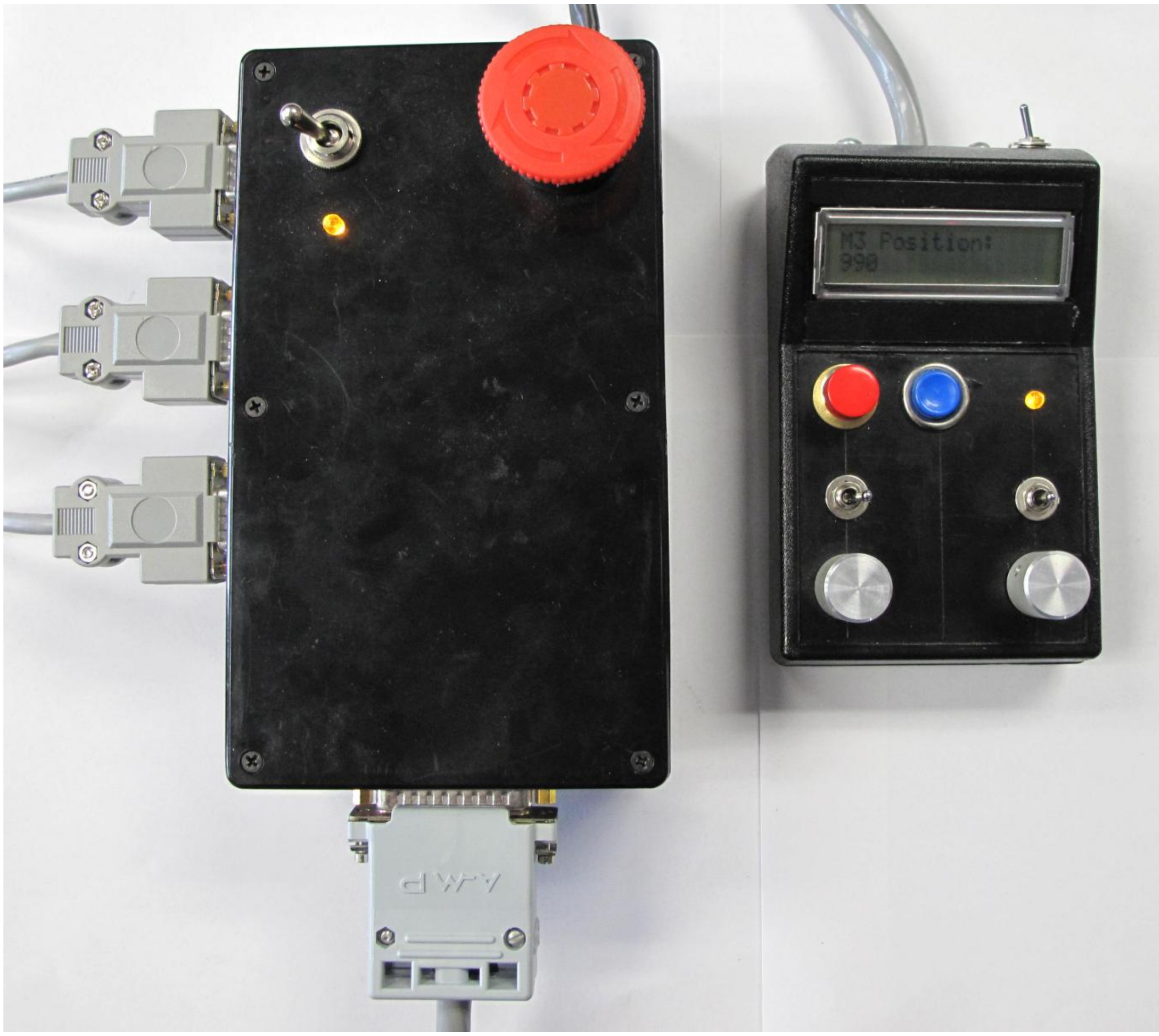


Figure 25: 3D Scanner Electronics

Notice that all logic components are housed in a small format box with an on switch and e-stop button readily accessible. An off shelf power supply with the needed 12V power line is used to power the system. Inside the box, the microcontroller board is housed along with a prototyping board that has the drive circuits for the three motors and a regulator board that provides a 5V regulated supply for the microcontroller and logic chips. The external connectors are standard d-subs that meet the necessary number of transmission lines, 9 for each motor and 21 for the pendant. Although the scanner will be fully operated via computer terminal, a manual pendant was made. This hand held wired remote is invaluable during the prototyping sages, and calibrating stages of the scanner design. It is equipped with an LCD screen that provides information such as step location, speed, or functionality mode. Also the pendant has two mechanical encoders, two three way mode switches, and two push buttons. The combination of these input methods allows the user to navigate menus designed for the pendant such that preliminary runs and calibration of the scanner can be done without any computer interfacing. Once manual control is no longer needed the pendant can be disconnect from the setup and kept only as a diagnostic tool or for maintenance use.

5.2.3.3 Embedded Software

To run all the operations needed for the 3D scanner, several structured classes were written in C++ to meet the functionality needs. The arduino microcontroller has the benefit of being compatible with object orientated programming, which provided a higher level approach to implementing the needed logic. Three independent classes were written to run the scanner. These are a stepper motor class, a scanner controller class, and a scanner communicator class.

The purpose of writing a stepper motor class was twofold. Firstly to have very low access to each independent step and step frequency. This keeps a precise count of motor position and run status, as well as it allows implementation of more advanced running modes that include acceleration to speed and deceleration when stopping. Secondly, this class runs an architecture utilizing time splicing which allows a single thread microcontroller to run three different motors simultaneously without the use of interrupts. This allows the running of motors while sending and receiving information via USB, and can even perform advanced functions such as using different scan speeds for motors if needed.

The scanner communicator class is used to securely send information in a bounded structure in between the computer user interface, and the lower level microcontroller. Its functions are written in a mirror fashion. One set in C++ for the microcontroller and another in Visual Basic (VB) to run as subroutines under the VB graphical user interface (GUI). Figure 26 shows the GUI developed to run the scanner. This small interface has an automatic mode seen on the left and a manual mode seen on right. The manual mode can be used for maintenance and recalibration without the need to attach the physical pendant. Behind this GUI the VB subroutines of the communicator class communicate with the microcontroller. Several handshaking and checksum validation methods were experimented with for integrity of sent data. The final chosen mechanic is a triple send bitwise agreement check. This resulted in lower bandwidth than other mechanisms and allows initiation of communication from both systems. Using a master and slave approach created too much port flooding since the master would always have to request information, and this was detrimental to the performance of the microcontroller. With the current system the microcontroller can update the computer as events finish and the computer can request new events without constantly checking for completion.

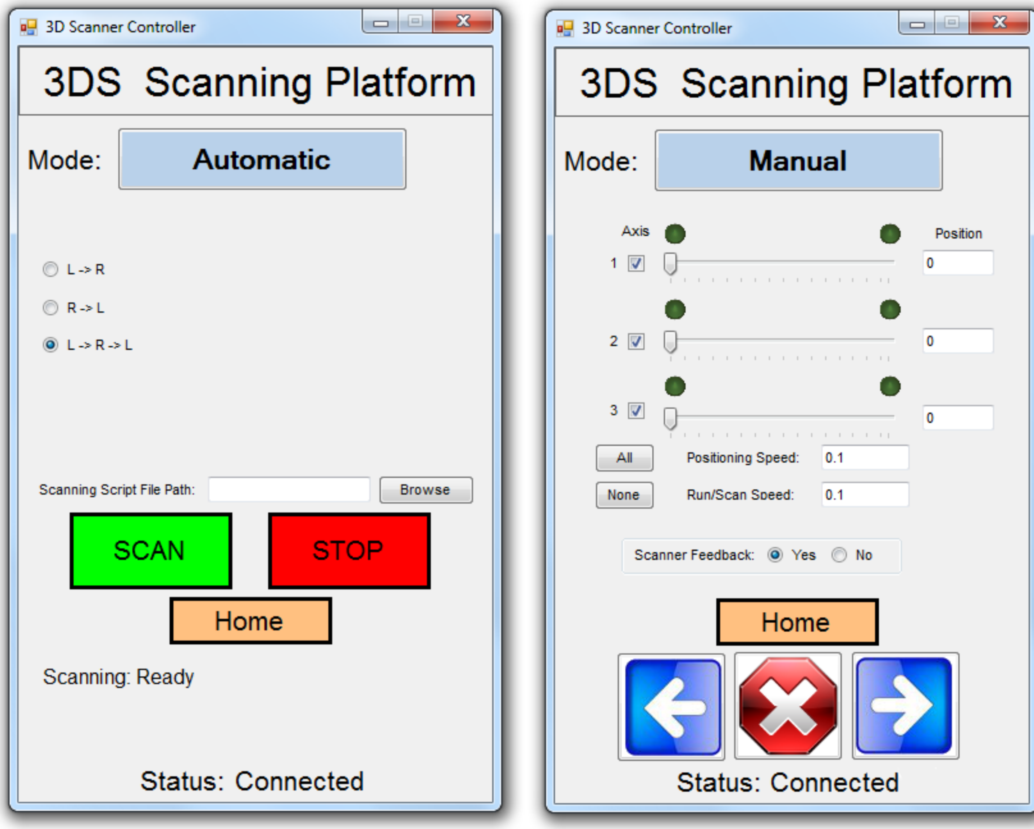


Figure 26: User interface for the 3D Scanner

The scanner controller class is a single object class that works as a mediator between the lower level stepper motor class, and the higher level communication class. It distinguishes and then operates under one of two modes. These are manual control with the pendant or direct remote control via USB. Once a mode is chosen this class performs the required logic to process incoming commands and send them to the lower level stepper motor class, or to communicate with the computer via the higher level communication class. This class is therefore the highest overhead class and possesses the function bindings that are needed to take an incoming command, process it, and call the requested stepper motor function.

After extensive testing and debugging, the embedded software and communication was able to meet the scan specs needed for the scanner. This included full control of scanning speed, and repeatable position accuracy of 0.01inch (0.25mm). The next section describes the high level software needs of the scanner. Note that coordination between image capturing and motor movement will be done through the VB subroutines of the communication class. Since the class was written in Microsoft visual studio.net, it can be an interface point with other higher level software.

5.2.4 Software Design

This is a brief description of ongoing work to complete the functionality of the 3D scanner. The completed optic system on a functioning electromechanical setup, now requires work on image processing and automatic image capture.

The image processing or image analysis refers to the work done on the set of images provided by the scanner. Each camera will provide of set of images from its view point. The number of images depends on the extracted resolution. A faster scan can use less images than a more accurate slower scan. Software must now be used to filter each image of noise and extract the laser line that indicates depth in that frame. Figure 27 shows a typical progression in filtering stages from the raw camera image to the extracted depth contour line. The image is first red filtered to isolate the laser line and remove other colour information. Following that a series of steps isolate and refine the laser line laser contact area and remove discontinuous segments and other noise. Based on the rising intensity of the laser at the middle of the beam a histogram map is then used to narrow the dispersed structured light to its middle point.

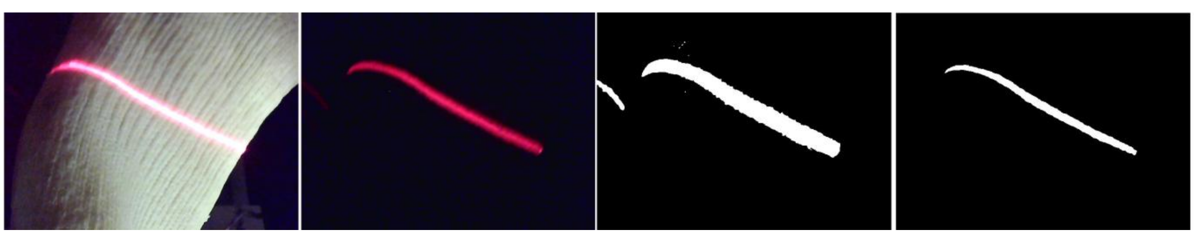


Figure 27: Image Filtering Progression

The last stage shown in Figure 27 is further sharpened to result in a single line that is located within the maximum intensity center of the laser plane. This now represents one partial contour slice of the 3D surface. The points on this line in the camera X and Y coordinate system is subsequently scaled to match the projection of the camera view angle in depth and width. Stitching several of these contours together shows the surface of the sock mold from the point of view of a single camera in 3D space. Figure 28 shows several contours of the sock mold in a 3D plot created during the calibration process.

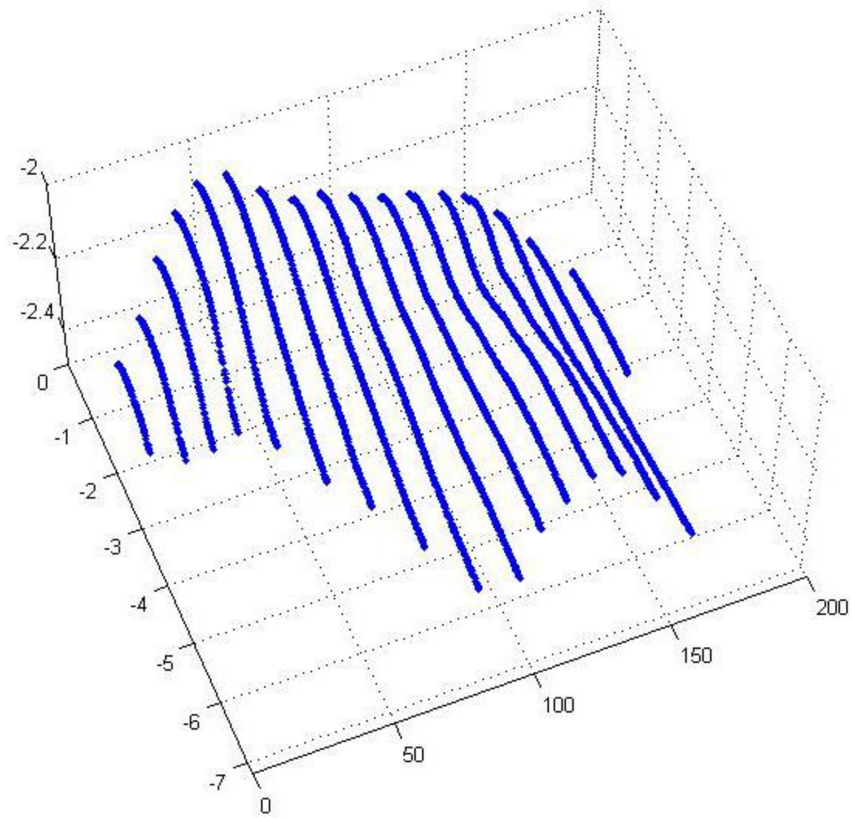


Figure 28: Single Camera 3D Plot

The surface showed above is incomplete as this is only a single camera view point that is occluded by the convex geometry of the foot arch. Notice that the first few contours are much shorter as occlusion beings between three and four centimeters. The later contours are longer as the surface is flatter and does not occlude the opposite side. To get the complete plantar surface of the foot this data would be matched with the data of the conjugate camera. Following this the other three scanning heads would provide information on the right side plantar surface and the upper left and right foot sides. As the calibration process is done manually the density of contours is sparse at 0.4inch (10mm) distance from contour to contour. In an automatic scan this can be reduced to the maximum resolution spec of 0.01inch (0.25mm) distance between contours. The exact depth resolution may not need to be this high and experimental testing will be used to obtain an optimal resolution that balances the required accuracy with a fast scan time. The cameras currently on the scanner can stream images at 30 frames per second which would result in a 40 second scan time for a 12inch (305mm) foot. This time can be cut in half by reducing the depth resolution to 0.02inch (0.5mm).

Once the image processing algorithms are finalized for one camera, they can be quickly implemented on the other eight. The only difference is the transform matrix that converts the local camera coordinate system to the global scanner system. The geometric data for this transform is extracted from the CAD model and then can be manually tweaked to compensate for any small variations that may arise from inconsistent camera mounting. The last stage of the calibration process will be to tweak each camera's position in software to match any differences on the physical device and validate this with a series of calibration parts.

The last task for full scanner functionality is the automation of image capture. Each camera on the scanner works by transferring its image information via USB interface to a computer. As there are eight cameras their images capture must be synchronized and automated. The electromechanical system can actuate and command the scanner via PC interface but as of now it has no link to the scanning heads. To have a fully working scanner this link must be established such that the existing interface of the scanner can command the start and stop of image capture as well as the rate of capture in correlation with the platform move speed. This requires the implementation of a data acquisition system with sufficient bandwidth for extracting the needed information from the cameras and drivers that will interface with the existing system.

5.3 Limitations of 3D Scanning

Although the 3D scanning system is far more capable than the 2D approach described in chapter 4, it still has one major drawback. This is that as in the 2D scanning case the foot is fully loaded and resting on a flat platform. It is known that the foot will distort differently on a flat surface than within the 3D surface of a shoe. Hence the digitized model obtained is still not the in the optimal loaded position. Therefore corrections and manipulations of the foot have to be done in CAD after the scan without customer feedback.

5.4 Application of 3D Scanning

Upon completion of a fully functioning scanner, the capability to create surface models of customer's feet will be readily available. As described in the introduction section a model is an invaluable asset in the creation of properly fitting foot ware. The application of this model can start immediately at making custom lasts that will produce foot ware highly superior in fit than off shelf or generic shoes. Specific applications include the manufacture of dress shoes or tight fitting shoes. With the high resolution of the 3D scanner more rigid shoe ware can be made custom and well fitting to individual client needs. Having a last made from a foot model also provides the benefit of detection of small injuries or chronic areas of damage such that they can be accommodated for with added space or cushioning in a custom shoe. Furthermore, a 3D scanner can accommodate the production of lasts or custom shoes for severe deformities or abnormalities. There is no generic assumed shape and hence whatever the scan result provides is the closest digital representation of the customer's foot. Although making a shoe for a deformed foot is very difficult, starting with an exact replica last will greatly assist the process. All these applications are only the beginning for the use of a foot model as they do not perform any manipulation on the foot, and mostly focus on creating a matching shoe.

The secondary objective of this research focus was to manipulate the model. This starts with creating accurate geometric foot models of the customer's feet in the loaded and unloaded form. This then allows manipulation in CAD that mimics the changes an orthopedist would to make when setting the foot in the right posture for taking an impression or mold. Corrective shoes do not keep the foot in its natural shape. This is because over time make the foot's natural standing shape is no longer a good support structure and it causes pain and discomfort during standing and walking. Corrective shoes place the foot in a corrected or better supported position. This position is unknown and has to be determined often on a case by case basis with lots of feedback from the customer and many trials and manipulations of the standing surface. One of the applications of the 3D scanner is to create functions that correct the foot in digital domain and then produce a superior starting point for a corrective shoe, specific to the customer. An example of this type manipulation is done with freeform, volume constrictive deformation as shown in Figure 29.

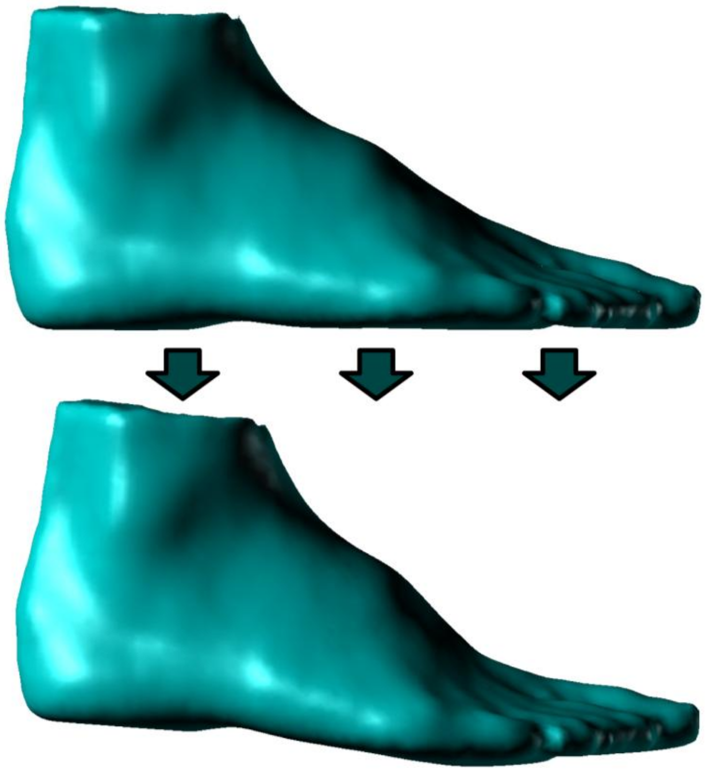


Figure 29: Freeform Deformation of Foot Model

In the figure above a controlled volume including a foot in its natural position is shown on the top. In the bottom of the figure the manipulated position of the foot is shown. Note that the heel is no longer in line on a flat surface and has been raised to represent standing within a shoe. This is the equivalent of performing manual corrective action in real life. The CAD model ensures that the foot maintains its volume and surface properties as it would in reality. Future work on better modeling the structure of the foot can be based on initial 3D scanning and also applied to create more manipulation functions for the production of custom shoes.

Chapter 6
3D Surface Pressure Measurement

This chapter describes research done for the purpose of creating a 3D variable surface pressure sensor to be used for foot modeling.

6.1 Reasoning for a 3D Surface Pressure Sensor

Thus far, methods were explored to scan a foot after being placed on a flat surface. Placing the foot on a flat surface creates an inherent distortion on the foot that is usually not comfortable. If the foot is in a non weight bearing or dangling position, the plantar surface will rest in the natural shape. Once the foot is placed on a flat surface, even non weight bearing, the plantar surface will flatten out partially on the surface. Furthermore as more weight is applied, more flat contact area is created and the foot geometry significantly distorts under compression. More significant distortions are seen in clients with collapsing arches where the foot no longer keeps its structured geometry under pressure. Due to these observed distortions, there are limitations to the foot surface models obtained from a flat surface. To gain a better understanding of the support structure of the foot, pressure maps have been used to identify the distribution of loading across the plantar surface of the foot. Figure 30 shows two examples of pressure maps on a flat surface with a legend in megapascals. Part (a) in Figure 30 shows a very high pressure concentration on the heal while part (b) shows a more distributed pressure load with more pressure on the first metatarsal ball joint. This type of loading analysis is extensively studied in the works of Natali [25], however the testing is still done on a flat surface. The objective of the work presented in this chapter is to obtain pressure measurements from a foot loaded on a 3D surface that best distributes the loading for optimal comfort.

Figure 30: Plantar Pressure Distribution - Natali [25]

The pressure information above, coupled with the geometric information obtained from scanning, allows the creation of better corrective shoes. This is because now not only is the geometry of the customer's foot known, but also the support structure needs are being assessed. Once corrected these parameters lead to a better shoe. Common practice in custom shoe design is to add support structure in various problematic areas of the foot; these include arch support; Metatarsal arch support; heel height and other structures for generic tilt and twist. The end goal of these features is to distribute high pressure areas across a better supported platform. This results in a significantly more comfortable shoe, which can often correct impaired walking and resultant injury aggravation. However, the process of creating these corrective shoes is extremely time consuming due to the trial and error methodology. Shoe makers will often have to try various support surfaces for a customer's foot and receive feedback until a comfortable result is obtained. Creating these surfaces is labor intensive and requires high skill and expertise that are not readily available. Even with the use of pressure mapping, trial and error in manufacturing still occurs due to the disconnect between the pressure distribution on a flat surface, and the pressure distribution on a shoe surface. Research into creating a 3Dvariable surface pressure sensor was begun to bridge this gap.

A variable surface pressure sensor is the 3D equivalent of a pressure map. This means that the proposed device must be able to create a surface approximating the concave imprint of a customer's foot. The surface should also be variable, or have the ability to change dynamically within a reasonable time period. Furthermore the surface should be pressure sensitive, or able to measure the force applied along this defined surface. Having such a device would allow for a customer to stand on a surface that geometrically matches their foot. The data for the starting surface would be provided from a 3D scanner such as the one described in chapter 5. Once on this surface, pressure distribution information would be available, along with customer feedback. The variability of the surface will allow for changes or corrective surface manipulations to distribute pressure and assume a form that is comfortable for the customer. The change in the surface can be a result of mathematical models developed to distribute pressure on the foot as well as direct customer input. The result would be a comfortable geometric surface, which supports the foot in the correct posture and minimizes high pressure areas. Once this surface is attained, it can be manufactured, without the need of modification or further customer feedback. Thus from a practical perspective the proposed device would allow for incredibly fast convergence on a desired shoe shape in a single customer session without any intensive labor requirements or rework. From a theoretical or research perspective, this device would allow the creation of algorithms that better map geometrical information of the foot to pressure distribution.

6.2 Prototype Concepts and Conventional Pressure Plates

The creation of a variable surface pressure sensor is a non trivial task and several concepts were investigated before converging to the proposed solution. The support mechanism concepts varied between different foam or gel materials to hydraulic or pneumatic bladder systems as well as a crosshatch of tension bands. Although foam boxes are used to take impressions or molds of plantar foot surfaces, they are not suitable for loaded applications. The foam needed to support a foot under weight is far more elastic and must have little memory effects. The bladder systems offered a simple approach to supporting a foot on a cushion type surface where pressure or release valves can be used to manipulate the foot posture. This however quickly resulted in an array of many small bladders that would be very complex to manufacture and prone to leakages. The crosshatch tension band system would allow some generic control of foot posture, however like all other concepts it highly exaggerates the hammock effect. The hammock effect occurs when you place a strap around a foot or submerge a foot in a pillow or cloth surface. What results is the downward pressure of the foot converting partially into a side force that squeezes the foot as it goes deeper into the surface. This side force or tension on the straps would deform the foot and make it into a rounder and highly uncomfortable shape. This drawback makes the above support methods impractical for creating a fully controllable surface. Hence, it became clear that the proposed device would have a surface comprised of a discontinuous series of control points. This eliminates any tension or side force applied on a foot or surfaces of high curvature.

Since the creation of the surface would be a done by a discrete set of points, a discrete number of pressure sensors may be necessary to obtain pressure data across the surface. Another option is to use a single 2D pressure platform that is mapped to the 3D surface via direct force transmission. Both of these solutions are presented in later sections. The device poses no constraint on the mechanic of measuring pressure measurement, as long as it is in the magnitude range needed and meets the accuracy and reliability requirements. This flexibility allows the consideration of resistive type pressure sensors, piezoelectric sensors, and strain based devices. The selection of the final sensor mechanic will be based on the mechanical drive system used and experimental data collected from the proof of concept prototypes.

6.3 Pin Matrix Concept

After establishing that a discrete surface will be created the pin matrix concept was developed. This concept is to create a two dimensional matrix of pins. Each pin will be individually actuated and have a pressure sensor built into its actuation system or support structure. This results in a pressure reading of each pin as well as the capability to set the position of each pin. Therefore given any surface, the pin matrix can approximate the surface by setting each pin top to a contact point of that surface. The overwhelming challenge of this concept is the creation of a drive mechanism small enough and powerful enough to accurately manipulate the position of each pin, under the load of a customer’s foot. The emphasis of individual pin actuation is critical to the functionality of this concept. Work has already been done with pin based arrays that did not have independent pin actuation. This is seen in products such as the VF-300 by Varifit Orthotics [31], which use a pin matrix to take an impression and then manufacture a custom orthotic as opposed to using more traditional single use foam box methods. The non actuation of the pins is a large downside since it requires the customer to stand on and off the device many times and operator assistance is required to get a good impression of the foot. With fully independent actuation of every pin the proposed system can create a custom surface in seconds. Furthermore the incorporation of pressure measurement has not yet been explored completely and may offer other benefits.

The form factor of the drive mechanism would also become the limit on resolution and pin density. Pin density is a parameter of the device that determines how well it will match a given surface, or what is the maximum curvature that can be obtained. Having many pins, as in a feeler gage, can provide sub millimeter resolution of the surface. This is not practical for the proposed device as it requires individually actuated pins. Furthermore a large number of pins create an incredibly complex and expensive electromechanical system that has to actuate the pins and collect position data as well as pressure data from them. Thus a larger resolution size was established that would work with several proposed actuation concepts. When moving to a larger resolution size, pin diameter also increases proportionately to avoid buckling and minimize distortion when side loads are applied. The specified resolution for the pin matrix device was selected to be 0.590inch (15mm) from pin center to pin center, with a nominal pin size of 0.375inch (9.52mm). Mostly imperial components and material sizes were used in this and previous prototypes as the industry suppliers used are based in the United States and adhere to the imperial system. This allows better matching of material sizes to available tooling and off shelf mechanical components.

Having established a resolution of 0.590 (15mm) the arrangement of pins must be setup either in a rectangular array or diamond pattern. The rectangular array is easier to actuate and is used in the proposed design concepts. The diamond has the benefit of ensuring that center to center distance of any pin to an adjacent pin is always the same and maximizes area coverage. To expand the supported area the customer would stand on, each pin is fitted with a 0.5inch (12.7mm) cap. This creates a more continuous surface with less unsupported areas as shown in Figure 31 below. Both rectangular and diamond orientations are shown.

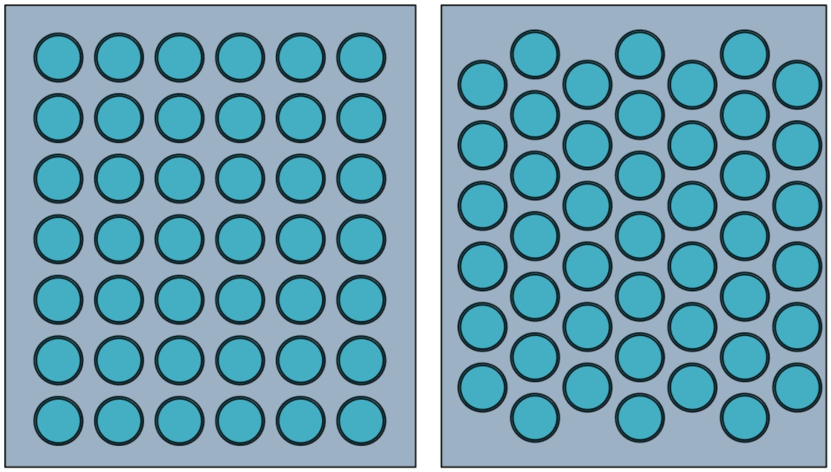


Figure 31: Top View Pin Array Segments

The proposed matrix size is 12inches (305mm) by 6inches (152mm) and would require 152 pins. To ensure that the device will match curvature without creating a staircase type surface each pin cap is mounted on a custom designed high tilt swivel cap. These caps can tilt in any direction up to 45 degrees and allow the matching of curvature throughout the plantar surface of the foot. Figure 32 shows a side view of an example pin position to match a given surface. The pin array caps are bound by an elastic membrane, not shown in CAD, which serves two purposes. First it keeps alignment between the pin caps, and second it prevents the creation of pinch points between two caps.

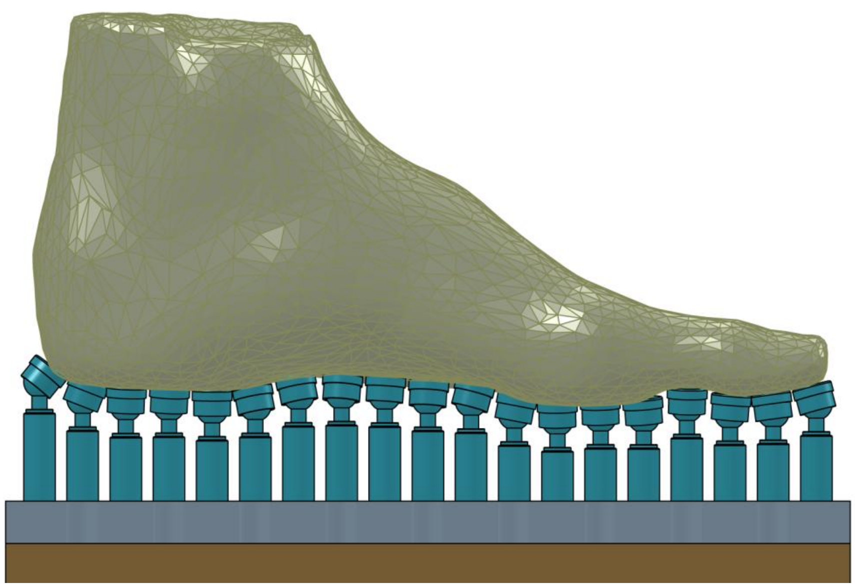


Figure 32: Side View of Pin Array

The figure above shows a reasonably close matching to the example surface, which was obtained from a 3D foot scan. A compressible foam collar is also an added option to maintain a vertical pin cap. The collar would fit between the pin top and the pin cap and act as a spring that returns the pin cap to its neutral position when no tilt pressure is experienced. This reduces the wear on the elastic membrane that connects the pin caps. Without the cover of the elastic membrane, Figure 33 shows how the pin array can match curvature of a scanned 3D foot model.

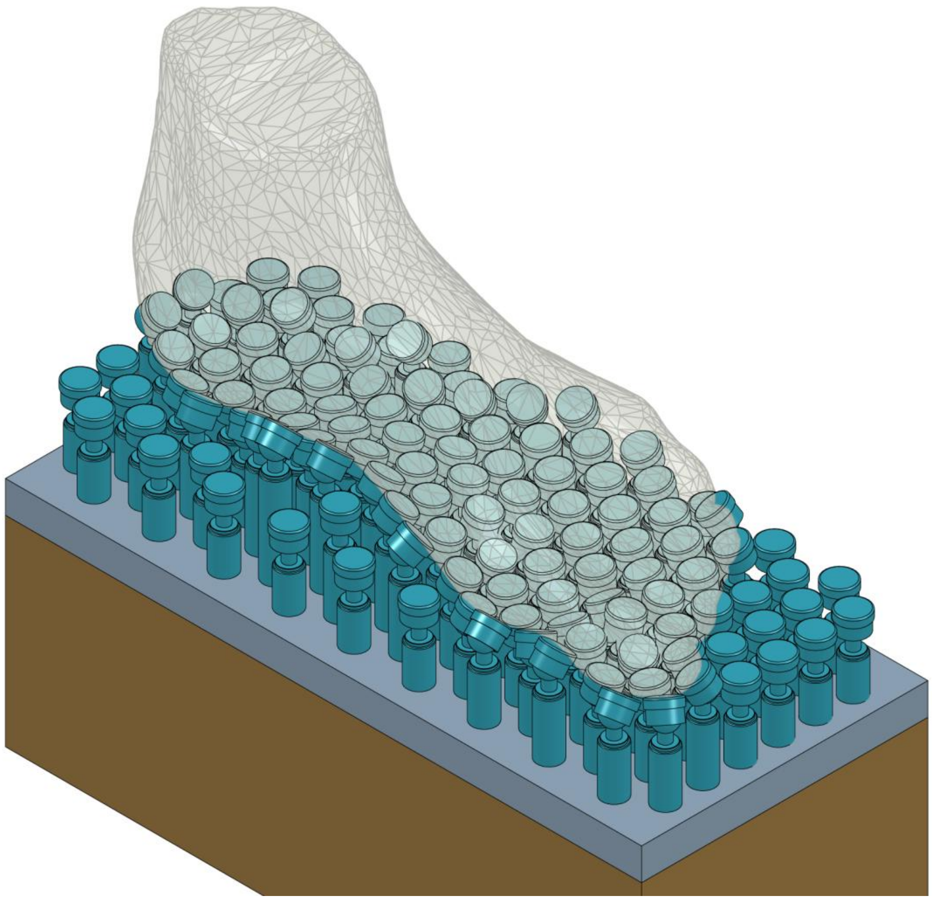


Figure 33: Pin Array Concept

It is important to state at this point that this research prototype would be vastly expensive to design and manufacture due to its complexity. This large expense is not justifiable without first proving the concept via successful testing of a subset of the pin matrix. Thus the prudent approach taken is to create several prototypes that test the actuation and sensing performance of one pin and then a group of pins. Section 6.4 describes the custom drive system developed to inexpensively create and test the proof of concept prototypes. Section 6.5 provides two preliminary designs for industrial grade actuation solutions that should be employed in the production of a complete pin matrix.

6.4 Proof of Concept Prototypes

This section describes the design and functionality of two proof of concept prototypes. CAD models are used to convey features and functionality of the design.

To prove the concept functionality of the variable surface pressure sensor, two proof of concept prototypes were developed. The first is a single pin platform. This platform will actuate only one independent pin, and be instrumented to obtain the performance of the pin and its capability under load. This will certify that the drive mechanism works within the specified accuracy parameter, and that the pressure sensor can be calibrated to work with the variable pin height. The second prototype is a row of pins, or a module. The actuation design concepts groups the pins into rows of eight. As it takes eight pins to create a module, twenty modules stacked will then create the entire device. The modular architecture also allows for subdivision of the electrical system into independent boards that run each module. The purpose of creating a row of pins is to verify that with functioning single pins a two dimensional surface can be created and manipulated with a single row of the pin array. The module prototype will focus on using the row of pins to match surfaces, and validate the design choices in pin resolution and pin cap design. Furthermore, having a row of pins allows the preliminary development and testing of algorithms to distribute pressure in a single dimension before the entire device is made available.

To create the required proof of concept prototypes, an economical and time efficient actuation system is needed. Thus, a cable drive system was developed as the actuation device. This system falls within the scope of the prototypes requirements and is designed for fast manufacturing. This then allowed for timely construction and testing of the two prototypes. The cable drive system also provides the benefit of a higher resolution pin matrix with larger more powerful motors. The next section describes the design and capability of the cable drive system.

6.4.1 Design of Cable Drive System

To independently actuate the pins requires each pin to have its own motor drive system. Initial concepts investigated the use of hydraulic or pneumatic drives for the pins as they are small in form factor and require only one energy source that can be remotely located. These concepts were not perused as they would require feedback sensors and a control loop per pin that would add to the cost and complexity of the system. The hydraulics would also require very high precision custom components that would take a long time to fabricate and again add to the manufacturing cost. To minimize cost a non feedback drive system is used. This system employs an individual stepper motor to drive each pin. The disadvantage is that small motors servos or steppers have very little power output. Increasing the size of the motor does not allow for the specified pin density. Hence a cable drive system is implemented.

The cable drive system uses a bowden cable to relocate the power transmission system from directly beneath the platform, to a lower lateral position. This allows the use of significantly larger stepper motors of 2x2inches (50.8mm). These motors provide 32oz-in of torque and drive a self locking screw that controls the position of the pin. The design of the cable transmission is shown in Figure 34. A cable and sheath system is used to relocate linear motion from a remote location to each pin. To achieve this the cable is connected to the top surface that restrains the pins. This is done by having a slot cutout through each pin and a cross member placed in the center of each pin. The cross member has a hole that secures the drive cable and is then welded in place. Thus when the cable is pulled in and out, change in curvature of the sheath results and is correlated to the up and down movement of the pin. With a low compression sheath the actuation is very close to linear but will require some compensation for compression under high loads as seen in section 6.4.2.1.

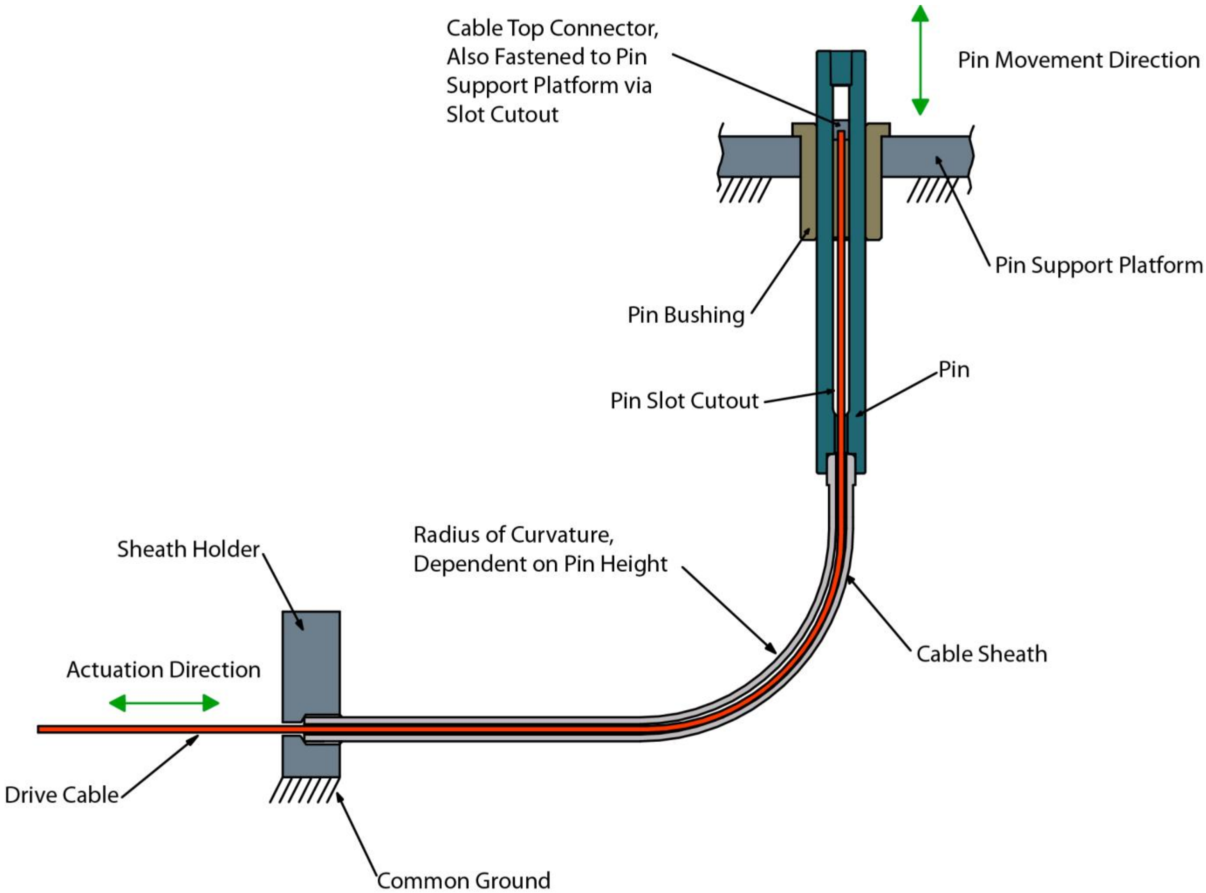


Figure 34: Cable Drive System

This system uses a very low compression outer sheath designed from derailleur's on bicycles. The low compressibility of the sheath results in more accuracy on the position of the pin. The rotational motion of the stepper motor is converted to precise linear motion using a precise drive screw. The drive screw actuates a locking nut that moves the cable in and out of the sheath to transmit the motion to the pin top. The cable is under tension when the pin is loaded, which allows the use of a stranded cable. Furthermore the motor is protected from any axial load since the tension on the cable is transformed to a compression force on the thrust washer at the end of the drive screw. The drive screw is self locking, this means that its pitch angle is low enough such that application of force on the movement nut will not cause it to free slide along the screw. This reduces the power consumption on the stepper motors as they do not consume more energy to hold a heavy load. If accidentally a very heavy load is applied onto the platform the motors will not lose their position reference if they are stopped. Hence this system has the benefit of protecting the drive motor from excessive or transient loads on the pin top. The self locking screw also creates higher torque amplification due to its smaller pitch and allows the controlled lowering of heavy loads with a smaller motor. The downside of the cable drive system is that it requires more calibration than a direct screw drive system and has position hysteresis under lowering an unloaded pin. The extent of these limitations is described in the next section, which evaluates the performance of the single pin prototype.

Despite the fact that larger motors can be implemented using the cable drive system, obtaining the needed torque to raise each pin is problematic. A large motor will have higher raising and lowering load, however even the 36oz-in torque stepper motors used in testing are not powerful enough to raise a pin under the expected maximal loading force. They are however fully capable of lowering the maximum loading force of 15lbs. The max loading force is created from a conservative estimate of how much weight would be supported by a single pin in the worst loading condition. The logic for its derivation is as follows: If a 200lb person was to stand with one foot on the device and shift most of their weight (70%) onto it, the device could experience total loading of 140lbs. If most of this weight (70%) was focused on the smallest area of the foot, the heel, then it would receive 100lbs. Based on average heel size this 100lbs weight would be supported by approximately 10 pins. This results in around 10lbs load per pin. A 50% increase was made to accommodate clients even heavier than 200lbs. The resultant 15lb maximum loading weight per pin is what was used to design the torque of the drive system to be capable of accurately lowering 15lbs of without missing steps. The equations used to calculate the power and pitch of the drive screw are from the Chapter 8 of Mechanical Design Engineering, seventh edition [35]. Attempting to create a drive system powerful enough to lift 15lbs resulted in much larger motors that would increase the form factor of the prototypes significantly. Thus a design decision was made to limit the platform in functionality to only lowering direction. This means a surface would be attained by lowering the pins into position, which can be done under full load with the smaller stepper motors. This does have the downside of requiring the customer to step off the platform after several surface corrections when the pin stroke has bottomed out. The stroke of pins was designed to be 2.5inches (64mm) in depth to allow several surface modifications before the pins need to be reset. Operation in this fashion will always create a bottom out case as the raising of a series of pins must be accomplished only by globally lowering others around them. This can become an inconvenience if too many platform resets are needed during use on a single customer. Section 6.5.2 shows an actuation concept that also allows rising of pins under full load.

6.4.2 Single Pin Prototype

Upon finalization of the cable drive concept, detail design was done to create the single pin prototype. This prototype was designed to incorporate more features than an independent pin would have, which are then used to instrument the pin and obtain needed calibration and system performance data. Figure 35 shows the design on the single pin prototype.

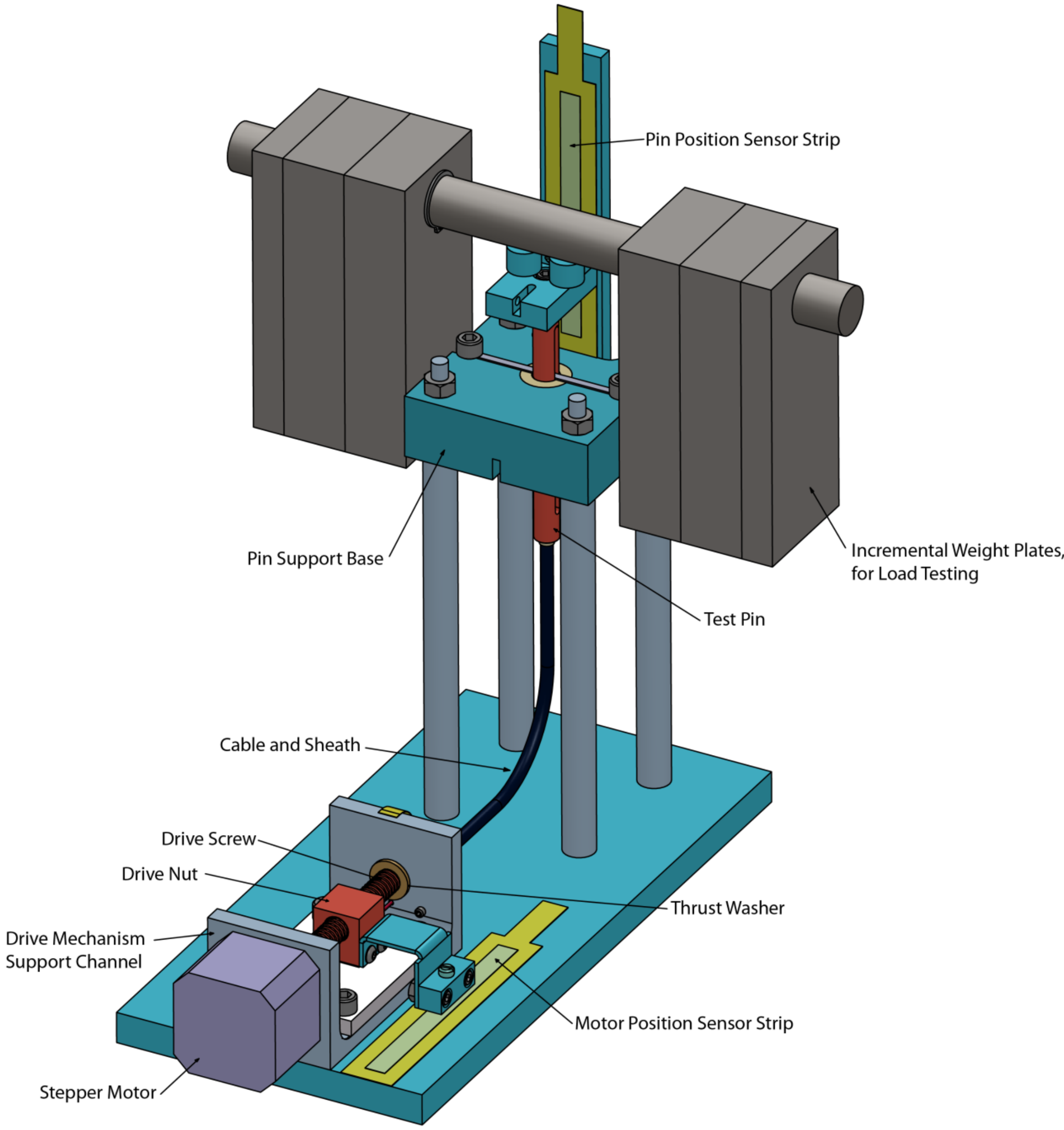


Figure 35: Single Pin Prototype

The pin is supported by a plastic base on raised pillars. This base is connected to the channel that holds the motor and drive screw system. The pin slides up and down on a Teflon bearing machined to fit the platform. The bearing slot is larger such that other bearing materials can be tested. During the initial stages of testing ultra high molecular weight polyethylene (UHMW PE) was used as a bearing material however it proved to be to constrictive and had binding problems. The Teflon (PTFE) bearing worked well however it wears out rather quickly and introduces a slight tilt clearance. The eight pin prototype features a redesign of the pin support system that removes the wear issue.

For the single pin prototype two sensors for linear displacement are installed. These are resistance strip sensors that use a pressure brush tip to vary resistance linearly along the length of the strip. One is installed in parallel to the stepper motor drive system and coupled to the drive nut that actuates the cable. This is shown in Figure 35 as the red drive nut block also connects to a sheet metal part that holds the sliding brush against the motor position sensor strip. The purpose of this measurement is to ensure the stepper motor is matching the given position via step inputs and no steps are missed. A large discrepancy between the motor counted position and this sensor would indicate missed steps or the inability to move under the load. The second position sensor is placed vertically and in parallel with the pin head. The purpose of this is to correlate the top position of the pin to the given motor position of the pin. This is especially important since it shows if the cable system is an accurate method of transmitting position. The sensor also allows for compensation of known and mapped inaccuracy. To calibrate the linear sensors a precise digital caliper is used. For the top sensor fitting slots were installed to mount the caliper to the platform as shown in Figure 36.

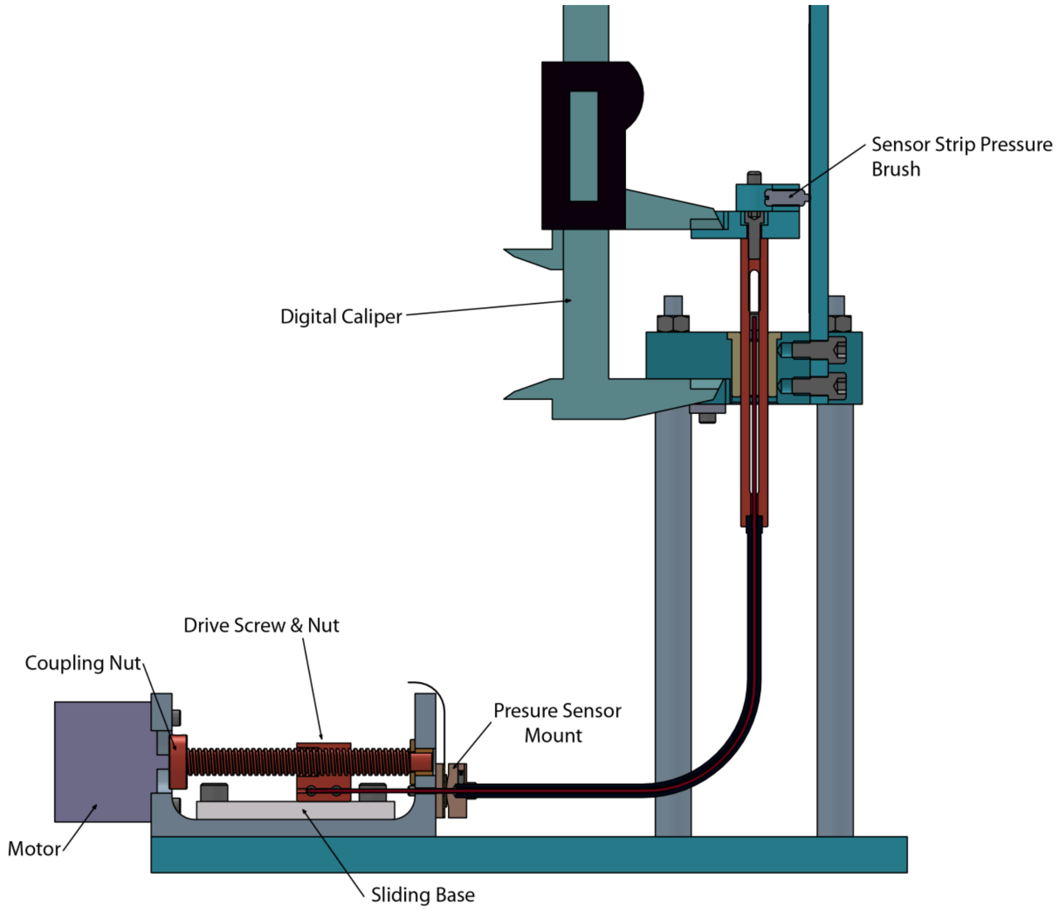


Figure 36: Calibration of Position Strips & Cross Section View

This allows fast and accurate calibration points to be mapped to the sensor output. The position sensor along the drive screw is also calibrated with a digital caliper where measurements are taken from the machine surface of the support channel to the back face of the drive nut. This scale calibration allows software offsets and gains to be set to match the two sensors in the home position and along the travel length. After calibration of the position sensors, drive electronics are connected to test the actuation capacity and accuracy capability of the system.

The electronics used to drive the pin matrix prototypes are based off work done for the 3D scanner. The Arduino microcontroller is used to run designated programs and acquire data from sensors. Data is transmitted via USB to a computer terminal for analysis. The stepper motor drive electronics are identical to the 3D scanner schematic presented in section 5.2.3.1 and use the same logic and amplifier chips. The application of familiar electronics and small modification of the embedded software allowed for quick testing and specification of the single pin prototype.

6.4.2.1 Capability of the Drive System

This section presents and reviews experimental data obtained from the single pin prototype. This includes a series of tests conducted to obtain performance specifications of this prototype. The following is a list of tests preformed and the reasoning for them.

1 – Stroke Cycle of Unloaded Pin: This test moves the pin up and down and identifies any hysteresis effects due to friction when moving the pin as well as the measuring the accuracy of pin position to commanded position.

2 – Stroke Cycle of Full Load Pin: This test verifies that the pin can lower under full load of 15lbs to designated positions and measures the expected compression of the cable sheath under load such that it can be modeled.

3- Stroke Cycle of Full Load with Compensation: Using data obtained from test 2, this test verifies the reduced steady state error under full load with the use of a compensation model.

4- Stroke Cycle of Half Load with Compensation: This test verifies the linearity of compression in the sheath with varying load. Its purpose is to measure accuracy on smaller loads with a proportionally scaled compensation model.

5- Load Cycle of Pressure Sensor: This test applies load on the pin that is transferred to the in system pressure sensor. The purpose is to obtain the sensor output characteristics and establish distinguishable resolution amongst the load weight.

6- Stroke Cycle of Pressure Sensor: This test checks the capability of the pressure sensor to measure load across the entire stroke of the pin. It is done by running all the loading cases on the operational stroke of the pin and measuring the difference in output. The purpose of this test is to ensure pressure measurement is not affected by the curvature of the cable sheath or the current pin position.

To begin with, Figure 37 shows the actuation of the pin in the unloaded case or test 1. Note that although the channel has 2.5inches (64mm) of stroke the tested range was reduced to 1.25inches (38mm). This is due to the unforeseen limited cable sheath length in the first prototype. In order for the cable system to actuate it must have enough curvature such that it can compress its radius of bend far enough to actuate the full stroke of the channel. In the first prototype the pin and drive screw were positioned relatively close with a sheath length of 7.5inches (190mm). This means that after exceeding a stroke of 1.5inches (38mm) the cable sheath starts losing its curve and becomes almost a straight connector. This does not accurately represent the desirable drive mechanic and hence the system was not used in that range. The multi pin module prototype resolves this issue by using significantly longer sheath lengths to provide the flexibility needed for full stroke actuation.

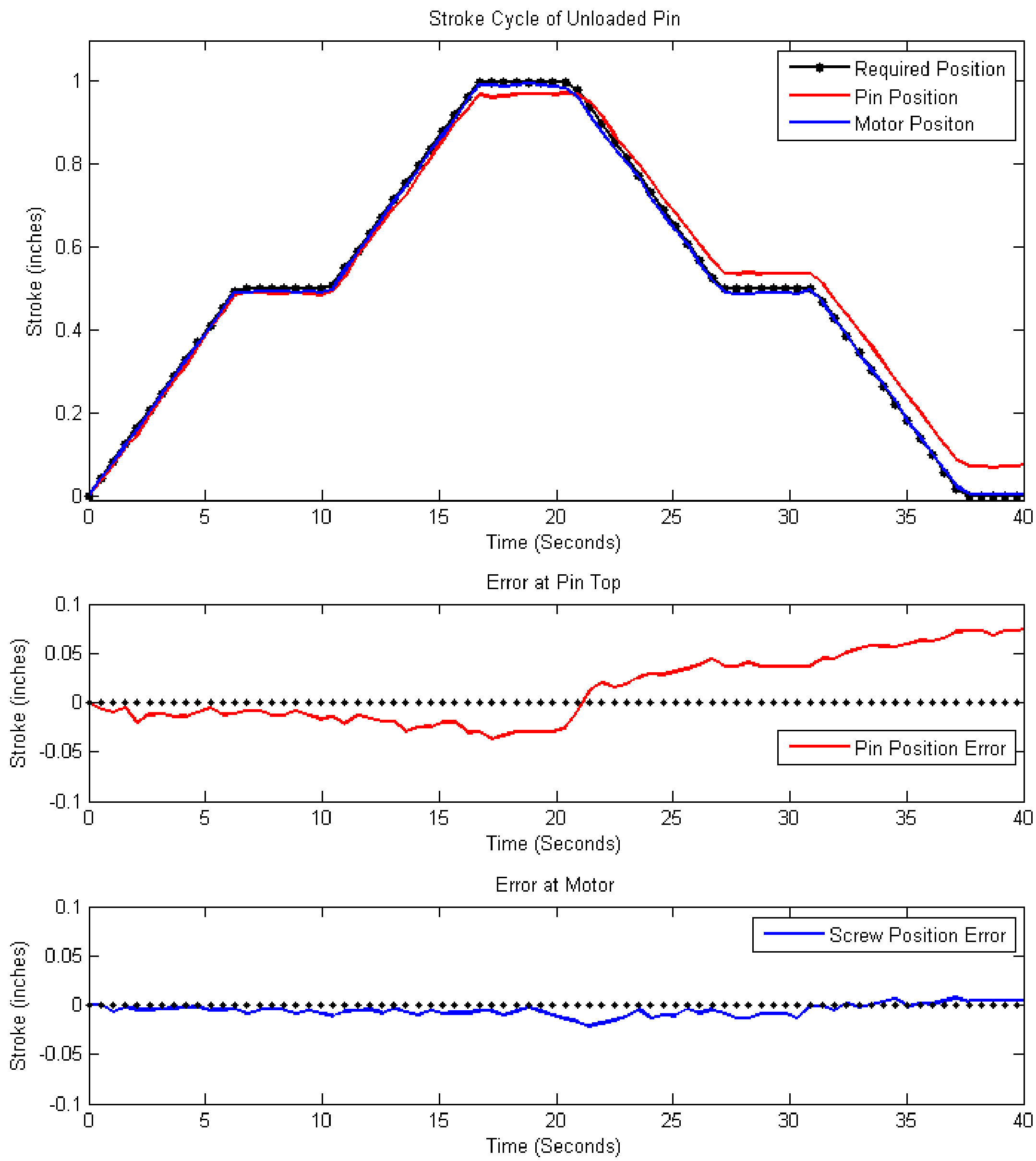


Figure 37: Stroke Cycle of Unloaded Pin

Notice that the motor position sensor follows very closely the actuated position which indicates no missed steps. None were expected in the unloaded case. The pin top sensor shows a very close position correlation on the rise of the pin, however the lowering of the pin exhibits hysteresis. This is caused by friction along the sheath and pin bearing that prevent the pin from lowering fully. Also any buckling in a stranded cable would create hysteresis. Using a solid or stiff spring cable would minimize this issue, except that will require a stronger motor as stiff cables do not adhere to new curvature easily creating more fiction within the sheath. The second test shown in Figure 38 is the full load stroke cycle.

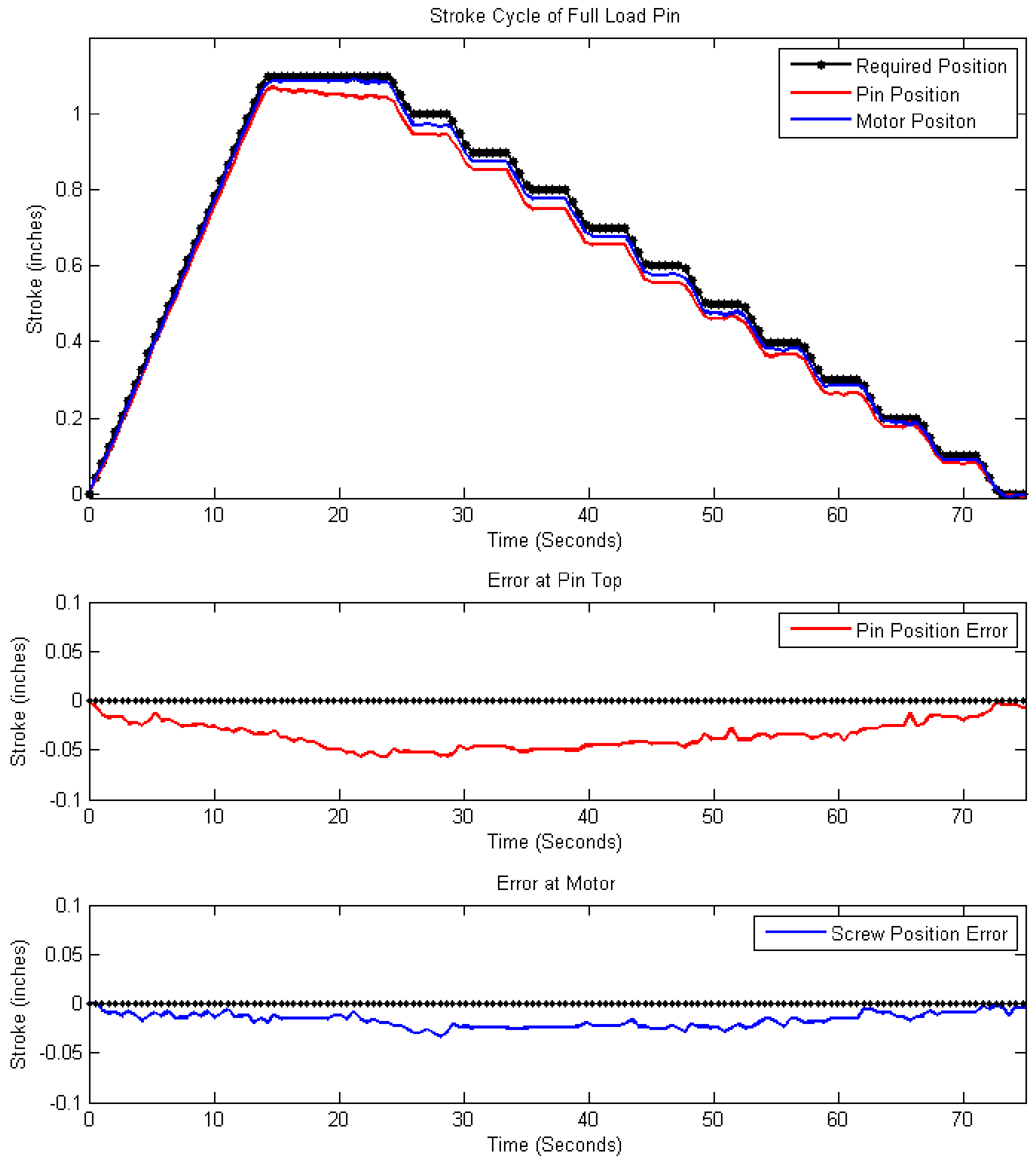


Figure 38: Stroke Cycle of Fully Loaded Pin Uncompensated

As seen in Figure 38, the downside of this hysteresis becomes a non-issue as soon as any load is applied on the pin. Performing preliminary load testing showed that 1.25lbs of weight was required to remove all hysteresis. Since the pin matrix is always expected to operate under some load, the lowering error will disappear as soon as a customer places their foot on the device.

The second test was more involved as the pin was programmed to lower to specific set positions along its decent. This is conducive to the functional operation of the device where the pins would lower to a given point to create a surface, and continue doing so as the surface is modified. The fully loaded pin (15lbs) was lowered in steps across the stroke of the pin. It is important to notice that the motor sensor again stayed very close to the given motor trajectory indicating no missed steps. The pin top sensor is gains significant steady state position error as it is loaded. In all subsequent test the applied load is placed upon the pin head after it attains the maximum height. The first dwell area is hence longer as it is used to mechanically load the pin. The result is compression of the sheath. As the pin descends to its preset points a repeatable undershoot of the desired point is observed, caused by the compression of the sheath. This was an expected downside of using a cable drive system; however it can be compensated for steady state situations. By measuring the undershoot and creating a compensation model, much higher position accuracy can be achieved. Figure 39 shows test 3, the compensated drive system under full load. The compensation model works by adding steps to the desired position based on the measured undershoot in the previous test. These added steps will cause the motor to stop movement above the target position under no load. As the pin is loaded the weight will result in sheath compression that will place the pin at the desired position in steady state. The amount of added steps depends on the error measured. Generally more compensation is needed at the higher pin positions than the lower pin position. In test 3 and Figure 39, the motor position shown is the desired motor position. The actual step count sent to the motor for each stage is higher such that the desired position can be closely reached with the compression of the sheath.

Observing the error plots in Figure 39, shows that in steady state sections, or areas where the pin has stopped moving at a desired position point, there is very little position error. On average less than 0.01inch (0.25mm) of error is seen at the top of the pin. During the dynamic stages there is a significant phase difference that cannot be compensated with the open loop drive system. This is irrelevant for the application of the device as the pin array is not intended to function dynamically; it attains a static surface and then measures pressure. The dynamic error occurring in-between different surface setups has no effect on functionality as long as the desired surface is accurately achieved.

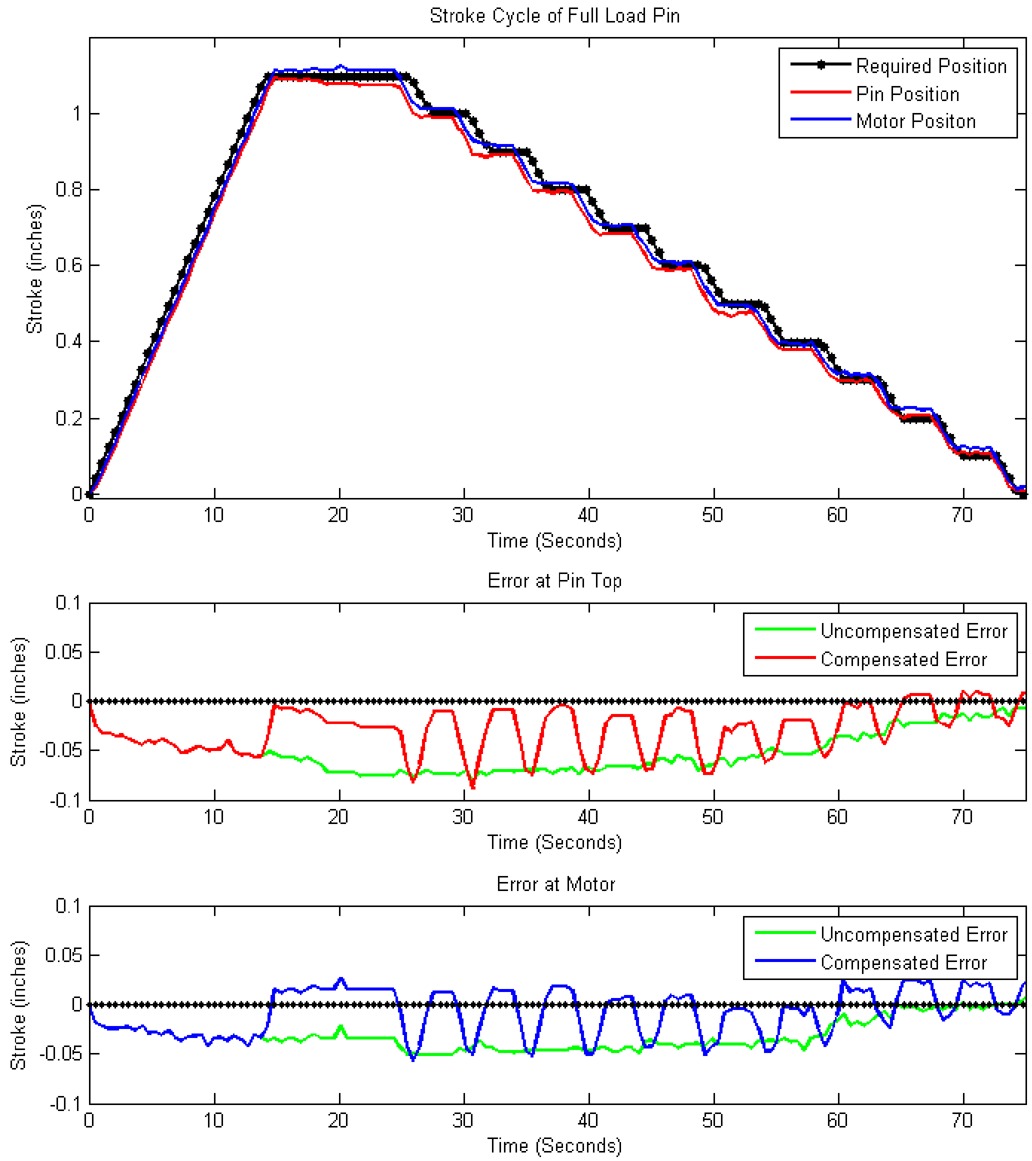


Figure 39: Compensated Full Stroke Pin Cycle

Test 4 verifies the compensation model of the cable sheath compression under reduced load. Several tests were done to verify the linearity of compression with different load. The result in test 4 was done with the half loading or 7.5lbs on the pin. The compensation values for added steps were also halved to match the reduced load. Figure 40 shows the result of test 4.

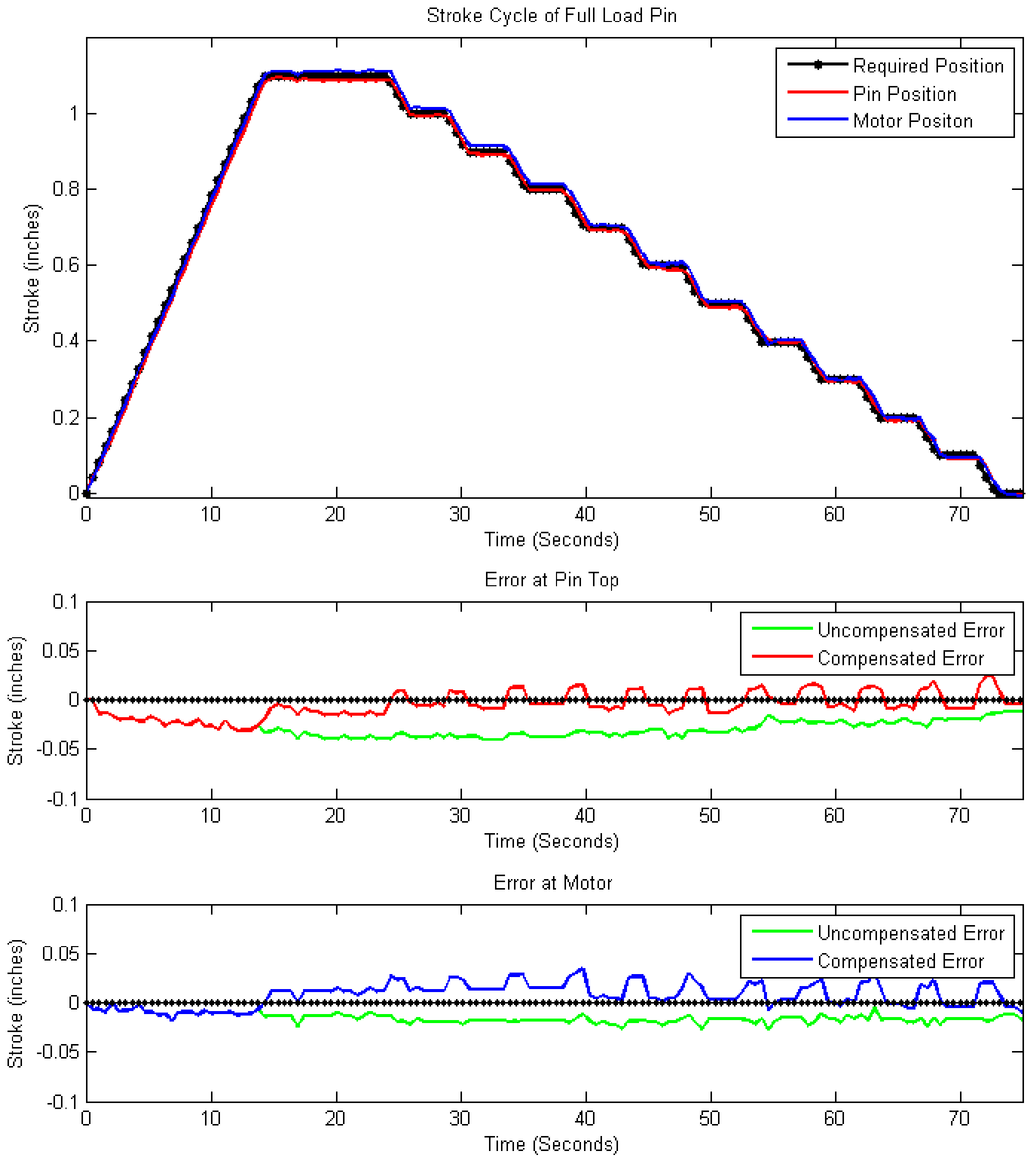


Figure 40: Compensated Half Load Pin Stroke Cycle

As seen above almost identical error rate of less than 0.01inch (0.25mm) in steady state is observed. This shows that the sheath compression is very linear and can be modeled as a spring. This is logical since the mechanical sheath construction is a densely coiled spring coated by a plastic casing. The modeling of this compression can then be used to obtain more accurate positioning of the pin. The added complication is that the loading on the pin must be known in order to select the proportional position compensation. This is not a limitation in this system as each pin is fitted with a pressure sensor that can be used to detect load and then compensate accordingly.

Throughout the modeling stages of the sheath compression and earlier stroke testing, repeatability was verified on the cable drive system. Over 60 stroke tests were performed with varying loading and they all had repeatable results. The rigid mechanical system is thus not subject to short term drift or inaccuracy.

For extensive use or other applications of this cable drive system, a calibration mechanism is recommended. As indicated above to meet the high accuracy needed for the pin device extensive calibration tests were done and a discrete model of compensated loading was created. This is time consuming and must be done on every individual pin. Hence, if calibration of many pins is needed, a mechanical drive system with a load cell can be used in conjecture with the stroke cycle of the pin. This system would provide different loading conditions on multiple stroke runs and ensure a complete model is created that maps the loading condition to the needed compensation. For the module prototype with 8 pins, calibration will still be done manually as developing a calibration device is not time effective unless an entire pin array is made based on this cable drive system.

6.4.2.2 Capability of the Pressure Sensor

Once the drive system parameters have been specified, the pressure sensor can be calibrated and evaluated for performance in test 5 and 6. The selected pressure sensor is a resistance type pressure film sensor model FSR 402 manufactured by Interlink Electronics [36]. This sensor was used for prototype testing due to its small form factor, low cost and easily made modifications to fit the cable drive system. Furthermore this sensor offered the sensing range of 0 to 20lbs needed per pin. Other sensing technologies such as larger pressure plates and strain based or piezoelectric devices are more cost effective if purchased in bulk to create an entire platform. Since this sensor needed to be mounted within the cable drive system, a custom holder was designed that would load the sensor. Figure 41 shows the mechanical design of the sensor housing. There are several key aspects to note about this design. The two screws that mount the sheath locking part do not apply pressure onto it, as that would result in loading the sensor. They are locked by set screws as to create an approximate 0.01inch (0.25mm) clearance that is only closed when the pin is lowering. This prevents the sheath from running up the cable when the pin is lowering with no load. As there is clearance between the screws and the locating holes, an angular tilt can occur when the sheath no longer applies a directly perpendicular load. Using shoulder bolts instead of machine screws will avoid this tilt, however that design was very prone to jamming as the cable sheath will never exert force at an exact perpendicular direction to the sensor mount.

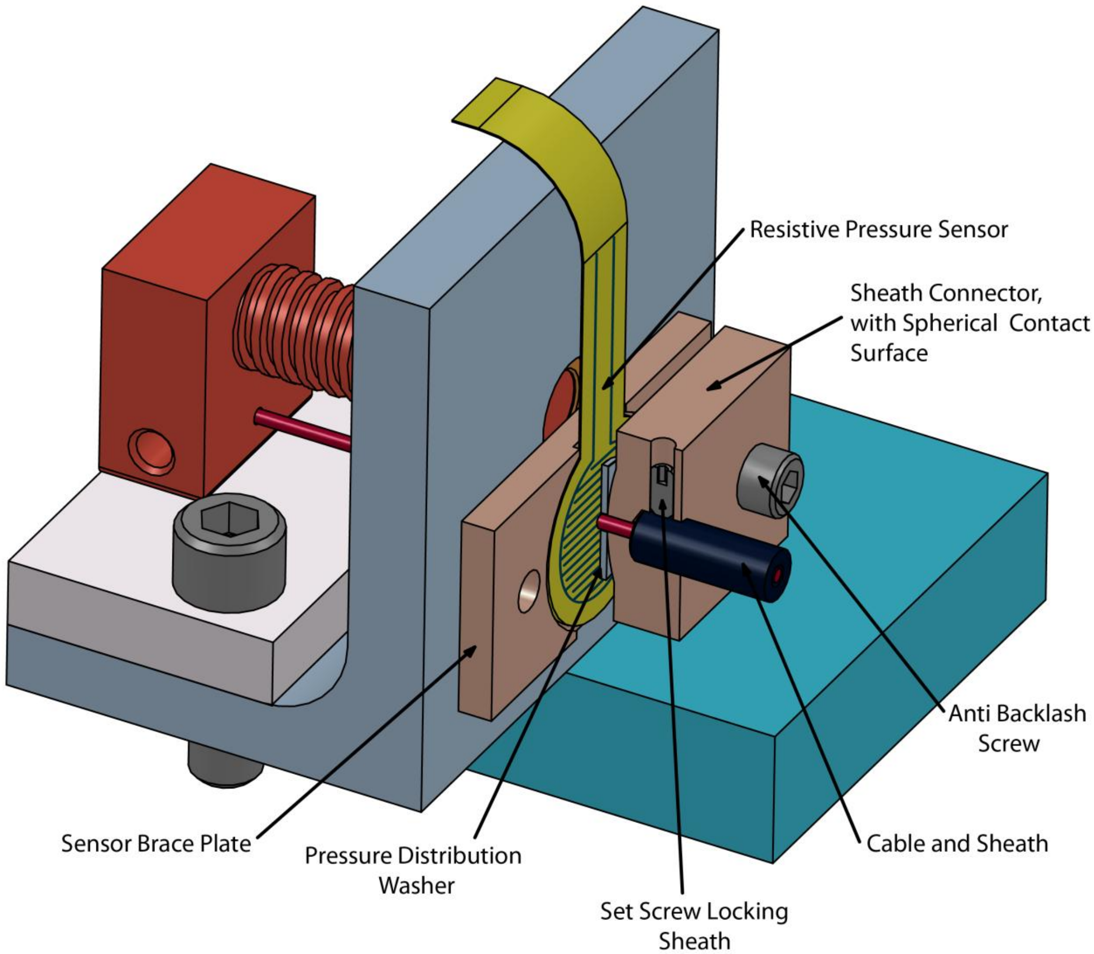


Figure 41: Sensor Housing

Extending the length of the sheath creates more stroke and a more perpendicular loading case. In the first prototype the smaller sheath length resulted in a significant tilt angle of approximately 15degrees once stroke exceeded one inch, hence the reduction in testing stroke. To allow for variation in sheath tilting a spherical surface is milled into the sheath connector which presses against a precision washer that in turn transfers the force to the sensor. This allows a 5 degree loading tilt in any direction and avoids any jamming or pinching of the sensor. The downside to this setup is that if the cable sheath presses against the sensor mount at an extreme angle of 10 degrees or more, the holder will act as a lever arm increasing force on the pressure sensor and producing an erroneous reading. This as mentioned before only happens with excessive stroke on the pin.

To create a complete calibration for the pressure sensor the loading stroke test must be done, as well as a position stroke test under the various loading conditions. Figure 42 shows test 5. This is the loading stroke calibration test of the pressure sensor with loading from 0 to 15lbs. From this initial calibration the output characteristic of the sensor is shown.

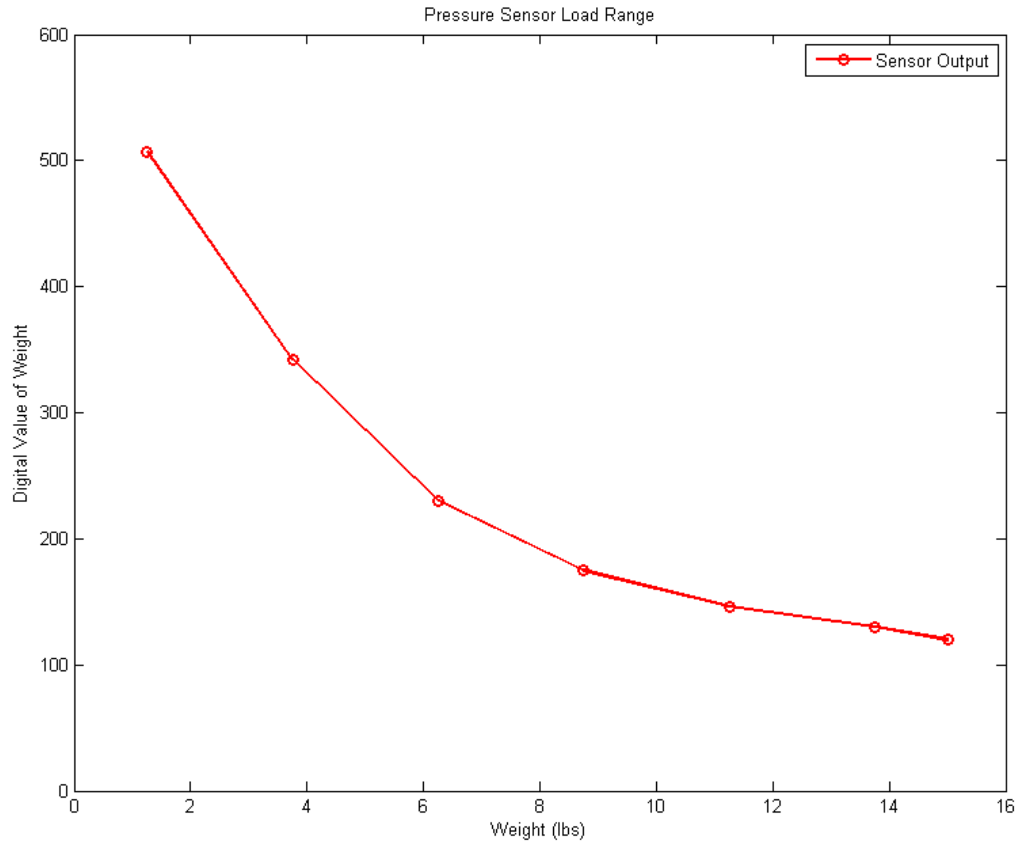


Figure 42: Load Stroke Test of Pressure Sensor

Based on sensor design its output is linear on a log scale or as shown above has an exponential output. Several trial cases were done and spaced apart by time for system warm up and other loading tests to ensure the sensor is repeatable. More testing showed that the sensor does not provide accurate readings of low loads on the cable drive system. Anything from 0 to 2.5lbs is not distinguishable and hence the operating range will be from 2.5lbs to 15lbs with this sensor. Note that to better scale the digital value on the vertical axis in Figure 42, a non-inverting amplifier with a gain of 2 was connected to the sensor such that its output would better match the analog to digital converter (A/D) in the microcontroller. The Arduino microcontroller uses a ten bit A/D across a 5V analog line that provides a digital value from zero to 1024.

The next calibration test, test 6, was to verify sensor operation dynamically while the pin is actuated. This was done by loading the pin at each incremental weight, and lowering it to ensure sensor reading is consistent across the entire stroke. This is consistent with the expected operation of lowering the load while measuring weight. Figure 43 shows the result of test 6.

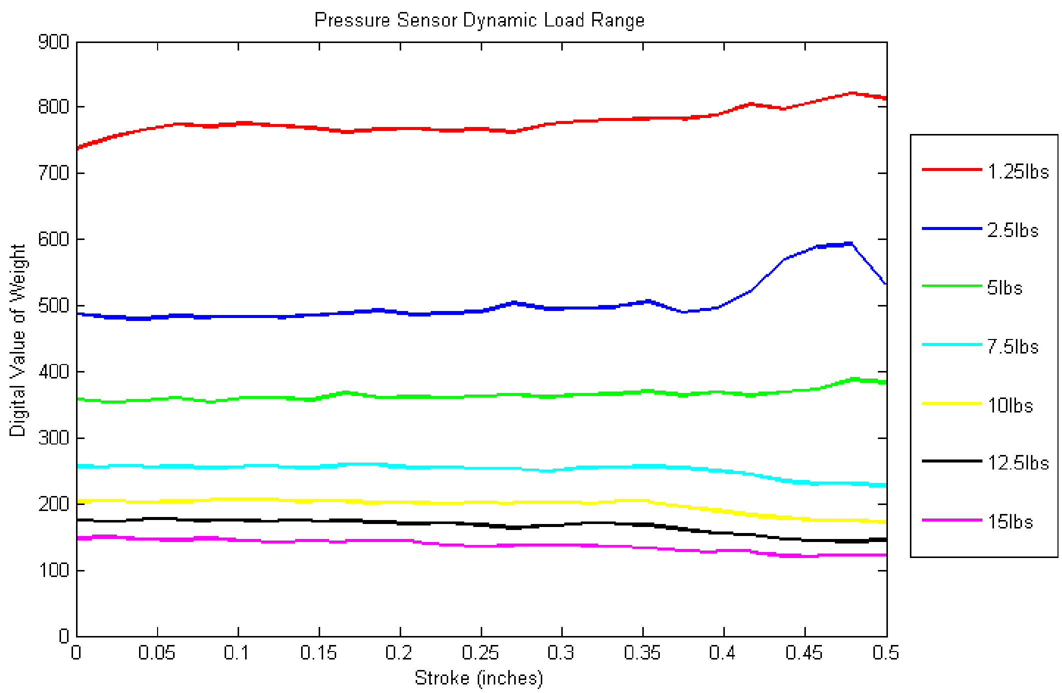


Figure 43: Load Stroke Test Combined with Position Stroke Test

As seen above, each line represents a different loading weight, across the stroke of the sensor. In Figure 43 there is no interference from one loading condition to another, and thus thresholds can be easily mapped to detect the applied pressure across the stroke of the pin. Based on this result, and the successful actuation of the mechanism under the design loads, the single pin proof of concept prototype has been verified for functionality. The only identified limitation is the reduced stroke in the first prototype which causes cantilevering of the sensor housing that in turn results in excess force on the sensor. This is illustrated in Figure 44. Notice that as stroke exceeds the zone where sheath angle is perpendicular to the sensor, the sensor readings collapse and produce a very high erroneous loading measurement even when loaded with lighter weights. To avoid this failure mode the sheath must always apply pressure on the sensor mount within the allowable 5 degree tilt from perpendicularity.

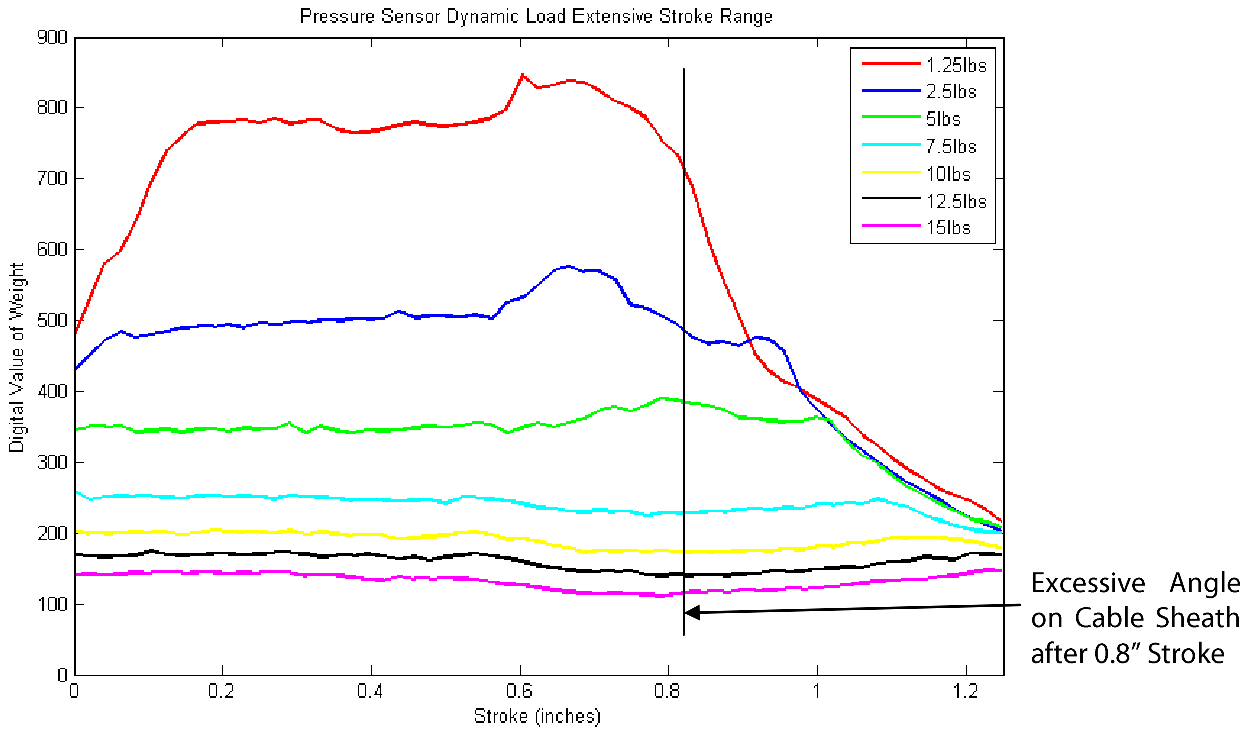


Figure 44: Excessive Stroke Test

The problem of sheath perpendicularity to sensor housing is also addressed in the next prototype by providing a longer sheath with a larger curvature that can create the required 2.5inch (64mm) stroke. For the single pin prototype a reduced length of stoke was verified. The next section describes the design of a module of pins, and the improvements in the mechanical system that minimize limitations encountered with the single pin prototype.

6.4.3 Eight Pin Module Prototype

The eight pin module is the second prototype developed for the purpose of validating the pin matrix concept. The focus of this prototype is no longer on actuation and sensing, but more on evaluating how well a series of pins can match a given surface and how this surface can be manipulated to shift a loaded weight. The second prototype also incorporates many improvements to the mechanical system based on refinements of the single pin prototype. Figure 45 shows the model of the eight pin prototype.

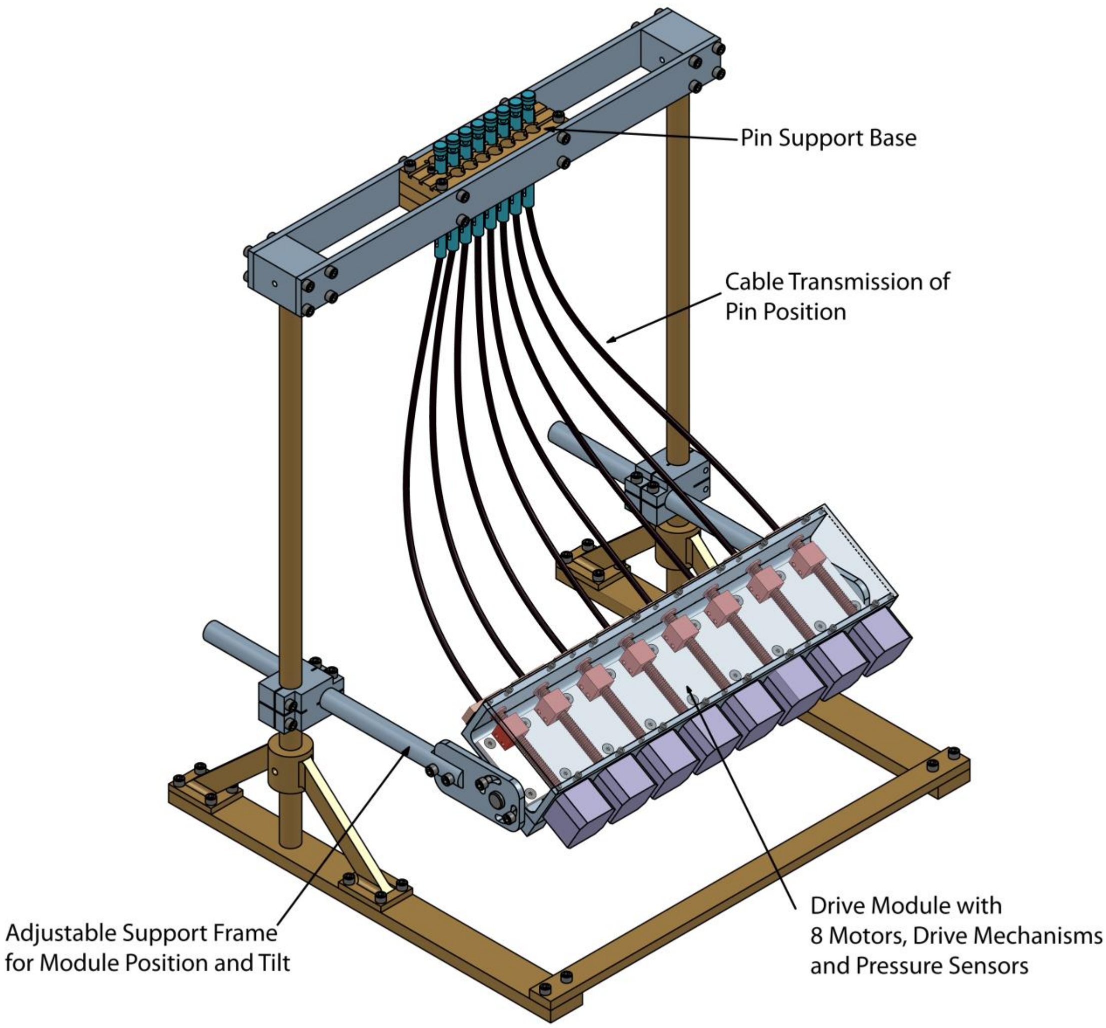


Figure 45: Eight Pin Module Prototype

Notice the much larger scale of this prototype. The cable sheath lengths have been more than doubled and the positioning area of the module is adjustable. This was done to create the desired stroke of 2.5inches (64mm) which was not achieved in the first prototype and to represent the approximate size of the system if the device was created using the cable drive method. In order to fit in eight modules on each side of the central axis of the pin array, a very large footprint is needed. The adjustability of the module has two purposes. It allows testing of different lengths of cable sheaths and it allows repositioning the module in many configurations. This helps in testing how multiple modules would function. Since two modules cannot be at the same location they would be located along an arc underneath the platform. The adjustability lets us test every position along the actuating arc of the platform.

The drive system remains unchanged in form, fit and function with only a material change to the drive nut and the extended cable and sheath. The nut was made from aluminum bronze for less friction and better contact mechanics than the previously used steel on steel interface. The rest of the module layout is the same. The pin housing has been more dramatically improved as shown in Figure 46.

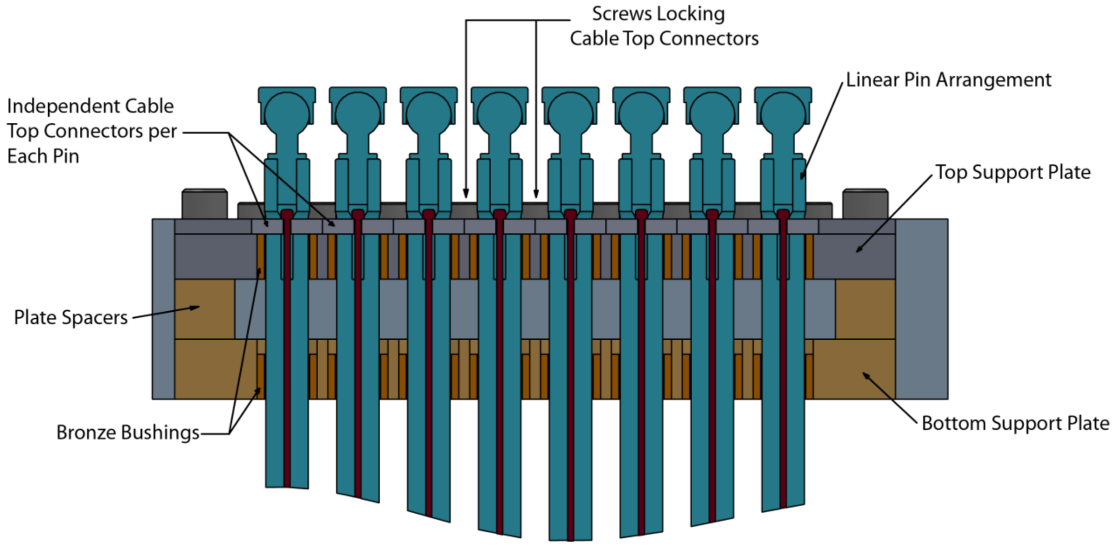


Figure 46: New Pin Support Structure

A change from a single thicker support plate and one bearing to a two plate system with two bronze sliding bearings was made. The creation of two sliding supports farther apart was done to minimize the tilt of the pin that would occur as a single bearing wore out in an elliptical fashion. The two plate system is lighter, and more stable than a single heavy block. To ensure misalignment due to bending does not occur closer to the center of the plates, a series of dowel pins with precise spacers are installed to maintain alignment. This new setup will provide a much larger lifespan for function and testing as well as increased resilience to side loading and wear caused by side loading.

The electronic setup from the single pin prototype is extended by adding more input channels and drive electronics to run eight motors and eight pressure sensors. A simple graphical interface and

USB communication will be used to automatically position the motors at a given surface. Several typical surfaces were created and supported by the module of pins. Figure 47 shows three different surfaces placed upon the pin module as well as a simple positional manipulation of the surface by changing the support surface of the pins.

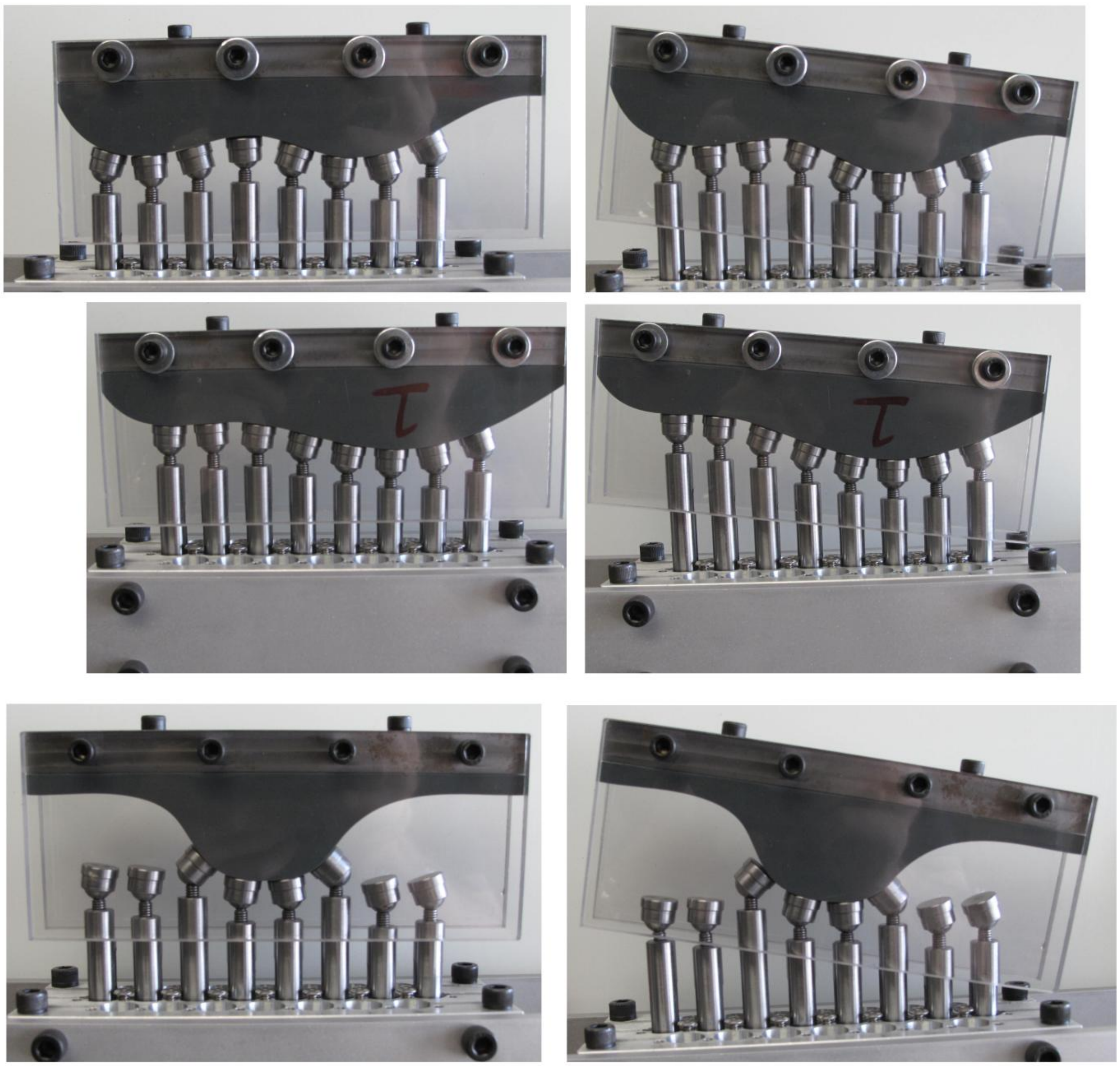


Figure 47: Surface Matching (Left) Orientation Manipulation (Right)

Figure 47 presents three distinct surfaces that the pin matrix would likely encounter. The first is a frontal cross section of the metatarsal area under the foot, the second is a lateral section of an arch and the third is a frontal section of a small heel. Notice that a membrane to connect the pin caps has not been installed at this point which allows better visualization of the functionality of the pin caps. It is observed that small curvature is very easily matched by the pin row and more aggressive curvature results in contact only at the edges of the pin caps. Thus to minimize this effect and increase comfort of standing on the platform a thin compressible buffer should be used between the elastic membrane that connects the pins and the customers foot. Aside from this requirement the overall surface matching fits very well and the swivel caps easily conform to become tangent to the surface that is placed upon them. The geometry of the above surfaces is known and hence the pin height locations could be easily implemented. When dealing with a customer foot the starting surface needs to be identified before the foot is placed on the platform. This starting surface will be created from a 3D scan or approximate 2D scan before the pin array is used. If a foot model is not available a generic surface based on a few size measurements can be the starting point, however this will require many more surface manipulation iterations to get the customers foot in a comfortable supported position.

Once the surface is matched as seen on the left side of Figure 47, surface manipulation algorithms will be used to manipulate and position the surface. These algorithms will take into account the pressure measurements from each pin and work to distribute high pressure regions. For the initial testing only rotational manipulation of the surfaces can be done as the surfaces are rigid and will not change shape as a human foot does when standing on different support structure. The right side of Figure 47 shows slight manipulation in orientation of the matched surfaces that would shift the loading distribution from left to right.

The limitations of the module prototype are mostly extensions of the single pin limitations as well as limitations in manipulating surfaces that are rigid. From a mechanical standpoint, the cable drive system creates a large complexity for assembly and maintenance. Since there is no low cost method of creating easy attachment and release of cables, any maintenance on a single pin requires entire module detachment. This fact in addition to the large footprint and dense transmission cable web make this solution very difficult to implement outside of a research environment. With regard to testing the prototype, good results in adhering to and manipulating the orientation of a rigid surface were observed. Future testing would include manipulation of a loaded, structured and deformable surface such as expected when supporting the human foot. The limitation is that at this point no such surface is available to test with on a single row of pins. Working with rigid surfaces can only be useful in the development of basic matching and orientation algorithms but not in the more advanced iterative methods for minimizing high pressure zones on a deformable surface.

6.5 Industrial design concepts

In parallel with the investigation of the pin matrix concept with the cable drive system, concept design work was done to create alternative actuation and pressure sensing designs. The following two sections show alternative concepts that could be employed given available funding, to create the pin array as an industrial product. Note that unlike the completed prototypes these are not detailed designs, they are primarily design concepts, modeled and refined to fit the desired pin density. Detail design would have to be completed with additional input from experienced industrial designers as these concepts include custom motor and clutch components beyond the scope of this research. The purpose of these concepts is to show how the implementation of more advanced manufacturing methods and engineering knowledge can be applied to create more robust and simpler solutions for the actuating the pin matrix. Both of the proposed concepts remove the limitations encountered with the cable drive mechanism. This means the removal of modeling is for compressive distortion and the increase of pin stroke.

6.5.1 Micro Motor Concept

The first concept is based on designing a custom micro motor to work within the given pin resolution constraint. Existing industry manufactures such as HaydonKerk [37] produce various lines of micro motor designs as seen in Figure 48. A collaborative project with one such industry partner can be created in order to implement the micro motor concept. These very small motors feature full servo control or stepper motor control and are small enough to fit in the tight spacing constraint of the pin matrix. The micro motor concept is to create two alternating stacks of micro motors, with custom made long transmission screw shafts that drive the pins in the pin array. The form factor of these motors will be custom fitted to the established pin density, and the drive screws will be self locking screws as in the cable drive systems. The sensing element for this system can be an array of pressure sensors or a single platform. Figure 49 shows a side view and an isometric cross section view of the micro motor concept.

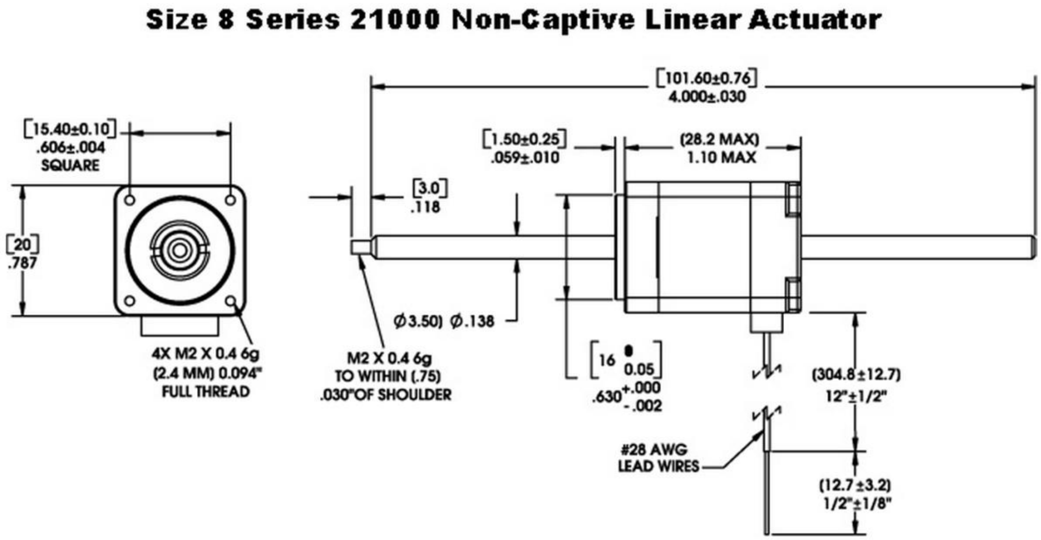


Figure 48: Small Format Stepper Motor – HaydonKerk [37]

Even with the use of micro motors, two stacks of motors are used to create the sufficient pin density required for the device. The housings for the motor components can be modular and mount to each stack plate such that a single motor can be removed if needed for maintenance. To remove a motor in the first stack, the entire bottom stack must be removed first. Mechanisms to separate or space out these stacks for maintenance can be incorporated into the support structure. The force on the top of each pin is transmitted through its actuation screw shaft, all the way down to a thrust bearing that sits on a pressure sensor or pressure platform. The screw shaft has a spline design such that rotation can be transmitted to it by the micro motor and still allow free transmission of force to the pressure sensor.

This design also allows motor stacks or individual motors to be easily removed by sliding down out of the shaft and not requiring a hard coupling. The transmission of force to a single flat plane is also extremely beneficial since this allows testing with various off shelf pressure platforms and removes complexity in creating and calibrating a custom pressure sensing system. Since the pins are round they would freely rotate if actuated by a screw, hence one side of each pin is flattened and rotation is prevented with the use of a tangent slotted plate in-between the two pin bushing plates.

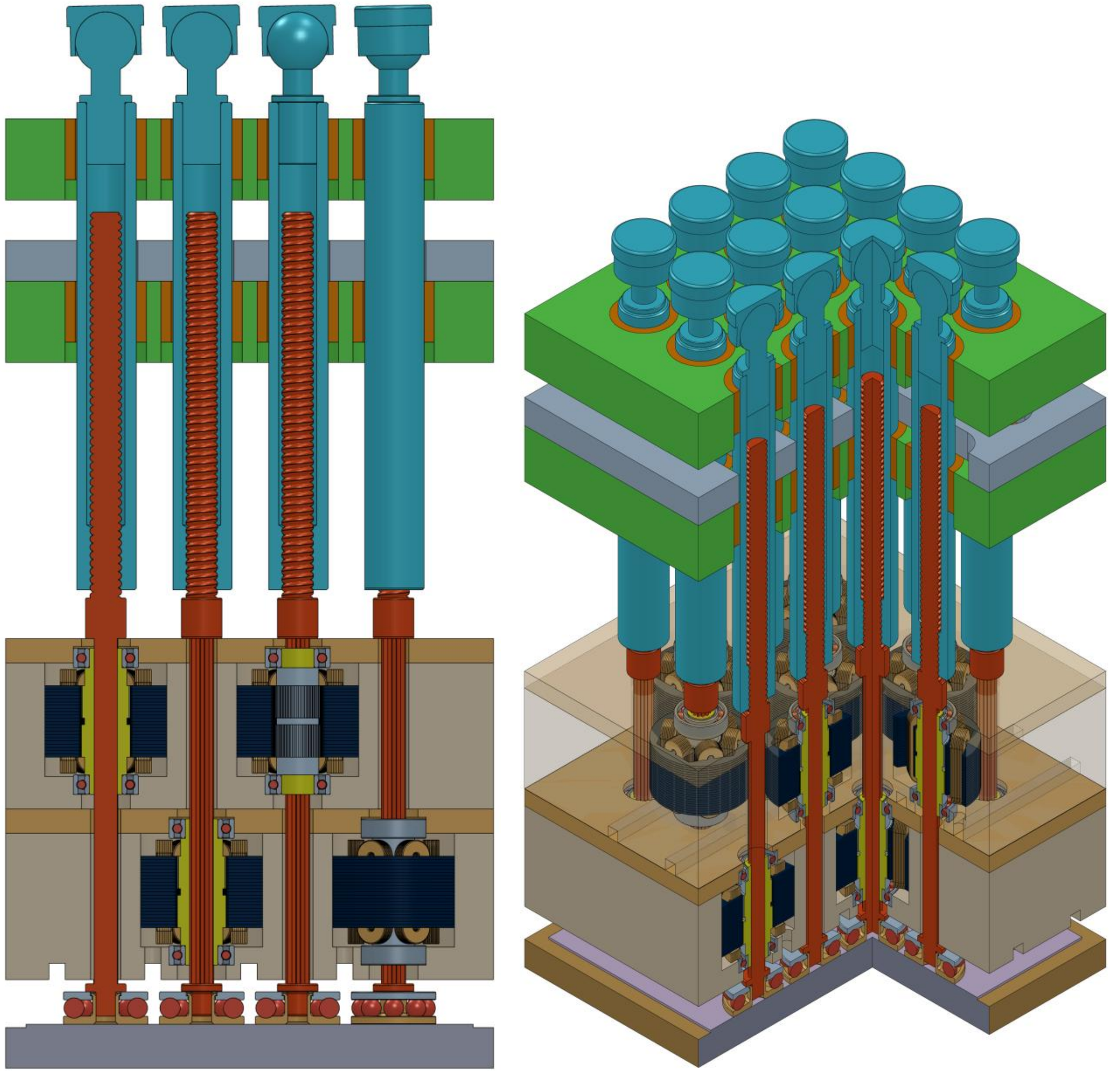


Figure 49: Micro Motor Concept

The only drawback of this concept is that as the cable drive system it will only work in the lowering direction. The custom micro motors are of such small size that their power output cannot be nearly enough to lift the 15lb weight required per pin. Hence they rely on the self locking screw to support the weight as they only provide force to lower the load, or position the pins under no load. The high complexity in the detail design of these small stepper motors will require additional expertise and extensive funding to create this prototype. However this solution is a feasible approach to create a robust and serviceable pin matrix platform and perform extensive testing of pressure distribution on a 3D surface.

6.5.2 Electric Clutch Concept

The second industry grade solution is slightly more complex as it requires custom mechanical transmission components and a custom clutch with built in encoder. This concept was created by modifying an existing actuation mechanism used on multi pin die forming devices. Figure 50 shows the base concept extracted from the works of Haasa [29]. Although many die forming devices use a single motor to drive a pin or a hydraulic system, some incorporate a clutch drive system as shown below.

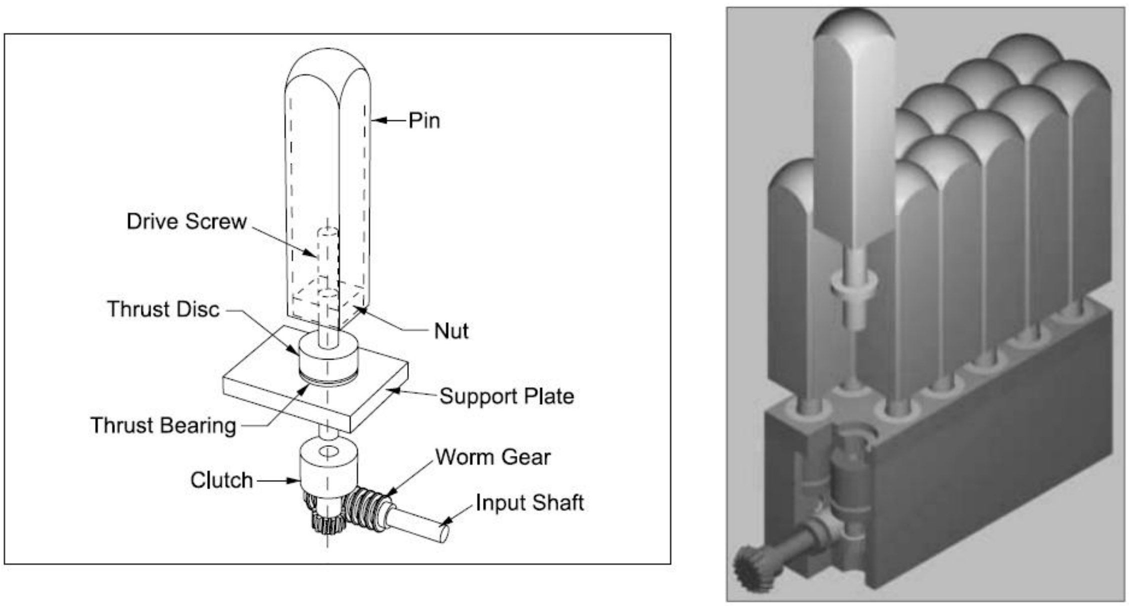


Figure 50: Reconfigurable Forming Die Actuation – Haasa [29]

Using this concept as a starting point, a CAD model was developed to determine the spacing constraints and coupling mechanism needed to fit the size constraints. Just like the micro motor concept, the pin is still driven by a drive screw that is a single component which transfers force to a pressure platform below. To accommodate this, a more complex electronic clutch system has to be designed that supports a through shaft and transmits rotary motion to it when the clutch is engaged. Figure 51 shows the side view and isometric cross section model of the clutch drive concept. Note that the electronic clutch would have to use an encoder to measure the position of each pin to facilitate accurate pin position.

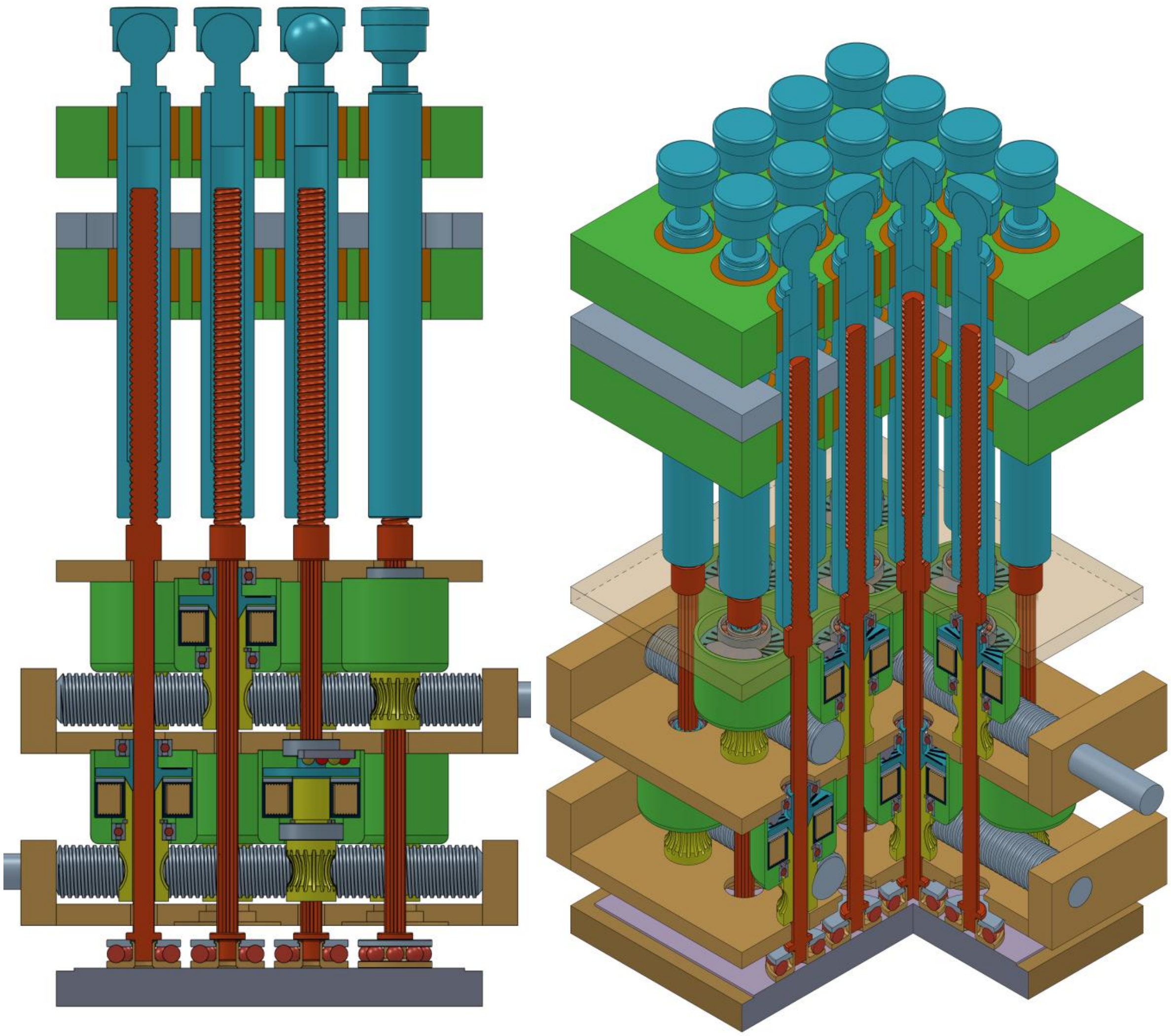


Figure 51: Clutch Drive Concept

The major benefit of using the clutch drive system is the ability to reroute mechanical transmission to each pin to a much larger motor. This motor uses an extreme torque gearing ratio via the worm drive that would then allow rising of pins under full load. To achieve independent pin position for creation of a surface each clutch would disconnect when its pin has reached the desired position. The pin will remain in that position based again on the use of a self locking screw that prevents any back drive. This system is expected to be more expensive than the micro motor concept as it includes a complex custom clutch and more custom mechanical transmission components. It does have the key advantage of being able to raise the foot under load and never run out of stroke.

6.6 Limitations of the 3D Variable Surface Pressure Sensor

As with the previous digitizers there are some drawbacks to the 3D variable surface pressure sensor. These are mostly based on the advanced nature of the tool which limits its application to patients with severe foot problems or deformities. This tool has complex use and would not be suitable for basing shoe sizing and fitting on healthy feet. The device also has a resolution limit correlated to the pin size. As such it is a macro scale tool that will provide an optimal surface geometry over the entire foot and will not be able to handle small defects such as bunions. With that in mind, the preliminary use of a 3D scanner to identify small defects and to create a starting surface is another drawback. Without a good starting surface from a 3D scanner the device would require more iteration cycles and be slow to adapt to the needs of the patient. The needed preliminary use of a 3D scanner and the high capital cost of this device make it exclusive to high end clinics and medical providers that can afford expensive equipment. Lastly as this device cannot reconfigure the surface very fast it cannot be used for dynamic motion in running or walking. The clearances for foot deformation during the different stages of walking or running would have to be incorporated via traditional methods.

6.7 Applications of 3D Variable Surface Pressure Sensor

As this tool offers new insight into the distribution of pressure in correlation to support surface it will be most useful in specialized foot clinics. This is where the largest variation in foot shape, injury and deformity is treated and this tool would help streamline the shoe making process and create superior shoes regardless of the patient’s condition. The patient feedback provided during the adjustment of the shoe support surface will result in the most comfortable fit for each patient.

Aside from the industrial application of the device there are many research applications available. This includes conducting studies and obtaining better models of feet and how they distort with shape and pressure. Also the development and refinement of algorithms for better equalizing pressure distribution would be another application. These are just some of the foreseen applications, as this device is still in the early stages of development some opportunities are yet to be identified.

Chapter 7

Conclusions and Future Work

This chapter restates the research objective in each research focus and provides the accomplished work to date. Furthermore next steps for short and long-term work are proposed in each section.

7.1 2D Scanning

The objective of implementing a 2D scanner was to create an affordable solution for fast and accurate scanning of the foot. This would provide a foot scan with accurate border contour and key landmark features such as the pivot axis, lateral ball joints and the toe crest. Using this scan a 3D surface would be created that approximates the plantar surface of the foot. The added depth parameter can then be incorporated into the algorithms for the automatic creation of orthotic surfaces providing better support to the client's foot.

Using a new approach of extracting depth with laser contour planes an approximate 3D plantar surface of the foot was created. The approach showed that it is possible to obtain a 3D surface from a 2D scan with the addition of structured light. The scanner used on the prototype was fitted with a platform that can withstand full loading of the foot and support the needed apparatus for depth extraction. Accuracy of the foot contour was also improved by adding more contrast via side lighting and compensating the optical distortion.

The next short term objective on the 2D scanner is to refine the algorithms for detecting the laser contours and minimize operator interaction. At this point manual verification and sometimes correction is needed on extracting the contours from the 2D image. To minimize human input and further automate the process, more filtering steps need to be applied for noise reduction and isolation of the three different colour contours.

The long term objectives are divided into two sections. The first is the continued research aspect in which testing and validation must be done on how to best incorporate the 3D surface information from the scan into the design of a custom orthotic surface. This will require more specialized software to be developed that also incorporates custom arch support and 3D surface matching on top of the 2D contours and landmarks currently used. The second objective is to redesign the prototype used to transform the system into a commercial product. As the prototype constructed for testing is overdesigned and has many built in adjustability features it is not well suited for clinical application. The redesign would incorporate industrial design principles and more advanced manufacturing techniques that can further reduce the cost of the apparatus. For instance, replacing the assembled machined parts with a single body molded part would greatly reduce the cost of the device and allow for large scale production.

7.2 3D Scanning

In the 3D scanning research focus the primary objective was to create a 3D scanner that will produce an accurate foot model at a low cost. This involved design and prototyping work in mechanical, optical, electronics and software systems to complete the objective. Thus far the electromechanical system and the optical layout have been fully designed and prototyped. Testing has been performed to validate the functionality of the electronic system and its communication with computer interface. Higher level software has also been created to filter the acquired images and obtain 3D position data.

The short term objective in 3D scanning is to complete the outstanding work required in software and integration. This includes two software tasks. The first is the low level programming of drivers for automatic and timed acquisition of images from all eight cameras. Thus far calibration has been done with manual acquisition of images from one camera at a time. The second software task is to take the current code for image processing and depth extraction developed in MatLab and incorporate it as a subroutine into the existing Visual Basic interface that runs the electronic system of the scanner. Completion of these tasks will result in fast and automatic creation of foot models.

The long term objectives of the 3D scanner mirror those of the 2D scanner. First is the continuing research which will focus on manipulation of the obtained 3D model and the development of simulations with pressure mapping. The second objective is to create an industrial version of the research prototype while maintaining low cost. This is done by using the same cost effective key components as on the research prototype and reducing complexity by eliminating modularity and machined parts. The prototype scanner has three motion platforms with independent control and limit switches, this system can be simplified greatly by shifting to a single drive platform and molded parts for mounting and locating the optical components in the needed positions. Other such design changes can further reduce cost and make this product very viable for implementation in foot clinics.

7.3 3D Variable Surface Pressure Sensor

The objective in this section was to create a design for a 3D programmable pressure sensitive surface that can be used to obtain the pressure distribution on a client's foot while positioned in the shape of the corrective shoe.

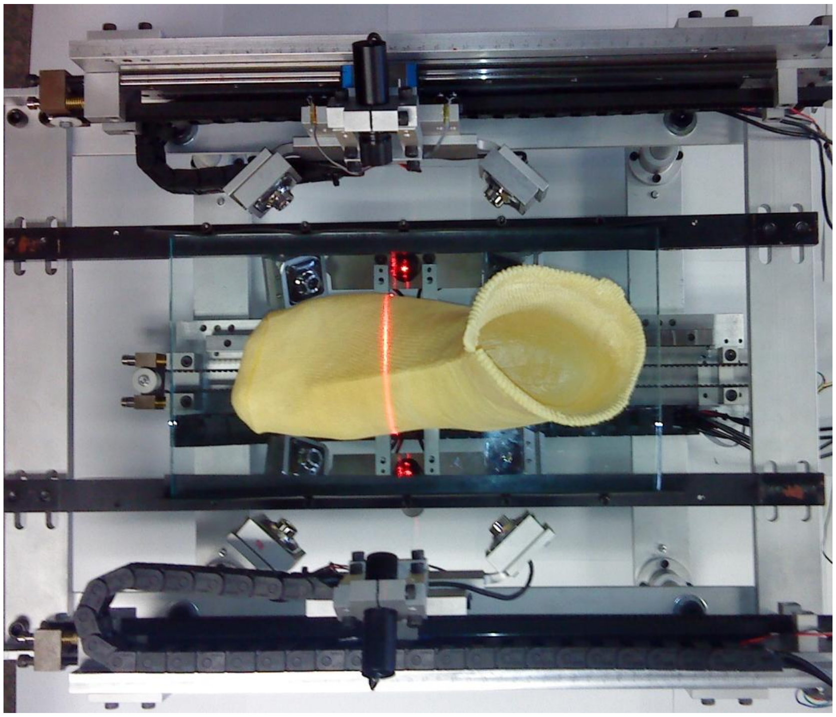
The work done on this research focus was to design a small form factor pin matrix with pressure measurement and individual pin actuations. Two concepts designs were created to illustrate how such a device could be actuated with small stepper motors or larger motors that actuated a series of pins via clutches. A third cable drive system was also designed and used as the basis for prototype testing and concept validation. The benefit of fast prototyping with the cable drive actuation mechanic allowed testing and full specification of a single pin. This showed the capability of the design to accurately control position under load and measure the load within increments of 2.5lbs. The second prototype constructed was used to validate the form factor and size of the pin matrix by matching and manipulating various sample surfaces with a row of eight pins. The validation of the two sub system prototypes now justifies the objective to create a full size platform.

The short term objective in this section is to obtain more project funding and industry partnership. As this device is very complex more expertise and availability to manufacturing technology is needed to refine the designs and choose the best actuation approach based on functionality and cost. With more available resources this research can proceed to building a complete prototype. As such the long term objective is to build a fully functioning prototype that can then be used to test and validate the expected design benefits of this device. With a completed prototype the final stage is the development of surface creation and manipulation algorithms. These will be used to generate the desired optimal pressure distribution on the specific client's foot and hence provide the best comfort in the created shoe.

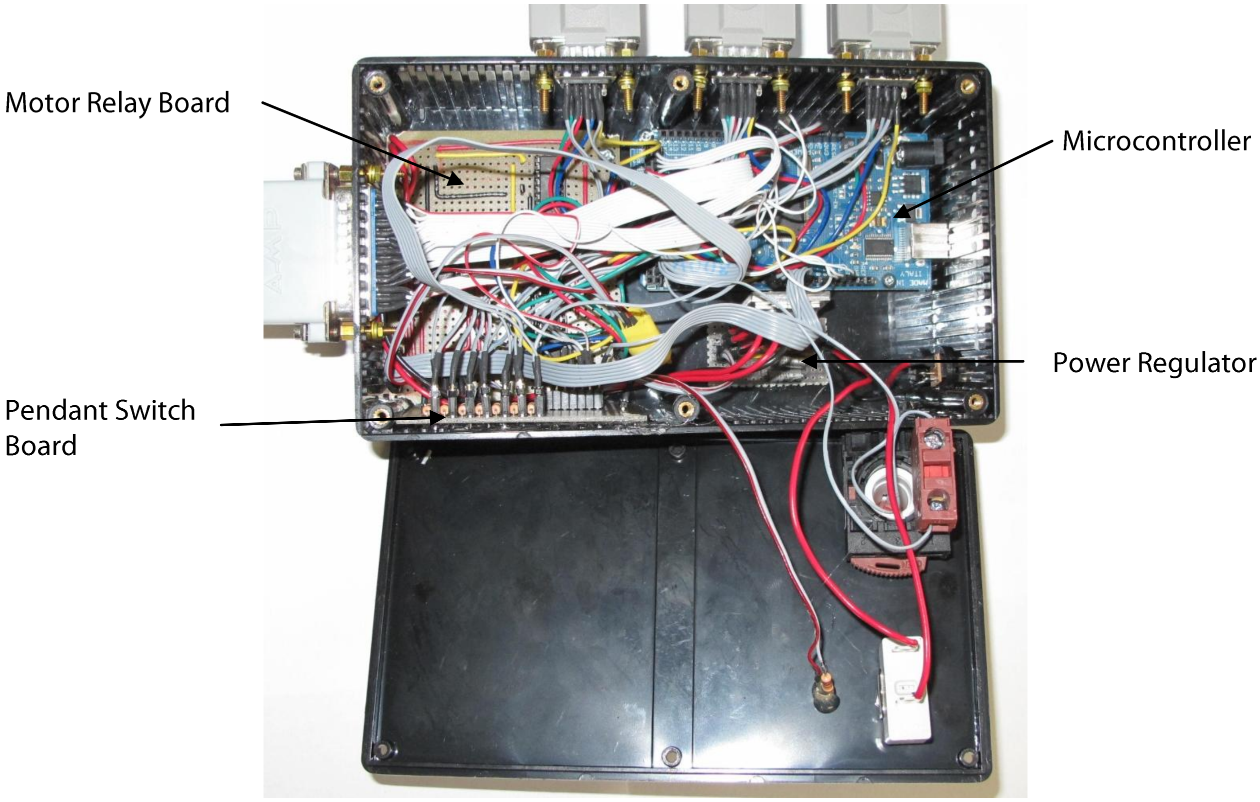
Appendix

This appendix includes images from the prototyping process of the 3D scanner.

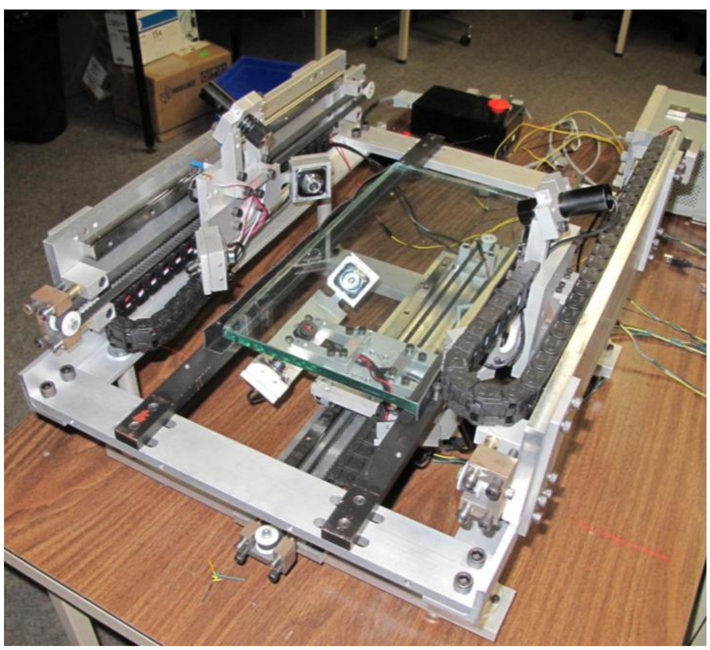
Above is the left side scanning head with laser contour projected on the sock mold. Below is a top view of the scanner prototype.



The internal contents of the scanner control box are shown below.

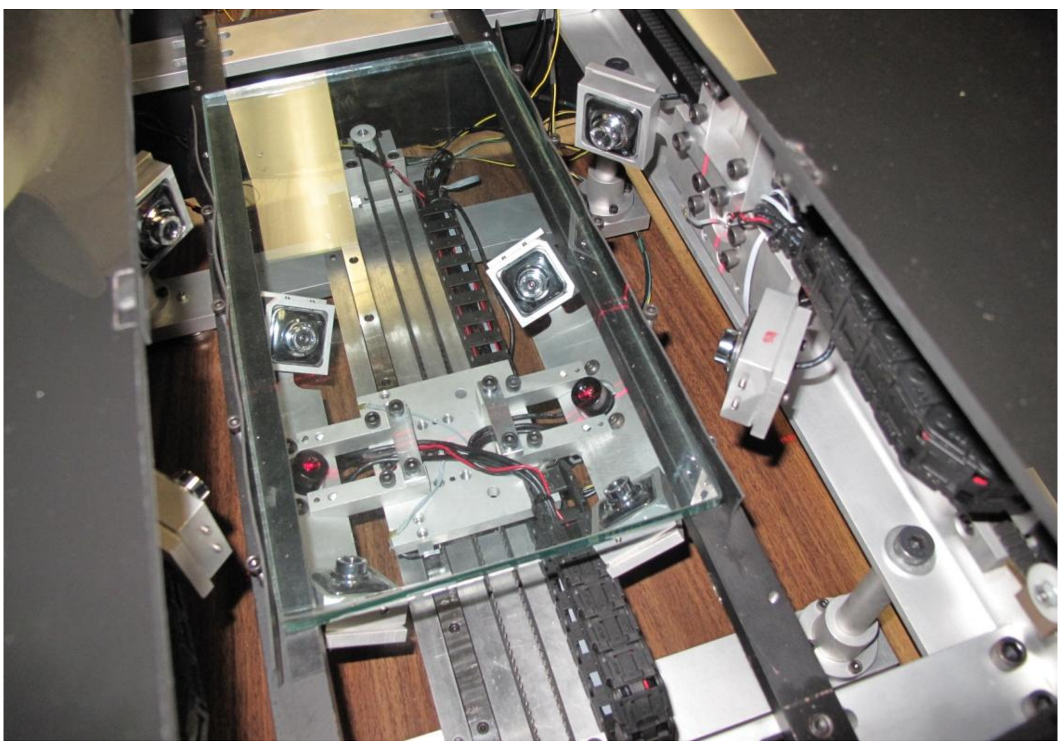


A perspective view of the scanner without casing.



The 3D scanner with casing.

Internal view of scanner components with casing.



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