FABRIC CONTROL FOR FEEDING INTO AN AUTOMATED SEWING MACHINE

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FABRIC CONTROL FOR FEEDING INTO AN AUTOMATED SEWING MACHINE

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To my brother, Adam Winck, who inspired me to grow up but stay young.

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LIST OF SYMBOLS AND ABBREVIATIONS

d1	Translation arm offset
R1	Translation arm radius
x1	Translation cable displacement
θ	Dog rotation
φ	Offset angle
x2	Dog foot translation
R2	Dog foot radius
x	Rotation cable displacement
R	Rotation arm radius
d	Rotation arm offset
T	Kinetic Energy
I	Dog's moment of inertia in translational direction
m	Moving mass
$\dot{x}$	Velocity of moving mass
$\dot{\vartheta}$	Angular velocity of dog
F_{motor}	Voice Coil Motor Force

SUMMARY

The importance of automating the garment manufacturing process has been understood since the early 1980s. However, in spite of millions of dollars spent on research, three decades later, the industry is still far from achieving a fully autonomous process. Previous work on fabric control in automated sewing focused on the control of only a single sheet of fabric using an industrial manipulator with an overhead vision system. These methods did not meet the accuracy and robustness requirements of the sewing process with respect to fabric position and fabric tension.

To address these issues, a new method for fabric control in automated sewing is described. It uses the current feed mechanism on sewing machines, feed dogs, but modifies them to be servo-controlled. These servo controlled actuators, servo dogs, individually control two sheets of fabric before the fabric reaches the needle and during the sewing process. The servo dogs actuate the fabric 180^{o} out of phase with the sewing needle, providing incremental control of the fabric when the needle is out of the fabric.

To achieve this type of control successfully for automated sewing, the servo dogs have been designed for short displacement, high acceleration motions using a cable drive system powered by voice coil motors. Feedback of fabric position has been determined to be necessary and is to be provided by a thread-tracking vision system.

This thesis outlines the general design of the system and discusses a prototype used to validate the design, and describes experiments performed to examine how the fabric will behave with the use of this type of actuation method.

CHAPTER 1

INTRODUCTION

This thesis describes a novel method of fabric control for the purpose of automated sewing. The method is centered on a device that emulates the feed dog currently used in industrial sewing machines that is modified to be servo controlled. The servo controlled dog is a multi-degree-of-freedom device that controls the fabric in coordination with the sewing machine. The servo dog is discussed within the context of an entire automated garment manufacturing system. A prototype is used to demonstrate the performance of the servo dog design and a number of fabric experiments are used to provide insight into the behavior of fabric being manipulated by the servo dogs.

1.1 Research Background

Clothing is one of the three basic necessities of human life. As such, clothing or garment manufacturing is one of the oldest and largest industries in the world. However, unlike other mass industries such as the automobile industry, the apparel industry is primarily supported by a manual production line. While many industries have used automation to increase productivity, garment manufacturing methods have remained largely unchanged for half a century. Nearly every phase of garment manufacturing involves skilled labor, and the procedures for production and quality control are based in general on a qualitative description of quality and understanding of the materials [1]. This results in less efficient, more costly production and a wider variation in product quality per product. The apparel industry's recent growth in developing countries with a low-cost labor force and its decline in industrialized nations where labor is more expensive is evidence of the lack of automation within the industry.

The need for automation in garment manufacturing has been recognized by many since the early 1980s [2]. During the 1980s, millions of dollars were spent on apparel industry research in the United States, Japan and industrialized Europe. This research was primarily aimed at maintaining these countries' stake in the apparel industry as production began to shift to the developing world. The largest push towards automation occurred in Japan. A joint $55 million program between the Ministry of International Trade and Industry (MITI) and industry, called the TRAAS program, was started in 1982. The ultimate goal of the program was to automate the garment manufacturing process from start, with a roll of fabric, to finish, with a complete, inspected garment. While the project claimed to be successful, and did demonstrate a method to produce tailored women's jackets, it failed to compete with traditional methodologies. Consequently, only parts of the results were integrated into specific processes of current manufacturing techniques, and it did not achieve complete autonomy of the machine involved.

In the United States and industrialized Europe, the push towards automation was not as strong, but it did receive some significant support. Draper Laboratories in the U.S. was created with $25 million of support from the government and industry with the goal of automating parts of the sewing process, beginning with setting a sleeve into a coat and then moving to automated seaming. In Europe, the BRITE project put millions of dollars towards automated sewing. Neither program resulted in successfully automating the entire process, although some minor gains were made.

Overall, after the 1980s, research towards automating the garment industry tapered off in favor of research aimed at addressing changes in the way people bought clothing, such as structural changes in retail and a stronger demand by the consumer for quality materials and trendy design. Outside of research by a handful of university faculty, little has been done in the way of automated garment manufacturing since the 1980s.

1.1.1 Sewing

Current industrial sewing is done mostly by hand with some processes being semi-autonomous. The primary tool is the standard sewing machine, shown in Figure 1. The important components with regard to this thesis are the needle, needle bar, presser foot, feed dog, and the bobbin. These parts are the essential components directly involved in fabric handling and actually making the stitch. A number of different modifications to standard sewing machines have been made to meet the needs of specific commercial or industrial sewing tasks and to increase productivity, but, in general, sewing machines are still hand fed and human operated.

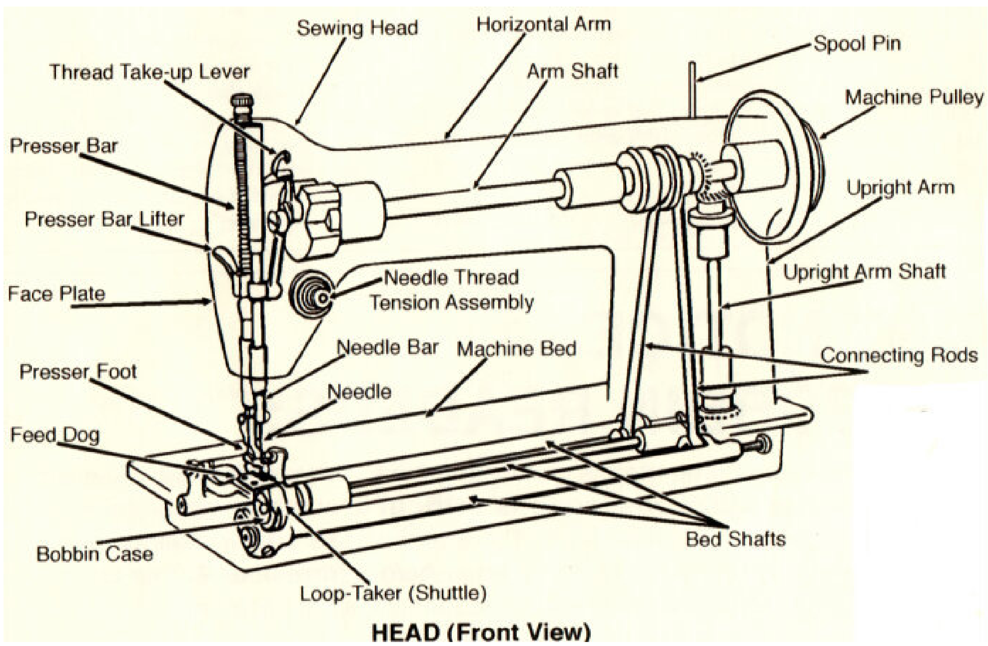


Figure 1 Standard sewing machine with components labeled [3].

The way in which a sewing machine makes a stitch is quite simple. While the needle is above the fabric, the dog feeds the fabric by pushing the fabric up against the presser foot and pulling it underneath the sewing needle. As the dog completes this motion, it begins to move down, and the needle also moves down. In the next step, the dog moves down and disengages the fabric. The needle penetrates the fabric, which is kept taut by the presser foot. The needle creates the stitch, called a lock stitch, using the bobbin, which holds a separate roll of thread. The needle is lifted back through the fabric, completing the stitch and tightening it as it continues to move above the fabric. As the needle is lifted, the dog is also brought up once again to advance the fabric for the next stitch. This process, shown in Figure 2, is repeated to form a seam. The timing between the needle, dog and bobbin is all mechanically controlled, and all three are driven by the same electric motor.

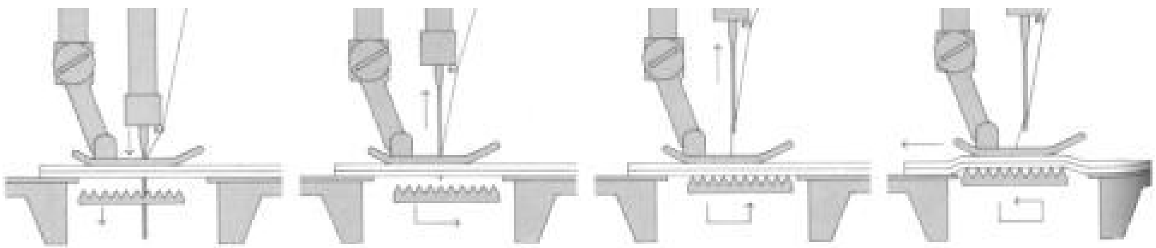


Figure 2 The sewing needle penetrates the fabric while the presser foot holds the fabric in place (a). The needle moves up through the fabric, making the stitch while the dog moves forward and up (b). The needle exits the fabric and the dog contacts the fabric (c). The dog advances the fabric for the next stitch while the needle is brought back down to the fabric (d)Dog and Needle pattern for making a stitch [4].

A good example of the variety of processes that are required to make a completed garment is a pair of denim jeans. A pair of jeans has 11 different components, with 22-24 fabric pieces in all. Due to the wide variety of parts and processes that must be carried out to assemble the parts, shown below, a flexible system that mimics the capabilities of a standard sewing machine, but that is automated, is desirable. Therefore, most attempts at automating the sewing process have started with the current sewing machine and have attempted to augment the device in such a way as to replace the operator.

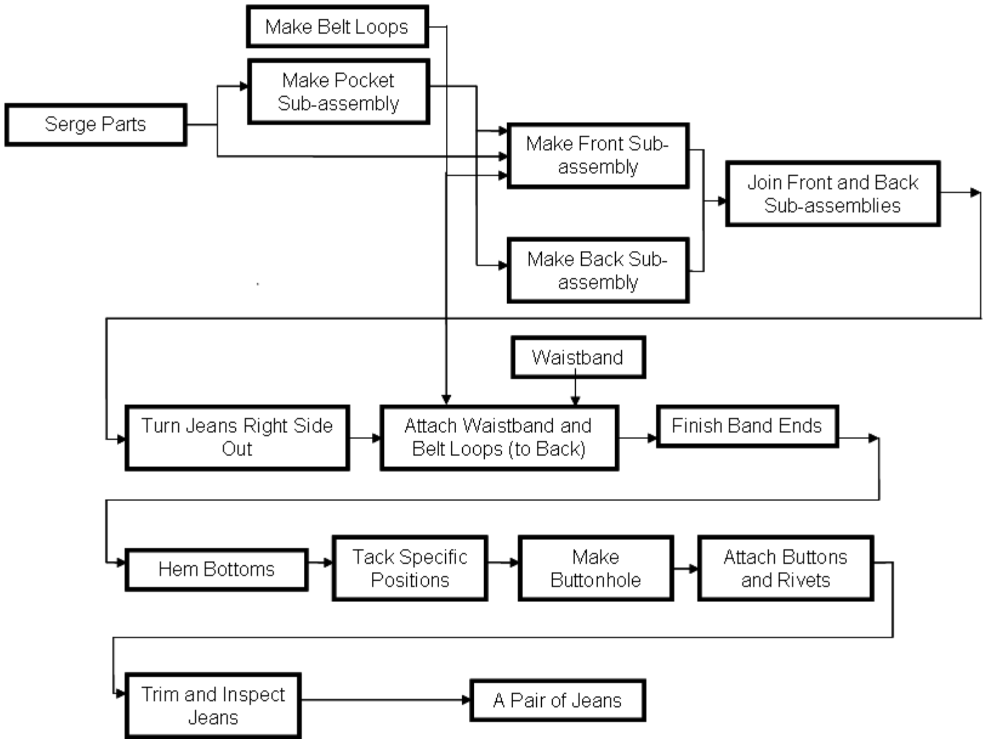


Figure 3 The process timeline of joining the pieces of a pair of jeans.

1.1.2 Automated Sewing

Early research efforts at the university level focused on control of fabric through a standard industrial sewing machine. A typical method involved fitting an industrial style robot, such as the Puma robot, with a custom end effector to hold the fabric to a surface and change the angle of the fabric while the sewing machine fed the fabric using its typical sewing dog system. One of the earliest attempts was by Frank Paul at Clemson University [5]. His system used machine vision to detect the edge of a piece of fabric and then plan a seam path at an offset to that edge. The vision system was also used to determine the placement of the end effector onto the piece of fabric based on the fabric size and shape but was not used to provide real time feedback of fabric position. Although the system was relatively successful, the use of vision to detect fabric edges has been identified as non-robust and insufficient for automated sewing [6]. Difficulties arose due to outgoing filaments, inhomogeneous cuts, and wrinkles in the fabric. In addition, the project dealt only with manipulating a single piece of fabric and ignored the joining of multiple fabrics. Finally, the results showed the need for real time feedback during the sewing process.

David Gershon, at the Weizmann Institute of Science in Israel, extended the work begun at Clemson [7]. Gershon used a similar setup with a traditional industrial sewing machine and industrial robotic manipulator. However, he added real time feedback and control. He decomposed the sewing process into four tasks: contour tracking, tension control, robot feed control, and sewing. To accomplish each of these tasks with a goal of complete automation, the sewing machine was altered to be computer controlled. The robot was used to feed the fabric into the sewing machine and used the measured sewing speed to calculate the feed velocity of the end effector. To account for error and to maintain proper tension in the fabric, a separate control loop was used to maintain the tension in the fabric based on a force sensor in the end effector. Finally, the robot was used to change the orientation of the fabric to follow any contour edge of the fabric using vision to detect the fabric edge. Unlike the system developed at Clemson, the vision system provided real time feedback to determine robot trajectory. The results were still not very robust with respect to fabric type and sewing speed. The work did outline a set of six performance criteria for automated sewing: (1) hold constant seam width; (2) maintain proper fabric tension; (3) prevent fabric buckling; (4) operate and control the sewing machine; (5) avoid obstacles and singularities; and (6) avoid torque limits. The robustness problem was centered on the first three objectives, which are associated with sewing quality.

To fix problems associated with tension control and difficulties arising from the range of fabric properties, fuzzy logic and neuro-controllers were applied to a similar system by Panagiotis Koustoumpardis and Nikos Aspragathos [1]. Using qualitative knowledge of fabric properties such as extensibility and flexibility to provide inputs to a neuro-controller, the objective was to meet the criteria set forth by Gershon with robustness and without the need for quantitative understanding of fabric properties. The results did show improved robustness over previous work, but they still did not address the issue of attaching two pieces of fabric together; instead, it focused on the control of a single piece of fabric.

No fabric control strategy to date has made a successful jump from prototype to a useful real-world method. Obstacles include the lack of an accurate and robust position control method, the difficulties arising from using a continuous robotic manipulator to maintain proper tension in the fabric as it is being fed by an incrementally applied actuator, and the focus of research on controlling a single sheet of fabric despite the necessity of controlling two sheets of fabric during the sewing process. In maintaining proper fabric tension, tension measurement has been used to detect error in the feed rate of the robot relative to the dogs. The objective of the controller was to prevent the fabric from buckling due to compression or tension, which resulted in a poor quality seam. Tension measurement has not proven a method that is robust enough given the wide range of fabric properties.

The use of an overhead vision system and industrial manipulator, coupled with a standard sewing machine, has not shown the ability to perform adequately regardless of the control strategy or trajectory generation used. In 2008, Honghai Liu at the University of Portsmouth identified five areas of current research in the area of automated fabric handling: sensing, handling, material properties, modeling and prediction, and intelligent planning [8]. The primary problem has been a lack of robustness in the design based on deficiencies in the sensing methods and inaccuracy in the manipulators. The use of more precise sensors and actuators and more advanced control methods has been shown to increase the robustness, but has not been entirely successful due to the limitations inherent in the design. New strategies are needed to meet the challenges of incorporating automation into garment manufacturing.

1.2 Research Objectives

Automation in garment manufacturing requires fabric actuation and sensing techniques that provide robust accuracy and an ability to reliably control multiple sheets of fabric. To deal with these issues, a radically new approach to automated sewing is needed. This thesis describes a new methodology by which automated sewing may be realized. It focuses on a subset of automated sewing, namely the precise control of fabric near the sewing head, and discusses some key fabric behaviors associated with that actuation. The method is described within a complete automated garment manufacturing system to add context to the fabric control problem at the sewing head.

A method of fabric control at the sewing head will be described, as well as a prototype demonstrating the concept's feasibility. Unlike previous research, the feed mechanism of the sewing machine is redesigned to control both the feeding of the fabric and the orientation of the fabric using an incremental actuation method. This method can be adapted to any high-speed, high-accuracy application. In order to provide position feedback of the fabric for closed-loop control, a new machine vision approach is suggested. In addition, the method is extended to multiple fabric sheets both before and after they are sewn together. Finally, a number of experiments will be discussed that explore key fabric mechanical properties that are specific to the actuation method described in the thesis and to the control of multiple sheet of fabric during the sewing process.

CHAPTER 2

SYSTEM DESIGN

2.1 Automated Sewing Process

To sew two pieces of fabric together, a number of processes must be coordinated. First, the individual sheets of fabric must be transported to the sewing table and placed flat on the table. Next, the two plies must be aligned properly and moved to the sewing head. The fabrics are then fed through the sewing machine and sewn together. While this is occurring, the sheets must maintain proper alignment with respect to the needle and with respect to each other and must be fed at the proper rate and maintained at the proper tension. It is important to note that these requirements are for each sheet of fabric individually. At the end of the seam, the seam must be serged to complete the seam and to prevent it from coming undone. Finally, the sewing thread must be cut and the finished piece must be transported to the next stage of the process.

In order to efficiently and reliably complete these varied tasks, an integrated system using multiple types of sensors and actuators is useful. A completely automated sewing system will be made up of three types of actuators and a number of sensors, as well as a modified sewing machine. The components must be integrated through a computer to ensure proper coordination.

An overhead pick-and-place robot with a special end effector is used to pull individual plies of fabric from a stack of pre-cut fabric pieces. A lot of research has been done focusing on developing a unique end effector that will allow a robotic arm to pick up a single piece of fabric at a time [9]-[13]. A number of different end effectors have been developed using a wide variety of methods including a “two-finger” pinching device, a vacuum plate, an electrostatic flat plat and roller, and a multiple-needle piercing design.

To move the fabric towards the sewing head and properly align the fabric for sewing, while maintaining the fabric shape, a different method is needed from a standard conveyor. Otherwise, the orientation of the fabric would be completely determined by the pick and place manipulator, which is unlikely to be sufficiently accurate. Also, using a standard conveyor the fabric cannot be guaranteed to be without deformation. In place of a conveyor, an array of small, inexpensive actuators provides a useful method for transporting the fabric to the sewing head while ensuring that it lays flat and in the correct orientation. Each actuator, or "budger," can be described as an upside-down computer mouse where the mouse ball is actuated by two motors to spin the ball in two axes as shown in Figure 4. The budgers have demonstrated effectiveness at moving fabric at rates of speed up to 160 in/sec, but with some slip.

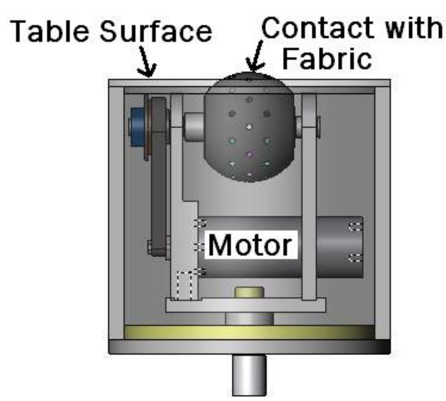


Figure 4 The budger is a powered ball that sticks out of the surface of the table and uses a small vacuum to pull the fabric to the ball. The motor identified in the image rotates the ball. A second motor actuates the shaft at the bottom of the image to steer the ball.

The motors that control the budgers must have position sensors in order to follow a given trajectory. However, due to the nonlinear mechanical properties and variety of fabric, and noticeable slip between the budgers and fabric, position feedback of the fabric itself is necessary. Because of these issues, the system cannot rely on preplanned paths and the feedback must be real time. To achieve this position feedback, an overhead vision system will be used. The vision system will observe the position, alignment, and shape of the fabric in order that the fabric remains aligned. The position knowledge of the fabric during this process can be considered gross knowledge. More precise sensing will occur at the sewing head.

At the sewing head there is also a need for more precise fabric handling. The actuation method will be an adaptation of the current sewing machine feed mechanism. Currently a sewing machine uses what is known as a feed dog to move the fabric through the sewing head. The motion of the dog is incremental and follows a pattern similar to the one described above and in Figure 2. On a standard sewing machine, the dog moves at a fixed speed that can be changed by the user at any time and which is directly related to the sewing speed and the stitch length. Longer stitches and faster sewing speeds result in faster dog movement. The sewing dog relies on the operator to maintain the fabric orientation and keep up with the feed rate. Previous attempts at automated sewing used the sewing dogs on a standard sewing machine and had a robot perform exactly the operations a human user would perform. Maintaining proper tension in the fabric was noted to be a major hurdle to this method, in addition to a lack of robust control of fabric position due to fabric's complex and highly variable properties.

This project endeavors to replace the standard sewing dogs and user with servo control dogs. Therefore, the actuators need to be able to feed the fabric through the sewing head in much the same way that the current sewing dog does. They must also be able to change the orientation of the fabric as the human currently does. By using the feed dog mechanism as the method by which to control the fabric, the difficulties of fabric feed rate, tension control, and fabric position control can all be more adequately addressed. In order to be able to function in the sewing process, the actuators must also work in conjunction with the sewing needle just as does a standard sewing dog. Thus, the fabric control method is not continuous, but incremental, which will more easily coordinate with a sewing machine that currently works with an incremental feed system.

Using an actuator that mimics the current method of the sewing dog but adds control provides a promising solution to an as-yet unsolved problem and, in doing so, suggests a solution to any system that requires high-speed and high-accuracy control. The rest of this thesis will focus on the servo dogs, how they work, how they interact with the rest of the system, a description of a prototype version and its performance, and some experiments exploring how fabric might deform during operation.

2.1.1 Thread-level Vision System

For the actuators at the sewing head to achieve high position accuracy, fabric position sensing must be precise because it determines the stitch position and stitch length. Attempts at automated sewing using pre-planned paths have noted the need for real-time position sensing. A major hurdle in using machine vision to provide position feedback has been the errors introduced by variability of the edges of fabric due to outgoing filaments and deformation of the cloth off of the table surface [6]. To alleviate this issue, a new vision technique is proposed and has been demonstrated as a prototype to provide fabric position information by tracking individual threads in the fabric. This method will provide feedback to the actuators to allow them to control the fabric through a closed trajectory. Therefore, the position of the fabric is measured in threads rather than millimeters or inches. In the previous research described above, fabric position is based on the shape of the fabric relative to a global coordinate system. As such, any fabric deformation results in position error. Using the fabric's threads for position detection avoids errors due to deformation. It also avoids problems of noise in the fabric edge.

The thread level vision system must be able to distinguish and track individual threads from one another from one frame to the next so that fabric position and orientation may be tracked. Using information recorded as the fabric is cut, it is possible to know, based on the threads, whether the fabric is in the correct position and orientation as it is being fed into the sewing machine. This will require keeping track of the fabric throughout the manufacturing process or for it to be marked in such a way that it can be distinguished by the vision system when it is placed on the sewing table.

No previous work has attempted to track fabric threads to measure position and orientation. However, a number of papers have been written on using vision to detect thread-based information on fabric, such as fabric defects or fabric weave patterns [14]-[19]. A common theme in the relevant literature was the use of thresholding to obtain a binary image and the use of morphological processes to separate the threads for detection. Therefore, these methods were adopted for an initial demonstration of thread-finding.

The ability of vision to detect threads has been demonstrated using a sample image of denim, shown in Figure 5, in Matlab's Image Processing Toolbox. The single image of denim was modified to various intensities and contrast levels and was rotated to several different angles to provide a test of the robustness of the solution. A number of thresholding and eroding methods were tested, and although they were all successful, the most accurate one will be described. The image was converted from a grayscale image to a binary image by parsing the image into smaller regions and then thresholding each region using a statistical method to determine the threshold level. The statistical method involved finding the mean and standard deviation of the intensity levels and calculating the threshold levels by the following equation: $TL = M + C*SD$. TL is the threshold level, M is the mean intensity value, C is a weighting constant determined through experiments prior to the sewing process, and SD is the standard deviation of the intensity values. The binary image was filtered using Matlab's area filter to eliminate noise. The angle of the thread lines, indicating orientation of the fabric, was determined using Matlab's built-in function *regionprops*. Using the orientation information, the image was eroded using a line structuring element to separate the threads. Finally, *regionprops* was used again to obtain the centroids of the threads. Sample Matlab code can be found in Appendix A.

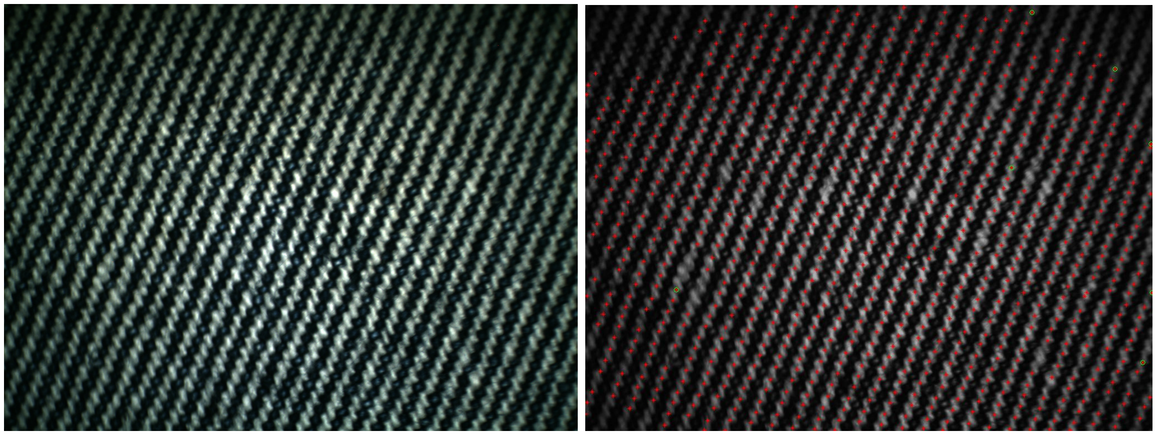


Figure 5 A sample image of denim used in the initial studies of finding the threads (Left). A sample image of the thread locations overlaid on the denim image (Right).

The results were evaluated based on the number of centroids found, the number of outliers, the mean, median and standard deviation, and the overall processing time. An outlier was defined as a centroid whose minimum distance between it and any other centroid was either 1.5 times the standard deviation less than the mean minimum distance or 2.2 times the standard deviation more than the mean distance. In other words, an outlier was a centroid that did not represent a thread or was a thread whose adjacent threads were not located. On average, the number of outliers found was less than 10% of the number of centroids found. The accuracy and robustness of thread detection was very good; however, the processing time was about 3 seconds on average. This obviously was unacceptable considering the speeds at which the fabric is moving. Further, consider the fact that, in order to track position, the fabric can only move less than or equal to half of the distance separating the threads between images based on the Shannon-Nyquist sampling theorem.

However, the poor processing time can be explained by a number of factors that are easily corrected. First, the program was running in Matlab on a slow Windows XP PC. Second, the sample image was of much higher resolution than necessary. Third, the greatest amount of processing time was used to find the orientation of the threads in order to identify the threads. If the threads could be found first, and the orientation found based on the threads, the computation time would decrease significantly. Finally, the test image contained many more threads than is likely necessary for fabric position measurement. The field of view could be reduced, thus decreasing processing time. In fact, only two threads have to be detected at any given time to determine position and orientation, but it would be useful to detect many more and use an average in order to obtain a more robust solution. Further work by Tom Collins and Ron Prado at Georgia Tech Research Institute has demonstrated the ability to track thread position and orientation on a moving piece of denim in real time.

2.2 Servo Dogs – Conceptual Design

The servo controlled dogs must meet a number of performance criteria to perform the task of precise fabric control for automated sewing, including the ability to operate at high speeds and in time with the sewing needle. The individual motions of the actuators are short in duration. The maximum travel needs to be only the distance of the longest stitch length anticipated for the application. Typical sewing speeds for non-autonomous sewing can be up to 5,000 stitches per minute, which is about 80 stitches per second or 1 stitch every $1/80^{th}$ of a second. Assuming an average stitch length of approximately 2 millimeters, the servo actuators must be able to accelerate up to about 23 gs or 225 m/s^2 in order to compete with the speed of the current manual sewing process. The accuracy of the dog's motion must be proportional to the length of travel because large variations in stitch length and stitch position cause unacceptably poor seam quality. In other words, the position accuracy should be on the order of fractions of a millimeter. With a system as flexible as the one being designed, it is impossible to use preplanned paths without feedback. Furthermore, it is necessary that the feedback be accurate enough to sense changes in position on the order of fractions of a millimeter to correct for errors that will arise due to factors such as slip between the actuator and the fabric. In addition to working in conjunction with the sewing needle, the servo dogs must be able to work with the budgers, described above.

A basic requirement of the servo dogs, unlike the current feed dog, is that they must be in front of the needle in order to be able to orient the fabric properly before the fabric reaches the needle. Therefore, they no longer will have the presser foot to push against and instead will be mounted above the fabric and push down against the surface of the table.

2.2.1 Fabric Control

In addition to the above performance requirements, the actuators must be able to control the fabric in multiple degrees of freedom. The actuators must move forward and back to advance the fabric through the sewing head in a manner similar to the current feed dog. However, to replace the human, the actuators must also be able to rotate the fabric. If one considers the fabric as a rigid body, then these two degrees of freedom would be sufficient for controlling the fabric on a flat surface. However, due to fabric's high extensibility, a total of six degrees of freedom must be controlled if complete fabric control is desired. Figure 6 depicts the six different degrees of freedom.

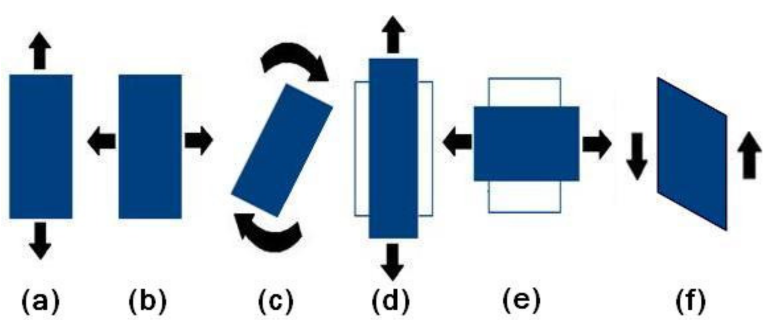


Figure 6 Fabric on a surface has six degrees of freedom: two directions of translation (a) (b), one direction of rotation (c), two directions of stretch (d) (e) and one direction of shear (f).

If one can assume that, with respect to the dogs, the stretch and skew are negligible and that the fabric only needs to be able to orient to the sewing head and feed into it, then the two degrees of freedom described above, forward/back and rotate, are necessary. However, because the fabric has the potential to buckle and stretch at the sewing head, it is likely the three degrees associated with fabric deformation will also need to be controlled.

In addition, if one wants to avoid the problem of rotating the fabric through large angles, which would result in large translations of the fabric far from the point of rotation as show in Figure 7, then the ability to rotate the sewing head and move the fabric left and right would be useful.

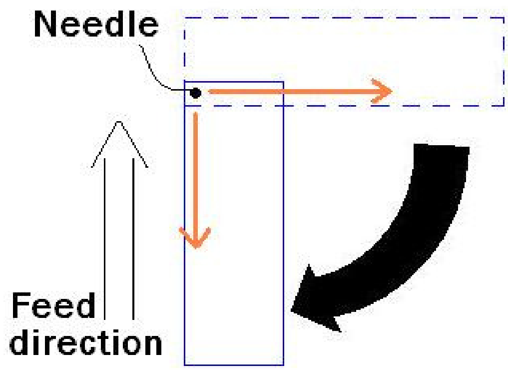


Figure 7 For the fabric to sew along the desired path (orange) it must rotated 90° to orient properly with the feed direction into the needle. For a long sheet of fabric, this requires a large motion. This problem could be eliminated if the fabric could feed from right to left.

Therefore, all six degrees of freedom could be necessary on a commercial system, but only two degrees of freedom are truly essential if coupled with appropriately coordinated budgers. To meet the performance requirements, the servo dogs must be small, light and fast. In addition, they must have multiple degrees of freedom that can be accurately position controlled, and they must be computer controlled to interface with the sewing machine, budgers and vision system. To understand how these actuators can move the fabric, it is helpful to think of the actuators as simple blocks that can move forward, backward, side-to-side and rotate. To obtain all six degrees of freedom, two servo dogs would be needed. Figure 8 demonstrates how five of the degrees of freedom can be controlled using two servo dogs.

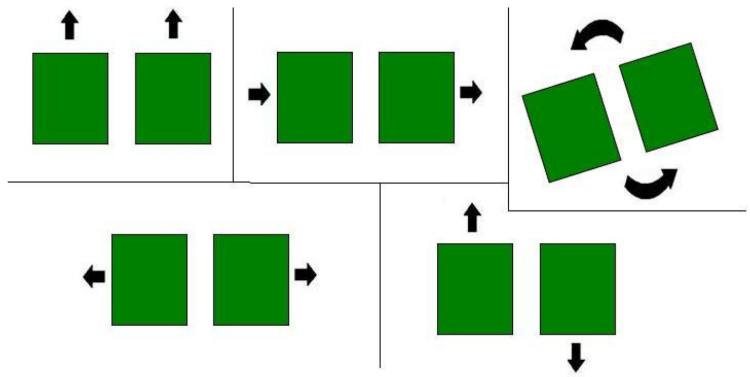


Figure 8 The blocks represent the servo controlled dogs and the arrows show how five degrees of freedom can be controlled: translation up/back (a), translation left/right (b), rotation (c), stretch in one direction (d), and Shear (e)

The sixth degree of freedom, fabric tension in the direction parallel to the sewing line, must be maintained using coordinated control between the dogs and the budgers. In this configuration, each servo dog would need three degrees of freedom of actuation – two for translation and one for rotation. This is omitting the out-of-plane actuation to provide incremental contact with the fabric as with current sewing dogs. The out-of-plane motion does not need to be position controlled, but does need to move up and down 180^{o} out of phase with the sewing needle.

In addition to multiple degrees of freedom, the servo dogs must be able to control two sheets of fabric, which overcomes a significant deficiency in previous designs for automated sewing. The simplest solution would appear to be to position the two plies perfectly aligned, one on top of the other, using a single actuator to control both plies simultaneously and relying on friction between the two plies to move the bottom ply. However, slip between the two plies would result in position errors for the lower sheet of fabric. Even if it were possible to control the two fabrics with a single actuator, the process of stacking the two fabrics precisely on top of one another would be difficult at best. A better solution is to separate the two sheets with a surface in between them, such as a thin steel plate, as shown in Figure 9, and have servo dogs above and below the plate, one set of two dogs for each ply. This allows both sheets to be independently controlled and properly aligned, although it doubles the number of sensors, cameras, and actuators. In addition, the thin plate acts as a surface for the actuators to push against, which on a standard sewing machine is done by pushing up against the presser foot. This is necessary because otherwise the dogs would be pushing the two fabrics against one another and the coefficient of friction would vary widely.

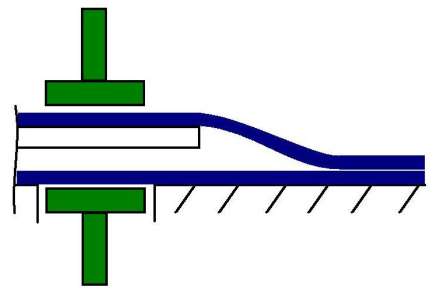


Figure 9 A thin plate separates two sheets of fabric. Each sheet is individually controlled by two manipulators although only one can be seen in this side view

Thus, for five degrees of freedom of control for two sheets of fabric, four manipulators would be needed, two for the top fabric and two for the bottom fabric. Each manipulator would use two motors. Each set of two manipulators would have a thread-level vision system for fabric feedback. One set would be above the fabric, controlling the top sheet, and the other set would be below the fabric to control the bottom sheet. This would allow for translation in multiple directions, rotation, horizontal stretch and shear.

In order to obtain the high accelerations required for the servo dogs to keep up with the sewing machine, an average DC or stepper motor is insufficient. Instead, voice coil motors will be used. Voice coils are used in speakers to project sound from electronic systems. They are used because they can change direction at very high frequency, thus vibrating at the frequency of the sound being output by whatever device is attached to the speaker. Voice coil motors operate in a similar fashion but can provide higher force and longer stroke than the voice coils used in speakers. In addition, voice coil motors can be position controlled using the same techniques as would be used for a

DC motor. In general voice coil motors have a low force output per motor mass and so it is beneficial to mount the motors apart from the moving part of the servo dog to reduce the inertia of the dogs. Therefore a cable drive system is necessary to transmit the force from the motor to the dogs. To accurately control the position of the voice coil motors, an optical linear encoder provides a precise non-contact solution.

2.2.2 Complete System

A complete fabric control system will thus be comprised of a thin plate just above the table surface in front of the sewing head, two to four servo dogs, one or two for the top sheet of fabric and one or two for the bottom, with the plate separating the sheets, and two thread counting vision systems to provide position information for both sheets of fabric being sewn. Figure 10 shows a visual representation of the system. In addition to these new components, some of the existing components of the sewing machine must be removed or modified. The current sewing dogs will be removed and replaced by the servo controlled dogs. The presser foot will need to move up and down in time with the needle to hold the fabric during stitching, but release the fabric to allow the servo controlled dogs to push the fabric through the sewing head.

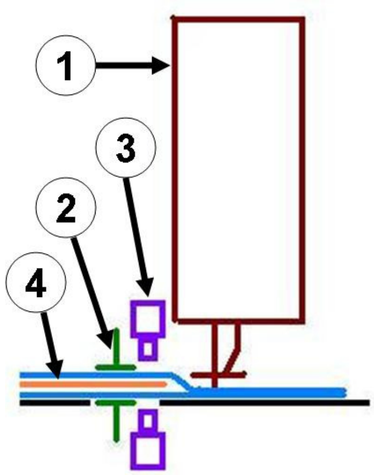


Figure 10 Complete automated system with components: sewing machine (1), manipulators (2), cameras (3), thin plate (orange) and fabric (4).

To test the feasibility of the design, a prototype of a servo dog was created and mounted to a standard industrial sewing machine. The following chapter will describe the prototype and the performance of the prototype will be discussed in Chapter 4. Experiments were performed to examine the effect the dog will have on the behavior width of the fabric. Further experiments were done to analyze the extent to which two sheets of fabric can be relatively controlled when they are placed one on top of the other as described above. Finally, some tests were done with the two sheets partially stitched together. The experiments will be discussed in greater detail in Chapter 5.

CHAPTER 3

SERVO DOG PROTOTYPE

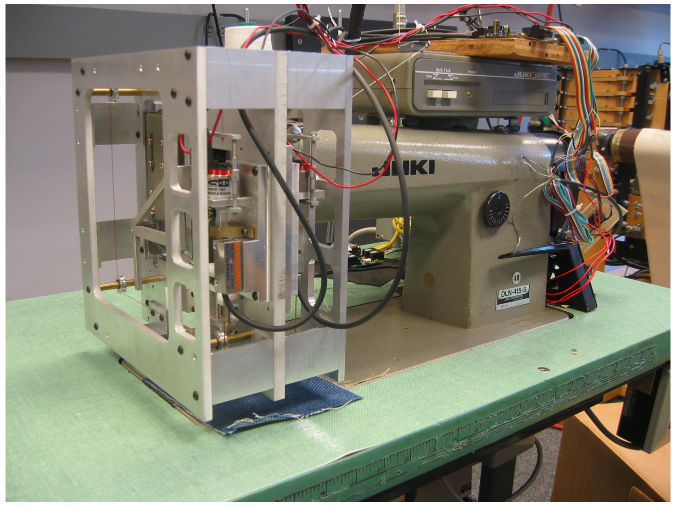


Figure 11 Prototype servo control manipulator mounted on a sewing machine

A prototype of the proposed actuator, shown in Figure 11, has been developed to demonstrate the feasibility of multi-degree-of-freedom servo control at the high accelerations, accuracy and precision required. The prototype is designed to have two degrees of freedom, the minimum number of degrees of freedom for controlling a fabric sheet on a surface. The prototype uses two voice coil motors and a cable drive system to transfer power to the servo dog while allowing the motors to be mounted apart from the servo dog. The system uses linear optical encoders for position control of the voice coil motors, but the position control of the fabric itself is open loop control. A single dog is used to achieve both forward and reverse motion and rotation, two degrees of freedom. This is sufficient for obtaining in-plane motion but cannot stretch or skew the fabric. The entire device is mounted on an industrial sewing machine that had been modified to allow for the servo dog. For out-of-plane motion, the dog is mechanically attached to the sewing needle to force proper timing between the contact of the servo dog and needle with the fabric. For the dog to function properly, it must be able to distinguish between when it is in contact with the fabric and when it is above the fabric. An IR reflective optical sensor is used for the dog to “know” when it is in contact with the fabric. The system is controlled by a Windows PC using a program written in C. The PC communicates with the motors, encoders and sensor using two motor controllers that interface serially with the PC. A block diagram of the system as it would be integrated into the entire garment manufacturing system can be seen in Figure 12.

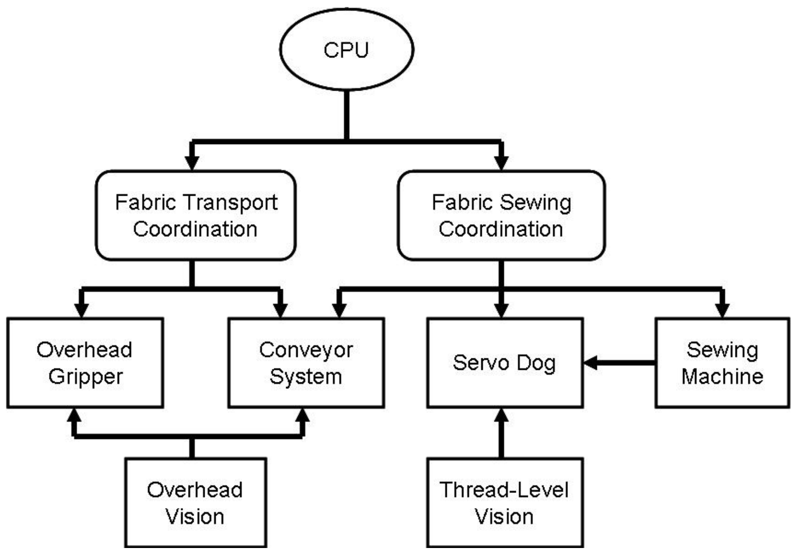


Figure 12 Block diagram showing the control hierarchy of the automated sewing system.

While a thread counting vision system could easily be integrated into the system, it is still under development, so the control is open loop with regard to the fabric. Open loop control is sufficient to demonstrate the feasibility of the servo controlled sewing dog design. The prototype is used to exhibit the capabilities of the servo dog design in terms of fabric control, as well as the speed and accuracy of that control. The benchmark for the design is a comparison with the current manual sewing method, which operates at 5,000 stitches per second. Figure 13 below shows a CAD model of the prototype made in Solidworks.

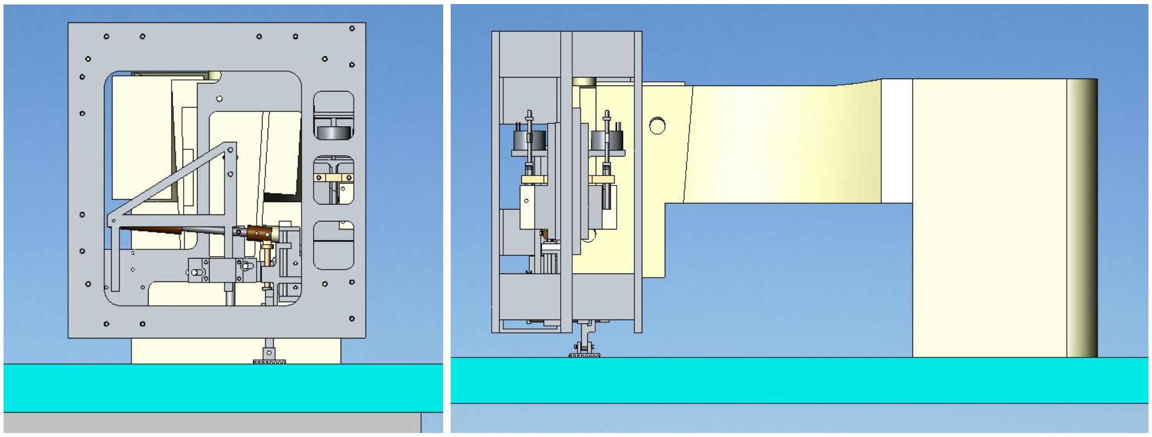


Figure 13 A CAD model of the servo dog prototype: side view (Left) and front view (Right).

3.1 Sewing Machine Modifications

The sewing machine used for the prototype is a Juki DLN-415-5 Single Needle Lockstitch Sewing Machine, shown in Figure 14, with the servo dog frame attached. It is a needle feed sewing machine, meaning that the needle itself is used with dogs to advance the fabric while the needle is in the fabric. This allows for greater flexibility in stitch length and sewing speeds. However, this particular feature will not be used for the prototype but may be useful for further studies. Other than the needle feed feature, the Juki is a standard industrial sewing machine with variable speeds and configurations. A number of modifications were made to allow for the addition of the servo dog and to aid in integrating the servo dog with the sewing machine.

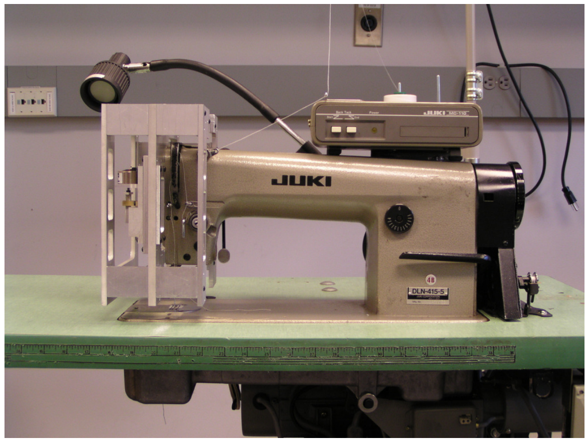


Figure 14 The sewing machine with prototype frame mounted.

The first modifications were made to allow the servo dog to be mounted to the sewing machine. The face plate and face plate gasket of the sewing machine were removed to provide a surface on which to mount the servo dog frame and to create a surface from which to take measurements when designing the size and position of components to be added to the sewing machine. Figure 15 shows the sewing machine with the face plate removed, revealing the needle bar assembly.

Figure 15 The face plate and gasket are removed to provide a mounting surface for the prototype and to gain access to the needle bar.

The other major modification for the purpose of mounting the servo dogs was the extension of the needle bar, shown in Figure 16, to provide a surface to which to attach the servo dog components.

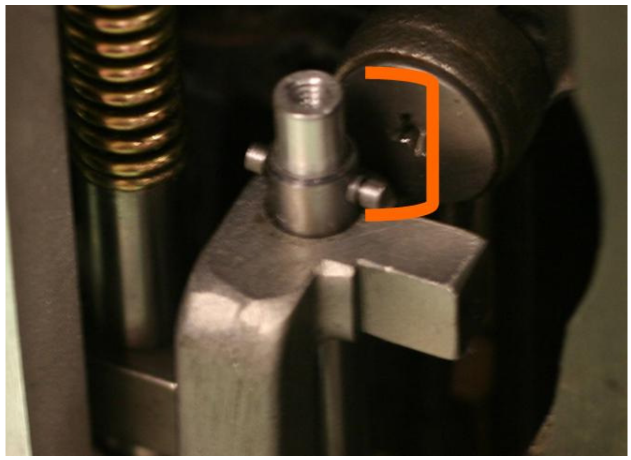


Figure 16 The extension of the needle bar allows the servo dog system to be mechanically connected to the needle bar.

Other sewing machine modifications were necessary for the prototype to function properly. The biggest change was the removal of the presser foot from the sewing machine. As mentioned in section 2.2.1, the presser foot cannot be down while the servo dogs are moving the fabric because the fabric would buckle as it is pushed against the presser foot. A solution for this problem is to have the presser foot move up and down with the sewing needle, holding the fabric tight while the needle makes a stitch, and then lifting off the fabric while the servo dogs moved the fabric. Because the physical process of making each individual stitch is a well understood, proven procedure, it was unnecessary for the demonstration of the servo dog design. Therefore, the presser foot was simply removed, allowing the servo dogs to control the fabric without buckling but eliminating the ability to sew fabric. The sewing machine feed dog also was removed to allow the new servo dog to have complete control of the fabric.

The sewing table itself was modified to create a better surface on which to move the fabric. The sewing machine had previously been used, and the table surface was bowed due to years of being the only support structure for the motor and sewing machine. Because of the bowed shape, the table surface sagged below the sewing machine, creating a lip between the sewing machine and the table. The curve in the table was removed by bolting a 3”x3”x1/8” steel angle to the bottom of the table, lifting the middle of the table with a jack, and adding shims between the beam and the table to further flatten and raise the surface. The result was a flatter table surface and the reduction of the lip between the sewing machine and the table surface.

To further even the surface, the plate at the sewing head which has holes for the feed dog and the needle was removed because it was slightly raised from the surface of the sewing machine. It was replaced by a flat aluminum plate with one hole for the needle. This was possible because the standard sewing dog that came with the machine was removed.

The sewing needle is driven by the sewing machine's electric motor at a speed that is defined by the user with an analog dial. Although the speed is variable, it must be controlled manually and is not computer controlled. Controlling the sewing speed using a CPU is not a difficult operation and has been done before. Having the analog dial allows for multiple speeds to be selected and for the speed to be changed by the user as needed for purposes of experimentation or demonstration. Being able to computer-control the speed is unnecessary for this prototype because the dog is able to adjust to any sewing speed using the IR sensor. However, in a final implementation, having the sewing machine speed defined by the computer would be preferable so that the complete system would be automated.

3.2 Servo Dog Mechanical Design

The servo dog consists of four main components: the frame, two actuator assemblies, the mechanical linkage between the dog and the sewing needle, and the dog itself. The components are highlighted in Figure 17, except for the frame, which is the gray structure on which everything is mounted.

As the sewing needle travels up and down, the mechanical link drives the servo dog assembly down and up. It ensures that the dog will be in contact with the fabric only when the needle is not in contact with the fabric. An IR reflective optical sensor is used to detect the position of the needle bar to determine whether or not the needle is in contact with the fabric. This allows the motion commands of the dog to be based on the position of the needle. The motion commands are sent from the PC to two amplifiers and from the amplifiers to the two actuators. The force output of the actuators is transferred to the dog using a cable drive system. Each actuator controls one degree of freedom of the dog.

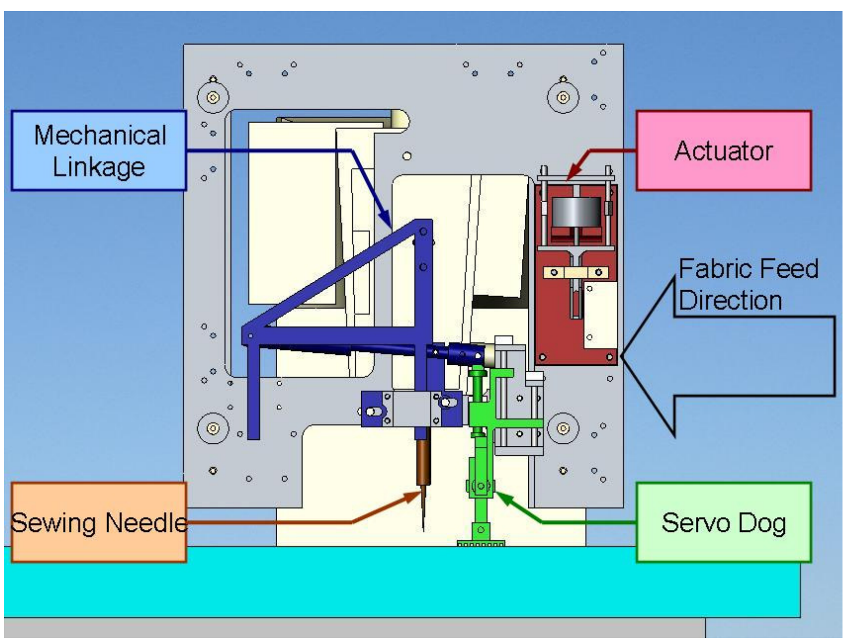


Figure 17 A CAD model of the servo dog prototype mounted on a sewing machine. The primary components of the system are highlighted.

3.2.1 Linkage Assembly between the Sewing Machine and Servo Dog

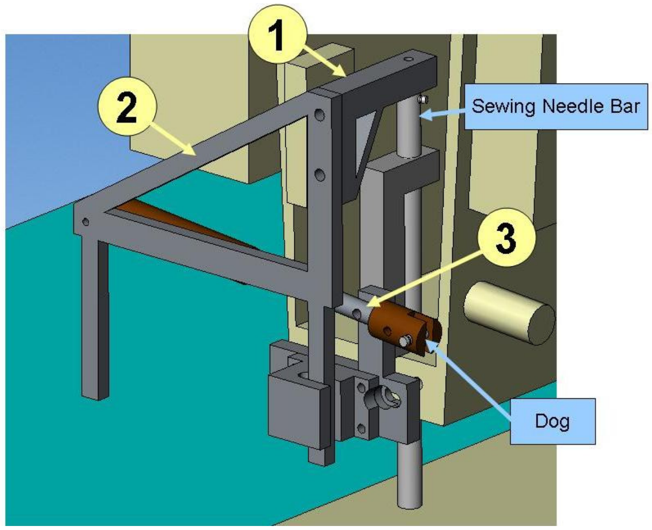


Figure 18 The linkage assembly is made up of an aluminum beam that connects the assembly to the sewing machine needle bar (1) and a frame (2) that connects to one end of a lever arm (3) that links the motion of the needle bar to the dog.

The sewing needle to dog linkage system, shown in Figure 18, mechanically connects the servo dog to the sewing needle, ensuring proper timing between the two devices. The system has four major components. The first is an aluminum beam that attaches to the sewing needle bar (1), which provides a solid connection to the sewing machine and extends the assembly outside of the sewing machine structure. In addition, the aluminum surface provides a reflective surface for the IR sensor to detect when the needle bar is up or down. The function of the sensor will be discussed in greater detail later. Next, the frame (2) connects the top of the needle bar to the lever arm (3) such that the lever arm can pivot about the horizontal.

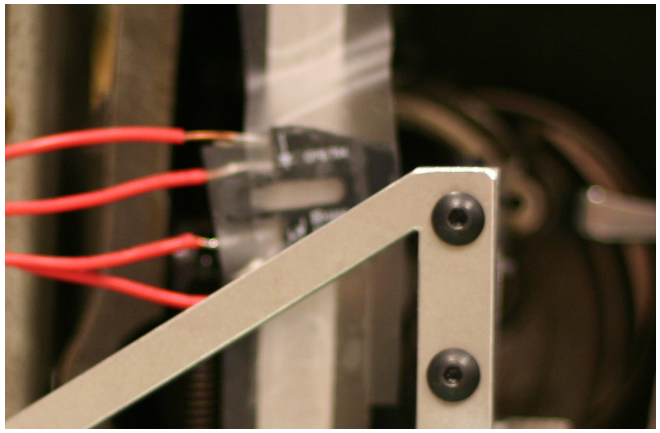


Figure 19 The IR sensor detects the presents of aluminum beam (1) to detect when the needle bar is up and the needle is out of the fabric.

The function of the assembly is to act as a lever arm between the sewing needle bar and the dog assembly. If the lever arm is level, as shown in Figure 20 (a), the moment arm ratio between the sewing needle arm to the dog arm is about 4.37:1, respectively. As the sewing needle bar moves, the ratio is maintained as shown in Figure 20(b). The sewing machine motor will require less force to move the dog assembly because of the mechanical advantage of the lever arm. The sewing needle has a stroke of approximately 1.193 inches. Therefore, the dog assembly has a stroke of 0.273 inches. This provides enough clearance for the dog to move without being in contact with the fabric, but reduces the acceleration on the dog assembly in the vertical direction proportional to the reduction in travel.

In addition, the reduced stroke benefits the design of the dog. The dog is intended to be in contact with the fabric the entire time the needle is out of contact with the fabric. During this time, the dog does not move in the vertical direction, but the lever continues to push down on the dog as the needle bar moves up. Because of this, a spring is used to maintain the normal force on the dog while allowing the lever arm to continue its motion as the lever arm pushes down on the dog after the dog has contacted the table. If the stroke of the dog were equal to the stroke of the needle bar, the spring would need to be able to compress about 0.6 inches and still provide a small force on the dog assembly.

With the dog stroke only being 0.273 inches, and only a fraction of that stroke compressing the spring, a smaller spring can be used and provide less normal force as it is only compressed a small amount. The details of the dog assembly will be discussed later.

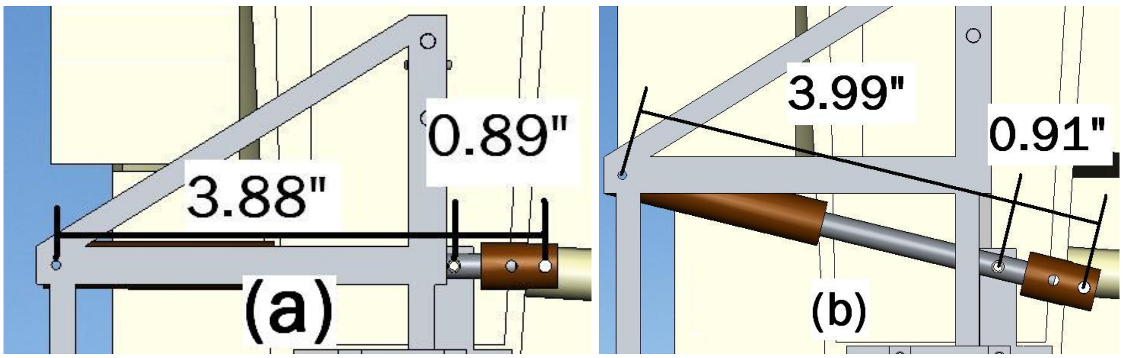


Figure 20 A CAD model of the lever arm with the moment arm lengths labeled. The lengths in the figure are rounded to two decimal places resulting in slightly different ratios between (a) and (b) due to rounding error only.

3.2.2 Actuator

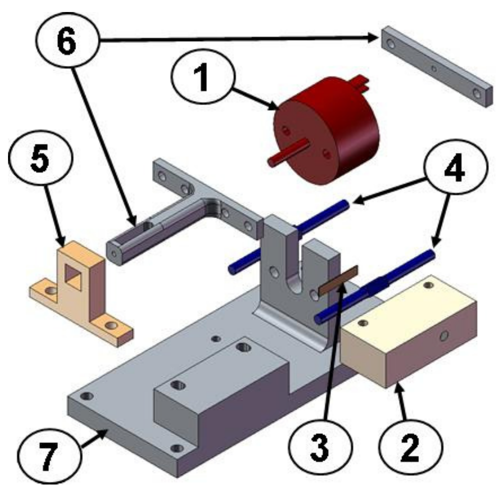


Figure 21 Exploded CAD model of an actuator with voice coil motor (1), digital encoder (2), encoder strip (3), turnbuckles (4), brass bearing (5), aluminum parts (6) and mounting plate (7). The moving parts are (4), (6), and the shaft and coils of the voice coil motor (1).

The actuator used for the prototype consists of a Gee Plus VM2618-180 voice coil motor and Renishaw RGH24Z30F00A linear optical encoder. The voice coil motor has a peak force of about 10 N and a total travel of 4 mm at a force greater than 90% of the peak force. The travel of the actuator is mechanically limited to just over 4 mm of stroke. Therefore, with a desired acceleration of 23 gs or 225 m/s^2, the total allowable moving mass is about 44 grams. The motor itself has a moving mass of 6 grams. Thus the encoder is not mounted to the moving assembly as it would add too much inertia. Instead, the encoder read strip is affixed to the moving assembly and is read by the encoder, which is attached to the actuator mounting plate. A square brass bushing is used to provide a low friction sliding motion along the motor axis and to keep the shaft from rotating so that the encoder strip will remain parallel to the encoder. The other moving parts are two turnbuckles shown in Figure 21 and two aluminum pieces used to attach the cables for the cable drive system. The T-shaped aluminum piece is threaded onto the motor shaft and positioned appropriately on the shaft by the nut as shown Figure 22. This allows for the amount of travel to be adjusted and helps lock the threaded connection in place.

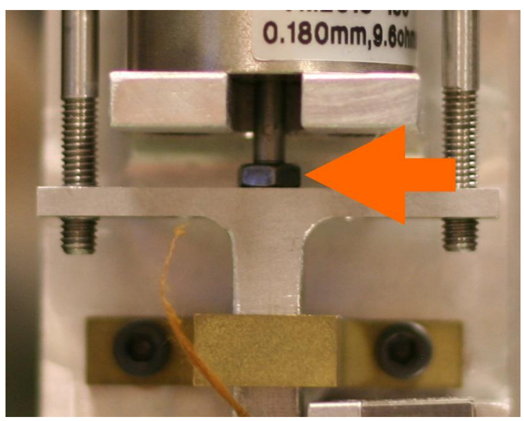


Figure 22 The nut on the shaft of the actuator adjusts the position of the T-shaped aluminum piece to create the proper motor travel and locks the aluminum piece in place.

The two aluminum moving parts are connected using the two turnbuckles. The turnbuckles are necessary to adjust the tension in the cable drive system that will be discussed later in more detail. Each turnbuckle is threaded on both ends, one end having right hand threads and the other having left hand threads. Thus when the turnbuckles are rotated clockwise, the moving parts they thread into are drawn closer together, increasing the tension in the cables. When the turnbuckles are rotated counterclockwise, the moving parts spread apart, decreasing the cable tension. Due to slop in the bushing, it was difficult to align the encoder and encoder strip to obtain a good signal in the encoder. To alleviate this issue, the mounting holes for the encoder allowed the encoder position and orientation to be adjusted and shimming washers were added below the bushing and the encoder until a good signal could be maintained. The shims also helped to properly align the T-shaped piece and bushing to compensate for misalignment due to machining tolerances, thus reducing friction in drive.

3.2.3 Cable Drive System

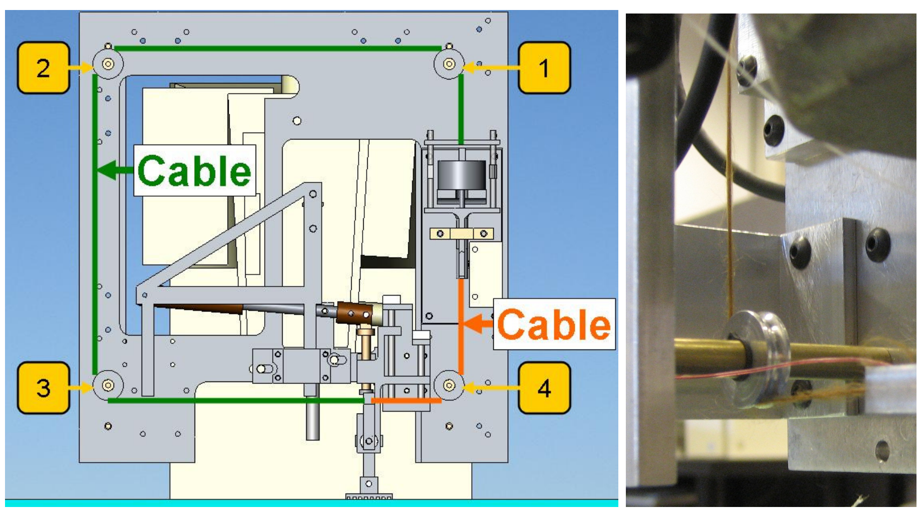


Figure 23 Two sets of four pulley wheels (one set not shown) guide the cables from the actuators to the dog (Left). One cable is routed around wheels 1, 2 and 3 respectively. The other cable is routed around wheel 4. Wheel 4 is shown on the right.

The cable drive system connects power from the actuators to the mechanical dog. This permits the actuators to be mounted separately from the dog. Neither motor has to be able to move both the dog and another motor to obtain two independently actuated degrees of freedom. It is a lightweight method of transferring power. The use of cables also permits the dog to move up and down while keeping the actuators stationary, and allows the actuators to control the dog regardless of whether it is up, down, or in motion. The cables are routed from the actuators to the dog using two sets of four wheels as shown in Figure 23. The wheels are machined aluminum and ride on brass rods. The aluminum provides the advantage of low inertia. The brass rods reduce the friction.

While the dog moves up and down, the actuators do not. This causes the effective distances between the dog and the pulleys to increase and decrease as the distance between the dog and the adjacent pulley changes. As described above, the dog has a stroke length of 0.273 inches. Therefore, the amount of increase can be found easily using the familiar Pythagorean Theorem. The amount of increase is about 1/100th of an inch or 0.254 mm.

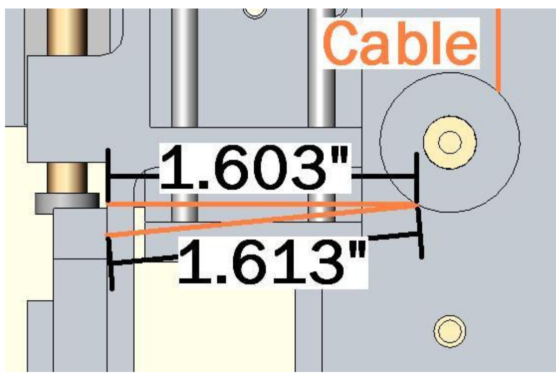


Figure 24 As the dog moves in the vertical direction, the cable length changes from 1.603" to 1.613".

Because of the change in distance as the dog moves up and down, albeit small, it is necessary that the cable be flexible. A flexible cable therefore was chosen as the long cable to allow the dog to move vertically while maintaining tension in the cable section regardless of the position of the dog. As the dog moves up and down, the tension in the system changes, but the motor does not move and the cable does not become slack leading to loss of control of the dog. In contrast, a non-flexible cable was chosen to act as a rigid link in the cable system. It is the shorter of the two cables. The non-flexible cable is Zylon thread, which is similar to Kevlar in material properties. The flexible long cable originally was metal thread, but it was too flexible even under very low forces.

Fishing line was chosen as an acceptable alternative, being strong enough to create the necessary tension in the system and to allow the dog to move in the vertical direction. However, as the tension in the cables is increased, the friction in the wheels also increases, creating unwanted drag in the system. The tension in the cables is adjustable using the turnbuckles on the actuators, allowing for some tuning between the optimum tension and the optimum level of normal force on the pulley wheels.

3.2.4 Dog Assembly

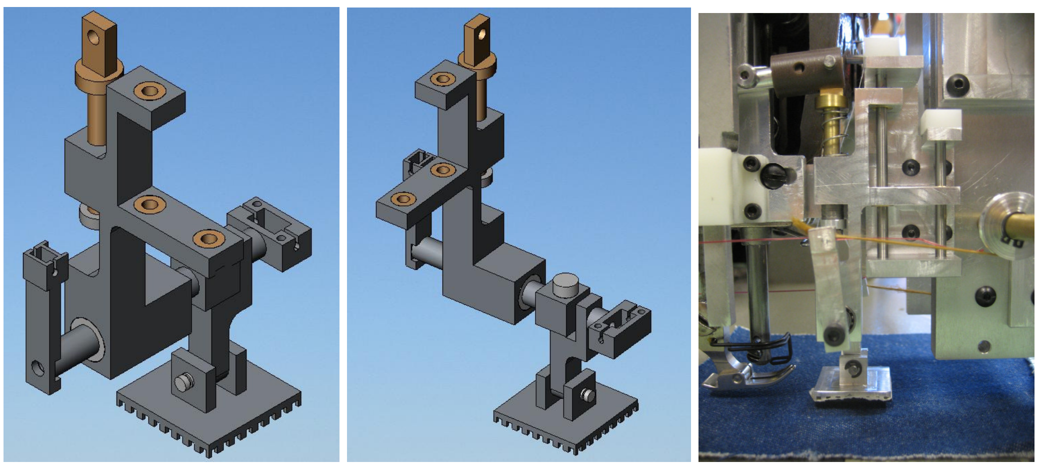


Figure 25 CAD model of the dog assembly (Left). Dog mounted on the sewing machine (Right)

The dog, shown in Figure 25, is made of mostly aluminum parts with a few roller bearings and bushings and a spring. It is L-shaped to place the "foot" of the dog in front of the needle. The dog assembly has four components to fulfill the three primary requirements of the dog. The first component, shown in Figure 26, attaches the dog to the linkage assembly that connects to the sewing needle. The second component, the translational component of the dog assembly, performs the function of rotating the dog so that the dog can translate the fabric forward or backward. The third component, the rotational degree of freedom component, highlighted in Figure 33, allows the dog to rotate given an input from the cable drive attached to one of the voice coil motors. The final component is the linear bushings which restrict the motion of the entire assembly to the vertical direction.

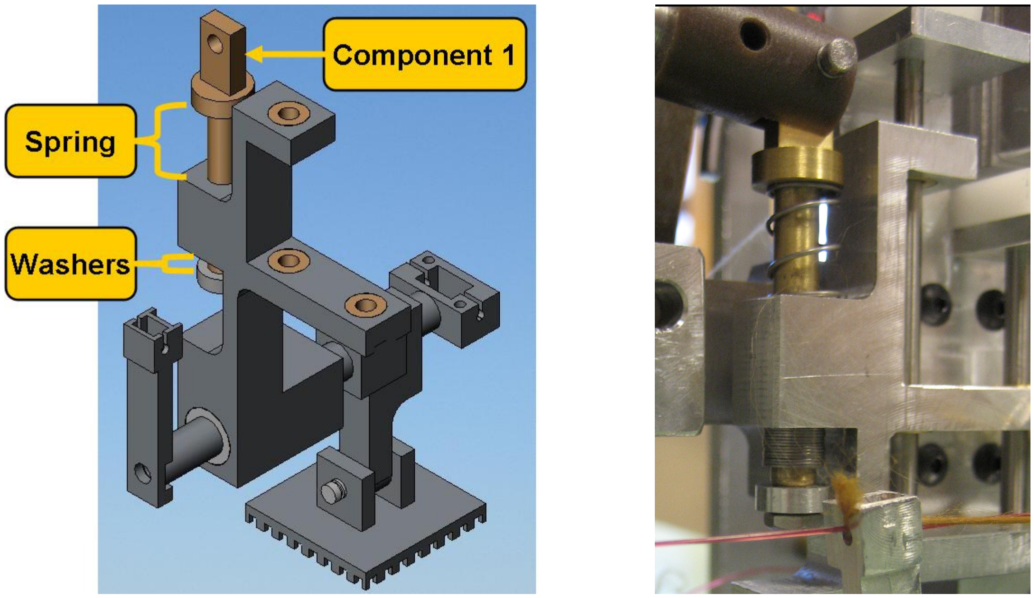


Figure 26 Component 1 attaches to the linkage system that connects the dog with the sewing needle assembly. The spring (shown on the Right) absorbs the downward force of the linkage assembly after the dog contacts the table. Washers underneath allow the point in the stroke of the dog where the dog contacts the fabric to be adjusted. Adding washers in the section with the spring adds a preload to the spring to adjust the normal force.

The key features of the first component that are essential to the performance of the dog are the spring and the ability to adjust the duty cycle of the dog with respect to the dog's contact with the fabric. The ½ inch spring provides a small normal force, 5.41 lb/in, sufficient for the dog to slide the fabric on the surface and to keep the dog in contact with the fabric while the dog is moving the fabric. This is necessary because the dog moves the fabric forward and back by rotating. Therefore, as the dog rotates, it not only moves forward and backward but also up and down, as shown in Figure 27.

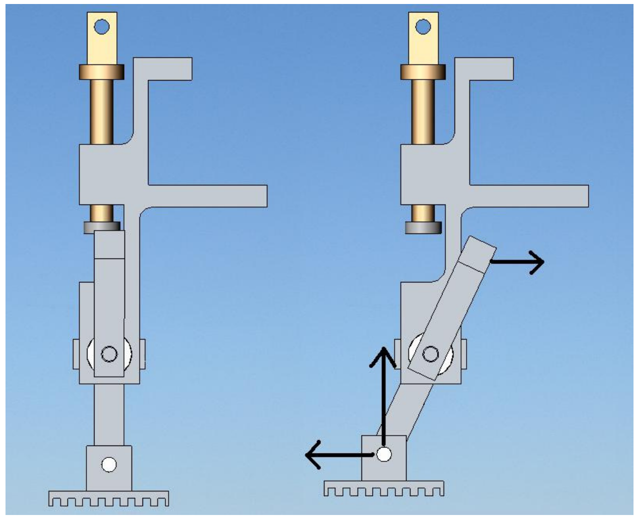


Figure 27 To translate the fabric, the dog rotates, causing the foot to move both horizontally and vertically.

Thus, a force pushing down is necessary to keep the dog on the fabric as it rotates upward. To better understand, consider a small snapshot of the dog's motion: while the needle is down, the dog is up and the spring does not act on the dog. Then, as the needle is raised up out of the fabric, the lever arm of the linkage assembly rotates, and the spring pushes down on the dog. The dog is pushed down onto the fabric surface, and the spring is compressed by the linkage assembly lever arm as the needle bar continues to move, placing a normal force on the fabric. The dog advances the fabric forward by rotating forward and upward. As the dog rotates upward, the spring continues to push down on the dog, thus maintaining the normal force on the fabric. Finally, the needle is pushed back down into the fabric for the next stitch and the dog is raised from the fabric and the spring returns to its uncompressed length. Force is needed because rotation of the dog is required to perform translation of the fabric.

The amount of force from the spring can be adjusted by adding washers to change the preload deflection of the spring. Increasing the normal force increases the friction not only between the dog and fabric, but also between the fabric and the table. An additional trade-off occurs because the higher the normal force, the harder the motors have to work to move the fabric. If the force from the spring were high enough, then the motors would be unable to move the fabric at all. The amount of friction can easily be changed by changing the surface material of the foot, currently 220 grit sandpaper, although other design considerations must be considered such as the effect on the inertia of the dog and whether or not the fabric adheres to the dog as the dog lifts.

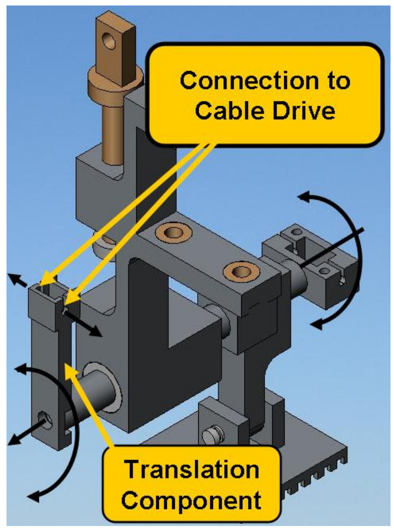


Figure 28 The cable drives pull the lever arm of the translation component causing a rotation or the arm that connects to the dog's foot.

The need to rotate the dog to perform the linear motion will be explained later and for now should be assumed. The dog connects to the cable drive system at the point shown in Figure 28. The arm, to which the drive system connects, acts as the moment arm to the nearly two inch shaft. The shaft rides on two bearings. The bearings reduce the friction in the rotation, thus reducing the load on the voice coil motor that drives the system. At the opposite end of the shaft, the dog's foot is attached to another moment arm so that the foot is placed in front of the needle. The foot is attached using a hardened steel pin and is secured using two e-style snap-rings. The foot is allowed to swing freely and is symmetrically balanced so that it hangs horizontal to the table surface even as the dog rotates, changing angle as shown in Figure 27. The effective moment arm attached to the foot is 0.9225 ± 0.005 inches long. The effective moment arm attached to the cable drive system is also 0.9225 ± 0.005 inches long. This is approximately a one-to-one gear ratio except that the point of contact between the cable drive system and the dog is off-centered from the moment arm as shown in Figure 29.

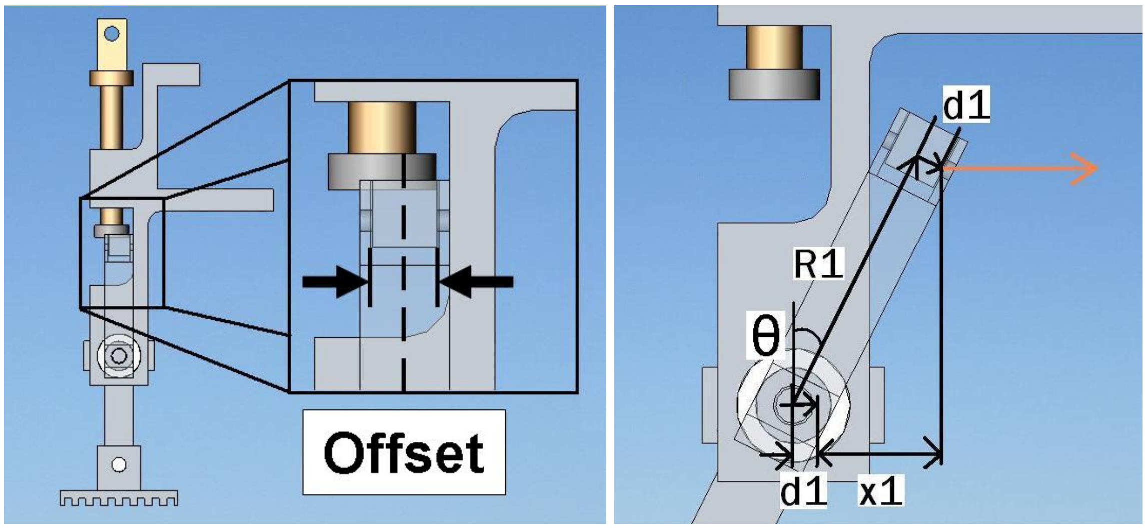


Figure 29 Offset in the lever arm due to the mounting points of the cables (Left). Kinematic relationship between θ and x_1 (Right).

The offset is necessary to allow for the cable drive to be attached from both directions, but it changes the moment arm of the cables. The relationship between the position of the voice coil motor and the angle of the dog can be expressed by either of two equations:

$$x_1 = R_1 \sin\theta + d_1(\cos\theta - 1) \tag{1}$$

$$x_1 = \sqrt{d_1^2 + R_1^2}\sin(\theta + \phi) - d_1 \text{ where } \phi = \tan^{-1}\left(\frac{d_1}{R_1}\right) \tag{2}$$

The distance that the voice coil motor moves is x_1. R_1 is the length of the moment arm, the offset is d_1, and the angle of rotation is θ. Both equations represent the same relationship between x_1 and θ, but equation (1) shows clearly the effect of the offset, d_1, while equation (2) allows for θ to be solved directly. Because the maximum travel of the actuators is only about 4 mm and the average stitch length is about 2 mm, the angle of rotation is small, and the small angle approximation can be used to linearize equation (1):

$$x_1 = R_1\theta \tag{3}$$

At x_1 = 4 mm, the percent error between the approximation and the true value is about 1.3%. Figure 30 shows a plot of the two equations and the approximation as well as the percent error.

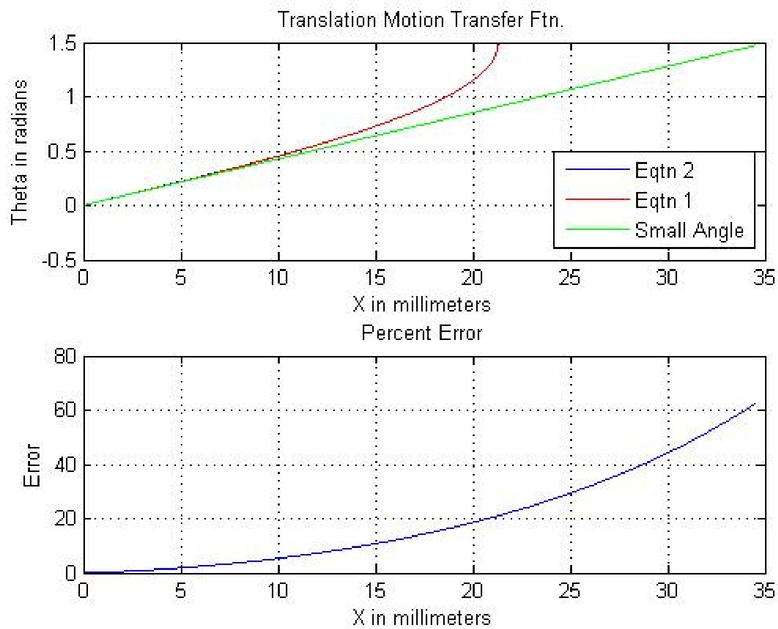


Figure 30 Equations (1) and (2) are plotted along with the small angle approximation, equation (3) (Top). The error between equations (1) and (3) are plotted as a percentage (Bottom).

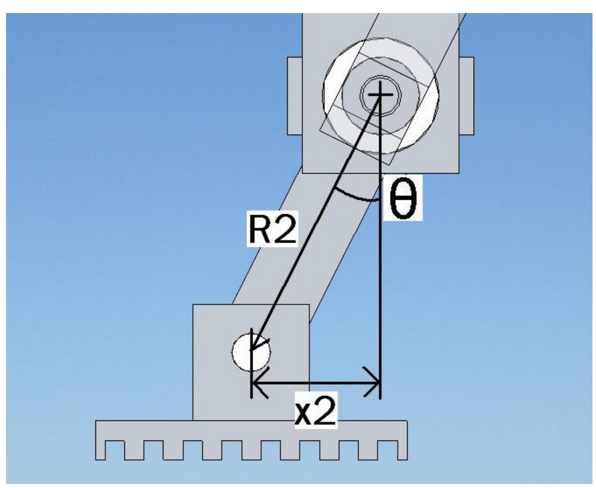


Figure 31 Kinematic relationship between R_2 and x_2.

To find the relationship between the translation of the actuator and the translation of the dog's foot or the fabric, assuming no slip between foot and fabric, the relationship between the angle of the dog and the foot position is described as $x_2 = R_2 \sin\theta$. Inserting this into equation (1) yields the new equation:

$$x_1 = \frac{R_1}{R_2} x_2 + d_1(\cos\theta - 1) \tag{4}$$

By small angle approximation, equation (4) gives the effective gear ratio:

$$x_1 = \frac{R_1}{R_2} x_2 \tag{5}$$

Because R_1 and R_2 were both chosen to be 0.9225 inches as described previously, the relationship between the actuator translation and the fabric is approximately 1:1 assuming no slip. In reality, slip will exist. This is the reason for the thread-level vision system. Also, the 1:1 gear ratio allows the force applied to the fabric to be equal to the force applied by the actuator and the distance moved by the actuator to be the distance moved by the fabric assuming no slip.

The need to rotate the dog in order to obtain a linear displacement is because the part of the dog assembly that controls the rotation degree of freedom cannot be translated with the rest of the dog in the forward and reverse degree of freedom. If the dog simply slid back and forth, it would have to translate the actuator (voice coil motor assembly) that controls rotation along with the dog. This cannot happen because the voice coil motor is not strong enough to move the whole dog assembly in addition to another actuator and still be able to obtain an acceleration of 23 gs. Therefore, the linear degree of freedom is controlled by rotating the dog, and the cable drive system for controlling the rotation degree of freedom is connected to the dog at the center point of rotation so that it remains stationary as the dog moves forward and backward. This is visually explained in Figure 32.

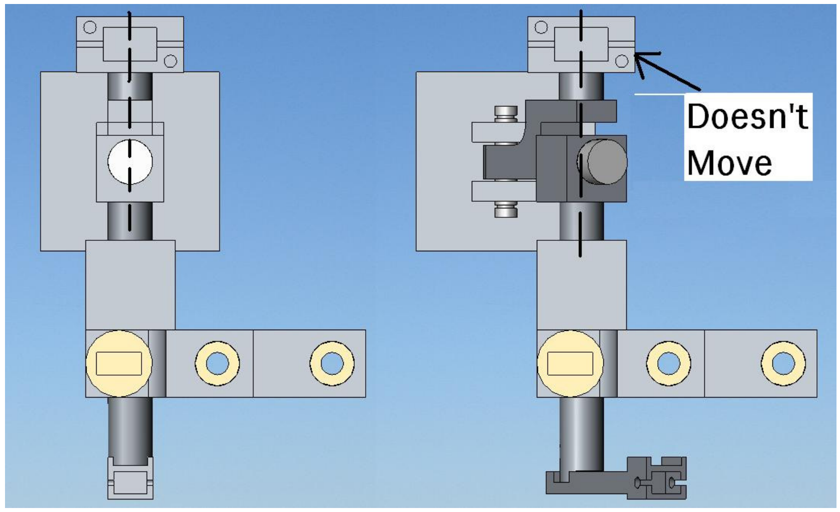


Figure 32 A top view of the dog demonstrates that the rotation degree of freedom is controlled at a point along the center of rotation of the translational degree of freedom.

The rotation degree of freedom component, highlighted in Figure 33, allows the dog to rotate given an input from the cable drive attached to one of the voice coil motors. The moment arm for rotating the dog is mounted such that it is at the center point of rotation of the linear degree of freedom. This decouples the two rotations so that one does not affect the other. The rotation of the foot has no effect on the position of the foot in the vertical direction. Therefore, the rotation has no effect on the stroke of the spring. The axis of rotation is vertical and runs through the center of the foot as shown in Figure 33. The rotation is about a shoulder screw which rides on two roller bearings. The relationship between the translation of the actuator and the rotation of the dog can be expressed in a manner similar to the translation degree of freedom:

$$x = R\sin\theta + d(\cos\theta - 1) \tag{6}$$

$$x = \sqrt{d^2 + R^2}\sin(\theta + \phi) - d \quad \text{where } \phi = \tan^{-1}\left(\frac{d}{R}\right) \tag{7}$$

Using the small angle approximation, the relationship can be linearized and equation (6) becomes:

$$x = R\theta \tag{8}$$

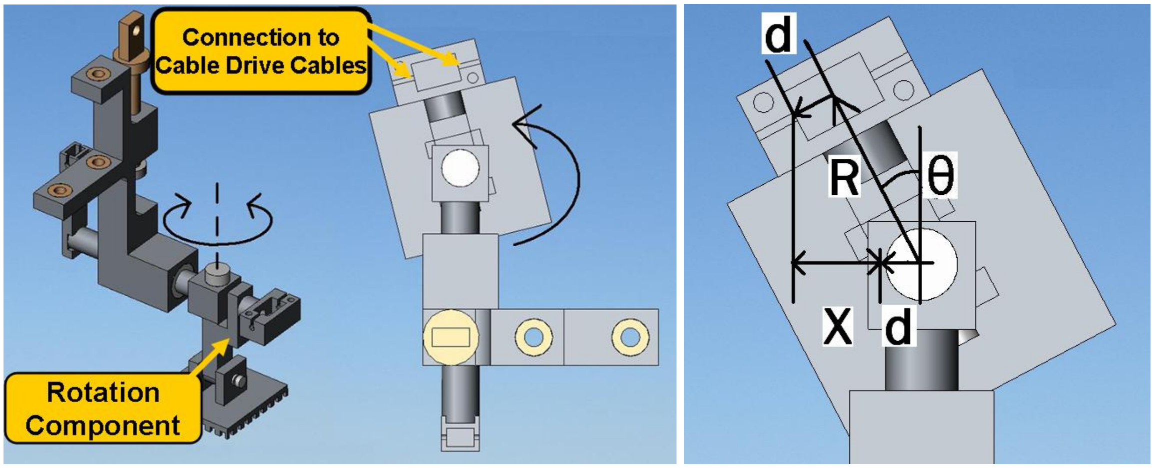


Figure 33 The rotational component of the dog converts the linear motion of the voice coil motor to rotational motion of the foot (Left). Kinematic relationship between x and θ.

The radius, R, is approximately 0.656 inches. Therefore, the maximum rotation is approximately 13.7^{o}, corresponding to a 4 mm translation of the voice coil motor. At 4 mm, the percent error is about 3.8%.

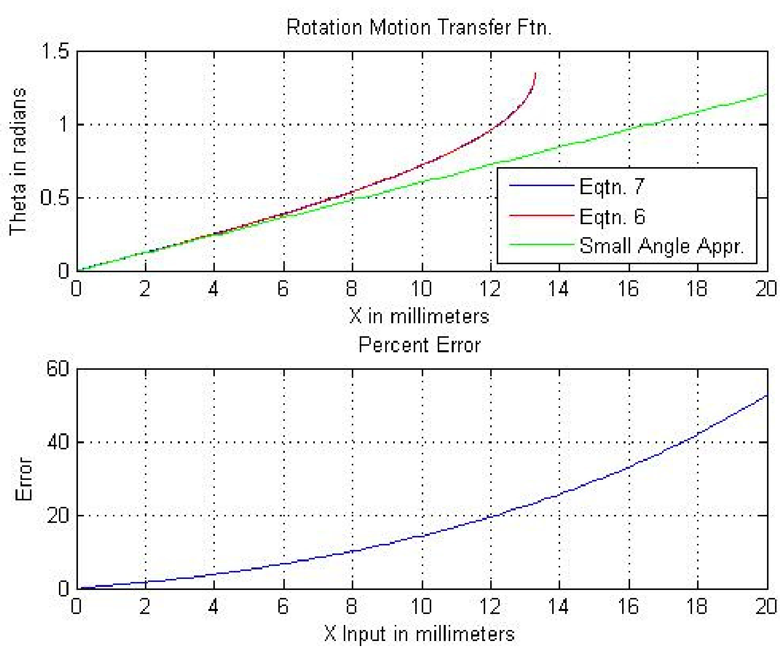


Figure 34 Equations (6) and (7) are plotted along with the small angle approximation, equation (8) (Top). The error between equations (6) and (8) is plotted as a percentage (Bottom).

The final component of the dog assembly, show in Figure 35, guides the vertical motion of the dog. It consists of three brass linear bushings that ride on two 440C stainless steel shafts. The steel shafts slide down into the aluminum frame and are press fit into the bottom of the frame. Two Delrin caps are screwed onto the top of the frame and hold the steel rods in place. The three linear bushings guide the dog on the shaft and are spaced apart vertically and horizontally in order to handle the moments placed on the assembly by the complex geometry of the dog. A previous design demonstrated the need to have the bushings spaced apart. In the previous design, a ½ inch thick aluminum bearing surface slid on a brass shaft. In spite of using an abundance of lubrication, the dog would bind on the shaft as it was being driven up and down by the sewing machine. This would cause the dog to jam and the aluminum lever arm would bend as the sewing machine continued to try to drive the dog. The current design, in Figure 35, has two bushings on one shaft, one approximately 1 inch above the other to reduce the effect of the moment. The third bushing rides on a separate shaft to maintain the alignment of the dog. The brass bushings riding on 440C stainless shafts reduce the tendency to bind because of the hardness of the steel shafts. This allows the dog to move the fabric even while being driven by the sewing machine at its maximum rate of 5,000 stitches per minute.

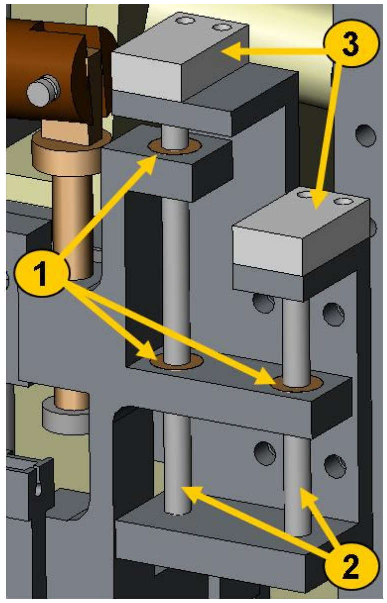


Figure 35 The fourth component of the dog consists of brass bushings (1), stainless rods (2), and Delrin rod caps (3) attached to an aluminum frame.

3.2.5 Moving Mass and Acceleration

One of the primary reasons for the use of the voice coil motors and cable drive system is the need to obtain high accelerations. The motors have the ability to move at high frequency and accelerations but only output up to 10 N of force. Therefore, the total mass and inertia of the system actuated by the voice coil motors must be small. In order to obtain 23 gs of acceleration, the mass must be less than or equal to about 44 grams.

Using a simple model of the system, it is easy to estimate the acceleration. Based on the moving mass associated with the actuator and the rotating mass associated with the translational component, the kinetic energy can be defined as:

$$T = \frac{1}{2} m\dot{x}^2 + \frac{1}{2} I\dot{\theta}^2 \tag{9}$$

I represents the inertia of the dog rotating in the translational direction as in Figure 28. The translational direction is used because it has a greater moment of inertia than the rotational component. θ represents the angle of the dog, x is the position of the motor and m is the total translating mass of the system. Using the relationship between x and θ in equation (3), the kinetic energy can be written:

$$T = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}I\left(\frac{\dot{x}}{R_1}\right)^2 \tag{10}$$

It will be assumed for these calculations that the flexible cable is stiff enough to ignore it as a spring, and it will be assumed that the damping in the system is negligible. Thus, using Lagrange's equations, the equation of motion is merely F=ma:

$$\left(m + \frac{I}{R_1^{\;2}}\right)\ddot{x} = F_{motor} \tag{11}$$

The maximum obtainable acceleration can now be easily obtained. Recall from section 3.2.2 that the actuator has five moving parts: the motor shaft and coil, two aluminum pieces, and two turnbuckles. These are all of the translating masses in the system. The total mass of these five parts, m, is 0.01911 kg. The total inertia of the rotating components associated with the translational direction of the dog is 6.87×10^{-6} $kg.m^2$. Using R_1=0.0234 m, the equivalent mass of the system is approximately 0.0316 kg or 31.6 g. This is about 12 grams lighter than the maximum allowable mass and permits theoretical accelerations up to 32 gs. This margin is useful to account for the assumptions made and machine tolerances, particularly with respect to the radius of the moment arm, R_1.

3.3 Prototype Electrical System and Programming

3.3.1 Prototype Electronics

The servo dog is controlled by a program written in C and run in DOS on a Windows PC. The PC connects to two Mesa 3C20 single axis servo controllers via the Mesa Q422 that converts the RS-232 signal from the PC to the RS-485 signal for the 3C20. A single DB-9 cable connects the PC to the Q422 that connects to both C320s using two RJ-45 cables. Because the two 3C20s share the same serial port, only one 3C20 can send or receive data at a time. The 3C20 allows for a baud rate of 115200. It has ports for motor output and encoder input, as well as 3 analog-in ports and 2 digital inputs. It provides 100 W to the voice coil motor. The motor and encoder ports are used to connect each amplifier to each actuator. Also, one analog-in port is used for the IR reflective optical sensor. The circuit for the optical sensor can be found in Appendix B.

The optical sensor is used to keep track of the sewing needle position. It is mounted on the frame of the dog opposite a thin, reflective aluminum sheet as shown in Figure 19. The aluminum sheet is used to reflect the IR signal when the sewing needle is up. This allows the dog to know when the needle is up, and it is in contact with the fabric, or when the needle is down, and it is not in contact with the fabric. When the needle is down and the IR signal is reflected, the signal to the Mesa amplifier is pulled low. The signal is an analog signal between 0 and 5 V. This is essential to operating the dog in time with the sewing needle because the motion of the dog must be coordinated with the time that it is in contact with the fabric.

Using the signal from the IR sensor, the dog can achieve synchronization with the sewing machine without the need to know the speed of the machine. Therefore, the dog can react to changes in the sewing speed and maintain proper timing. For example, if a straight line is desired, the dog would wait until the IR sensor reads 0 V, meaning that the needle is in the fabric and the dog is above the fabric. The dog would then move backwards a commanded distance. When the needle comes out of the fabric, the IR sensor will read 5 V and the dog, now in contact with the fabric, will then move forward a commanded distance. This cycle can repeat itself indefinitely, moving the fabric forward in a line.

3.3.2 Programming and Control

While the majority of the program controlling the system is written in C, the Mesa amplifiers have their own command set that includes all of the direct commands to the motors, encoders and the analog signal. The C executable was written to govern the serial communication between the PC and the amplifiers and to lay a framework for executing programs written as text files. The programs used the command set for the Mesa amplifiers in addition to some added notation to specify time delays between commands. For an example, see Appendix C.

For initial testing purposes, the commands to the Mesa boards were given a designated time delay between commands in order to establish the timing of the serial communication between the PC and the amplifiers. Between most commands, a 5-ms delay was used. Shorter delays are possible, but as the command sequences grow longer, the communication often falls behind. Backing up in the processing is most likely to occur and easiest to observe when the executable on the PC tries to read responses from the amplifiers, such as the IR sensor voltage. This is likely due to the use of a Windows PC instead of a real-time operating system. When communication loses synchronization due to time delays between commands, the program cannot react properly to the IR sensor readings. Therefore, extra logic was added to guarantee the timing. Every command sent to the amplifiers that pertains to motor control and the reading of the sensor values results in a carriage return from the amplifier. By waiting for the returned character to be received before moving to the next command, the PC can remain in synch with the amplifiers. This allows the servo dog to operate for long durations and still use the IR sensor to coordinate its motion with the sewing needle. The use of the response does not remove the use of manually set time delays. The executable does not look for the response from the amplifier until after the programmed time delay. This allows the programmer to manually add long delays into the program if needed. However, the program can also be run at a higher rate because the time delays can be reduced to less time than the time required to send and receive a signal and the program can rely on the returned signal to operate as fast as possible. Even when utilizing this method, significant time delays still occur when the PC does not read a response from the amplifier as it is sent.

In order to make any desired number of motions, the executable added a jump command to the command list used in the text programs. The jump command loops back through the motion commands and can do so for a programmed number of times. To perform different length motions, the jump commands still have to be written into the program manually, but this could easily be changed by adding logic to the executable that determines the desired position of each move. The jump command is labeled in the sample code in Appendix C.

The programs used for initial testing of dog control capability did not use the jump command. The tests run with the sewing machine did use the jump command. This is simply because the executable containing the jump command would not run on the lab computer but was run on a laptop computer that had limited availability. Instead, every set of motion commands was listed in the text program, resulting in long command lists.

Long time delays between motion commands were used for testing purposes. During initial tests of the dog control, the servo dog was not run with the sewing machine. Instead, the sewing machine was turned by hand. A 4-second delay was added between motion commands to allow time for the sewing machine needle to be moved by hand and for measurements to be taken between moves. These time delays were used only for testing, the dog in general runs using the sewing machine motor.

Although the fabric motion was demonstrated using open loop control, the position of the actuators was accomplished using basic servo control. The chosen control method used was classic PD control to follow a trapezoidal profile. The setup of the PD control and trapezoidal profile was done using the built-in features of the Mesa amplifier. This was sufficient for position control of the actuators. The PD gains were chosen by experimentation, and performance could be improved by employing a more systematic approach. However, the tuning of the gains is not essential to the demonstration of the current prototype.

A given sewing path can be divided into a number of discrete, straight-line paths given in polar coordinates. The dog can readily achieve these paths by moving the fabric a particular distance and rotating it a particular angle. The process of converting a path to a sequence of moves currently is done manually but would not be difficult to automate.

CHAPTER 4

PROTOTYPE TESTING

The prototype actuator has demonstrated the capability of controlling fabric over a closed trajectory. The prototype has also demonstrated the capability to control the fabric in time with the sewing needle at sewing speeds.

A number of tests were carried out to demonstrate the closed loop control of the servo dog using the cable drive system and the open loop control of the fabric. The performance of the dog in each test is discussed. The control of the fabric was possible, but was limited due to lack of feedback. Accurate position control was impossible due to the varied nature of the slip between the dog and fabric. Still, the tests demonstrated that, with position feedback, control of the fabric is possible with the servo dog concept.

4.1 Closed Loop Control of the Dog

The cable drive system has been shown to allow the servo dog to move in the vertical direction while maintaining control of the dog position in both the translational and rotational directions. To demonstrate this ability, the dog was raised and lowered after setting the voice coil motors to hold at the zero position. Figure 36 shows the deviation from that position as the dog is raised and lowered with the needle. The dog starts up, off of the table and at the zero position. The maximum deviation recorded was about 0.02 mm from center. Note in Figure 36 that the deviation of the translational component is significantly higher than the rotation. This is due to the forces placed on the translation component by the spring, shown in Figure 26, as the dog contacts the fabric or, in this case, the table surface. In addition, the cable drive system is capable of controlling the dog movement while the dog is moving in the vertical direction.

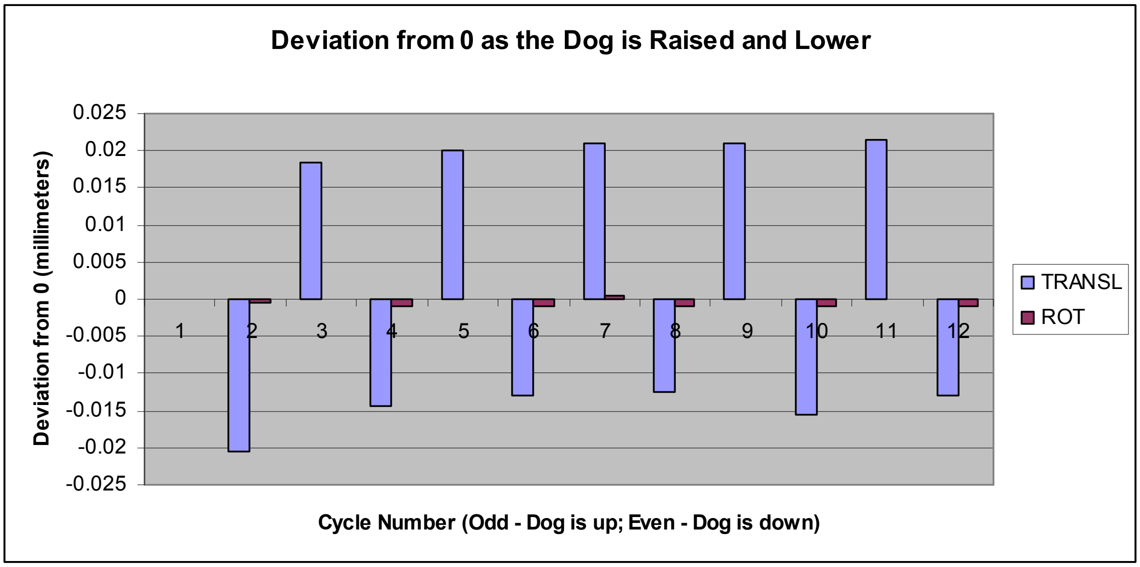


Figure 36 The deviation, based on encoder readings of the actuators corresponding to the two degrees-of-freedom of the servo dog as the dog is moved up and down in the vertical direction. Each number on the x-axis represents either up or down, with odd numbers measured when the dog is up and even numbers measured when the dog is down.

Without any external forces, the servo dog has demonstrated position control. In one experiment, the dog was placed above the fabric and moved 2 mm and 4 mm forward and back in the translational direction as well as 6.875 and 13.75 degrees in the rotational direction. The angles were chosen as they theoretically correspond to 2 mm and 4 mm of travel of the actuator controlling the rotational degree of freedom. The complete results of this test and subsequent tests of the prototype can be found in Appendix D. The percent error between the encoder readings to the desired value was 2.2% and 6.8% for forward and back, respectively, for the 2 mm translation. The 4 mm translation had 1.5% error in the forward direction and 3.8% error back. The rotational percent error from the encoder readings to the desired value was about 4.0% and 9.2% for forward and back of the 13.75^{o} rotation, and 10.9% and 13.2%, respectively, for the 6.875^{o} rotation. These errors can easily be reduced by tuning the PD gains. The angle change of the foot of the dog was measured with a protractor and the percent difference between the measured value and the encoder reading was about 5-6% moving out and about 0.1-0.5% coming back, meaning that the cable drive does not exhibit significant mechanical hysteresis for the rotational degree of freedom. This error is partially due to the reduction in resolution when measuring with the protractor relative to the encoder readings.

4.2 Open Loop Control of Fabric

The motion of the dog was also tested while moving the fabric. A 5x5 inch piece of denim was used for all of the tests and was placed in the same orientation at the start of each test. The dog was moved as before in 2 mm and 4 mm translations towards the needle and back to the starting position and 6.875^{o} and 13.75^{o} rotations counterclockwise and back to the starting position. The motion of the actuator was measured using the encoder readings and the motion of the fabric was measured using calipers and a protractor. Each test was performed twice. The second time, the first motion was away from the needle for translation and clockwise for rotation. This compared the motion of the dog from one direction to the other irrespective of the effect of hysteresis. In other words, in the first test, the dog would move the fabric towards the sewing machine 4 mm and then move it away. In the next test, the dog would move the fabric away from the sewing machine and then back towards.

For translation, the percent errors ranged from about 3% to about 14% for the motion of the dogs and can be found in Appendix D. The percent difference between the fabric displacement and the dog displacement averaged about 25% and showed more slip in moving away from the needle. This is caused by the rotation of the dog lifting the dog off of the fabric. Even though the spring is able to maintain contact, the normal force does change as the dog rotates. If the dog is not moving about the vertical position, then the normal force will be greater when moving fabric in one direction than another.

The percent errors of the encoder readings with respect to the commanded input for rotation can also be found in Appendix D and ranged from about 5% to about 27%. The percent difference between the encoder readings and the rotation of the fabric was about 20% on average, which is evidence of significant slip between the dog and the fabric.

The servo dog is able to move fabric successfully with some significant slip. The slip is largely dependent on the friction coefficient between the dog's foot and the fabric as well as the coefficient of friction between the fabric and the table surface. The coefficient of friction between the dog and the fabric can be adjusted as described above in the prototype section by adjusting the preload in the spring that provides the normal force on the fabric. However, if a different fabric is being controlled, the coefficient of friction will change. Furthermore, the friction coefficient of many fabrics is dependent on the orientation of the fabric. Therefore, the amount of slip from one motion to another can also vary.

To test the ability of the dog to incrementally move the fabric with open loop control, the fabric was translated 12 mm and back using 2 and 4 mm steps. Each test was performed twice, starting in alternating directions. Over the entire 12 mm displacement the percent error ranged from about 1.8% to 10.3% with respect to the encoder positions. The percent error in returning to the original position ranged from 2.5% to 9.3% showing no hysteresis with respect to the actuator. The translation of the fabric was difficult to precisely measure as each translation also resulted in a slight rotation ($\sim 1^{o}$) of the fabric so that the fabric was no longer parallel to the reference position. This rotation is caused by a number of factors. The surface types of the sewing machine and the table are wide-ranging, resulting in uneven friction forces on the fabric. Also, as the dog lifts up, it actually disturbs the fabric slightly. This is likely due to the added sandpaper causing the dog's foot to be unbalanced. To compensate for this rotation, the fabric was measured at two corners and the center along one edge, and the three values were averaged. The percent difference between the fabric motion and the actuator motion was about 24% on average and was not significantly different in either direction. The percent difference for the 4 mm steps was about 5-10% less than for the 2 mm steps.

Likewise, with rotation, the fabric was rotated 41.25^o and back using 6.875^o and 13.75^o steps, with each test performed twice, starting in opposite directions. The percent error ranged from about 6.5% to 19.5% error in both directions based on the encoder positions. The percent difference between the actuator position and the measured angle was significantly different for each direction. When rotating the dog clockwise, the percent difference was about 9.4% on average. Rotating counterclockwise, it was about 31.7%. This demonstrates the complexity of fabric properties with respect to its friction coefficient and confirms the need for feedback control.

The servo dog is able to move the fabric in two degrees of freedom over a closed trajectory. To visually demonstrate the trajectory control of the dog, a mark was placed between each motion at the same point relative to the dog as shown in Figure 37. This created a visual recording of the dog's motion, recording both the incremental motion and the overall trajectory. Using this method, the dog's ability to move the fabric in a straight line and arc was demonstrated. The accuracy of the motion varied as shown in Figure 38.

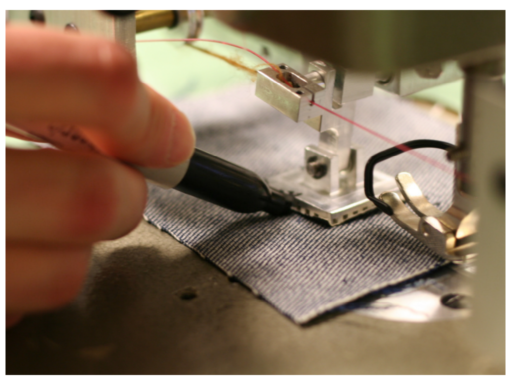


Figure 37 A mark was placed on the fabric between each motion of the dog to record the trajectory of the fabric.

In order to further determine the control of the servo dog, different test trajectories were recorded using the method described above. Two test trajectories are shown below in Figure 38 and Figure 39. The control is entirely open loop with respect to the fabric position. Although the control is open loop, some test runs were used to correlate the commanded position to the motion of the fabric. A major correction that was made was the addition of a slight rotation during each translation. As mentioned previously, the fabric tends to rotate slightly each time it is translated. The added rotation attempted to counter this tendency. The effectiveness of this addition can be evaluated by examining Figure 38. The first line was able to track more or less straight. After the left turn, a slight curve to the line can be seen. After the right turn, the final straight line exhibits a more significant curve. This shows the effect of direction on the slip of the fabric.

Attempts at following a closed trajectory confirmed the need for feedback control of the fabric position, primarily to account for fabric slip at the point of contact with the actuator. This can be seen in Figure 38 where the final straight line is not at a perfect ninety-degree angle to the vertical line and also in the varied lengths of each motion, even though the motions were programmed to be the same length. It also shows the effect of the dog position on the fabric sheet and the resulting amount of slip. If the dog is pushing the fabric on the left side of the fabric, the fabric will be more likely to rotate to the right. In spite of this, even though the dog makes two turns and moves a couple of inches down the fabric, it maintains the general trajectory of the fabric with some error.

The circular trajectory further demonstrates the ability of the servo dog in open loop control. The trajectory to be followed was a 360^{o} arc of constant radius. As can be seen in Figure 39, the dog was able to complete the trajectory and finish at the same point at which it began.

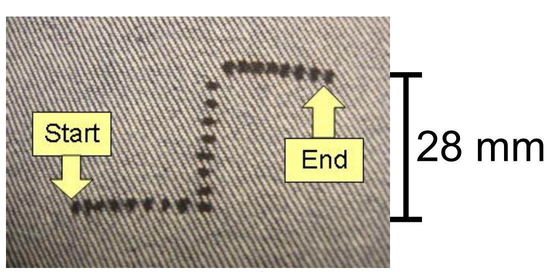


Figure 38 Trajectory showing two 90^{o} turns, one left and the next right

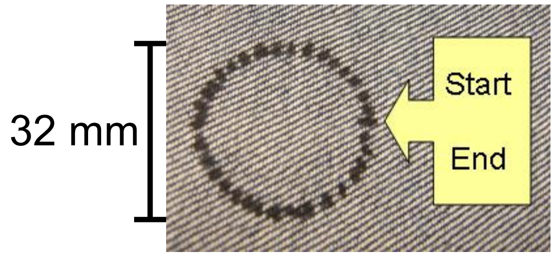


Figure 39 A circular trajectory with the endpoint being the same as the starting point

4.3 Control in Time with the Sewing Machine

In order for the servo dog to be able to control the fabric and stay in time with the sewing needle, it must be capable of high accelerations. The cable drive system coupled with voice coil motors has proven to be a useful method by which to perform high acceleration tasks with multiple degrees of freedom. The acceleration of the dog was tested using the PCB 303A02 accelerometer, which provides a resolution of 0.01 gs at 10 mV/g and a maximum acceleration of 500 gs at a frequency range of 1 to 10,000 Hz. The accelerometer was mounted to the actuator as shown in Figure 40 using mounting wax provided for the accelerometer. Acceleration was measured for both degrees of freedom with the dog above the fabric. It was also measured with the dog moving fabric of a known mass.

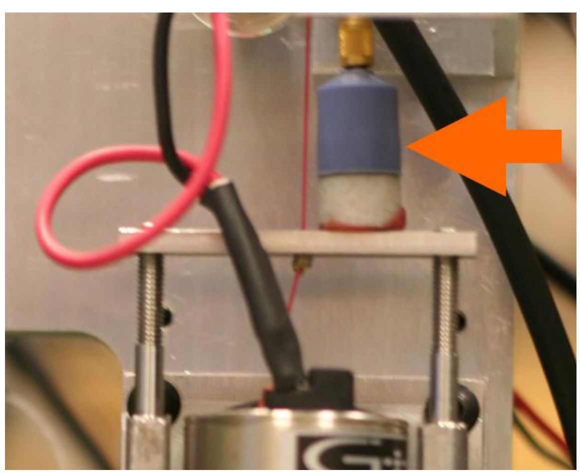


Figure 40 The accelerometer highlighted in the figure was attached, using wax, to an aluminum bar on the actuator to measure the accelerations of the actuator.

Measured accelerations reached approximately 27 gs, without taking into account the mass of the accelerometer, 5 grams. Assuming an ideal controller, 27 gs of acceleration would result in nearly 5.460 stitches per minute. No noticeable resonance has been observed over the operating frequencies.

The servo dog finally was operated using the sewing machine to cycle the dog and using the reflective optical sensor to determine the needle position. The sewing speed was measured with a tachometer. The servo dog was able to control the fabric in time with the sewing machine at sewing speeds up to 500 stitches per minute. The limiting factor to the rate at which the dog could keep up was the serial communication and the processing of the commands by the Mesa amplifiers. Five commands are required to be sent to the amplifier from the PC for each motion, in addition to the commands needed to read the analog voltage from the optical sensor. The servo dog itself, in fact, is capable of much higher sewing speeds based on measured acceleration. If the computation and communication time can be reduced, then the sewing speeds could be increased.

4.4 Conclusions

The prototype of the servo controlled sewing dog demonstrated the capabilities of the cable drive system to allow the voice coil motors to control the dog, even as the dog is moving perpendicular to the forces applied by the motors. Closed loop control also was demonstrated. Control of the fabric through different trajectories was performed without the use of feedback. Noticeable slip showed the need for feedback control. The prototype also demonstrated the ability to move in time with the sewing machine and to control the fabric in time with the sewing machine.

CHAPTER 5

FABRIC EXPERIMENTS

5.1 Motivation

The complex material properties of fabric present a key challenge for designing an automated sewing device that is not present in designing other types of robotic handlers. For example, during the sewing task, fabric can buckle due to in-plane compression or due to tension [20]. Fabric buckle results in lower quality seams and loss of fabric control by the manipulator. While buckling due to compression and tension has been thoroughly studied per unit width, the deformation of the width of the fabric given an input, such as with a dog, has not been examined. A second key property of fabric that needs to be examined is the deformation of fabric being moved relative to a second sheet of fabric while the two sheets are in contact with one another. Past research in automated garment manufacturing has dealt only with control of one sheet of fabric. Therefore, the dynamics involved in translating one sheet relative to another during the sewing process have not been investigated.

In the case of automated sewing, as proposed by this thesis, it is necessary to examine the way in which fabric deforms a certain distance to the side of the point of actuation in order to be able to design a flexible device. Does the fabric bend in plane or buckle out of the plane? Is it possible to "correct" any deformation if it is detected? The answers to these questions currently are not well understood. Thus it seemed beneficial to identify the failure mode of the fabric for the given circumstance and to determine whether the error can be corrected.

As noted, another unique challenge presented by fabric's mechanical properties is the control of two sheets of fabric lying on top of one another. In the task of sewing, two sheets of fabric are joined together and transition from being separate to being a joined body. One experiment examined the extent to which the two sheets, after being sewn together, must be considered a single body, or whether they can still be independently articulated. It was possible that there is enough flexibility in the stitch to allow the fabrics to be independently articulated.

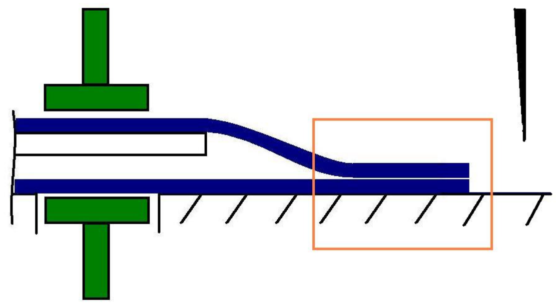


Figure 41 The fabric is briefly in contact before being sewn together as highlighted in orange even with the use of a thin metal plate to separate the two plies.

Before the fabric is sewn together, there is a period of time during which a given length of fabric is placed on top of another sheet of fabric off the edge of the plate as pictured in Figure 41. It is useful to understand how the fabric deforms in this situation, when it lies on top of another sheet, and how it fails. It is also important to know whether the position or orientation of one sheet of fabric can be changed relative to another sheet without affecting the other sheet. During the sewing operation, even when both sheets of fabric are commanded to move in the same trajectory, the two sheets in reality will not follow the same exact path due to factors like slip between the servo dog or budger and the fabric, or friction between the fabric and the table surface. This is the reason for feedback with the vision system, and also is important in determining whether each sheet of fabric can be independently controlled to correct relative errors detected by the vision system. In other words, if two sheets are both rotated through an angle θ, they will actually each rotate θ-e_1 and θ-e_2 and will not be at the same orientation. Therefore, during the next motion, the two sheets will need to be given different inputs in order to move relative to one another. Thus, it is necessary to independently control each sheet of fabric simultaneously even though the two sheets are in contact with one another.

Given these factors, three sets experiments were undertaken – one to examine the reaction of a fabric's width given a translation, another to examine the effect of fabric being translated relative to a fixed sheet when the two sheets are in contact, and a third to examine the effect of translating fabric sheets relative to one another after they are sewn together.

5.2 Experimental Test bed

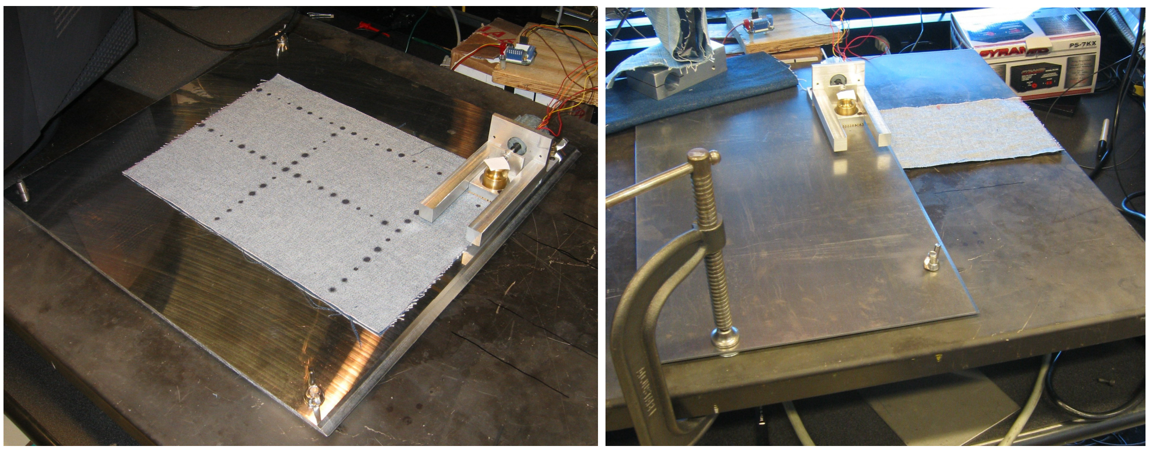


Figure 42 The experiment test bed with the aluminum plate for the first set of experiments (Left) and with the steel plate for the second and third set of experiments (Right).

A test bed, shown in Figure 42, was created because of the difficulty of mounting a camera on the servo dog prototype to measure the gross fabric motion, as well as the prototype's lack of closed loop control at the time the experiment was undertaken. This is unrelated to the thread-level vision system proposed to be used with the dogs as that will measure threads of fabric near the needle, not fabric deformation over the entire sheet. In addition, the prototype was set up to control one sheet of fabric, while two sets of the experiments used two sheets separated by a plate. Considerable rebuilding would have been necessary to modify the prototype, which at the time the experiments were performed, was still under construction. Therefore, a simple test bed was constructed to reduce extraneous variables and for ease of measurement.

The test bed consists of four primary components. The first is the plate. Two different plates were used. A large aluminum plate was used for the single sheet experiments because of its size, its relatively large coefficient of friction despite being a smooth and level surface, and its reflective surface provided good contrast for the vision system. A smaller steel plate was used for the two sheet experiments because it was half the thickness of the aluminum plate, reducing the vertical drop of the top sheet off of the edge of the plate, and was still adequately flat and stiff. Both plates were secured onto an epoxy table surface and were raised from the surface using a set of washers. For the experiments using fabric underneath the plates, the washers provided the clearance needed for the fabric to slide under the plate. Wing nuts were used to hold the plates down when the dog underneath the plate pushed the fabric up against the bottom surface of the plate.

The second component is the mock up of the servo dog underneath the plate, shown in Figure 43. The dog replicates the servo dog that would control the bottom sheet of fabric by pushing it up against the lower surface of the plate. The mock up was made of aluminum and was bolted to the bottom of the table with springs between the table and the bolt heads to provide a constant and adjustable force pushing the fabric against the bottom of the steel plate. It was used to hold the bottom sheet of fabric in place in the same way that the real servo dog would in the final design.

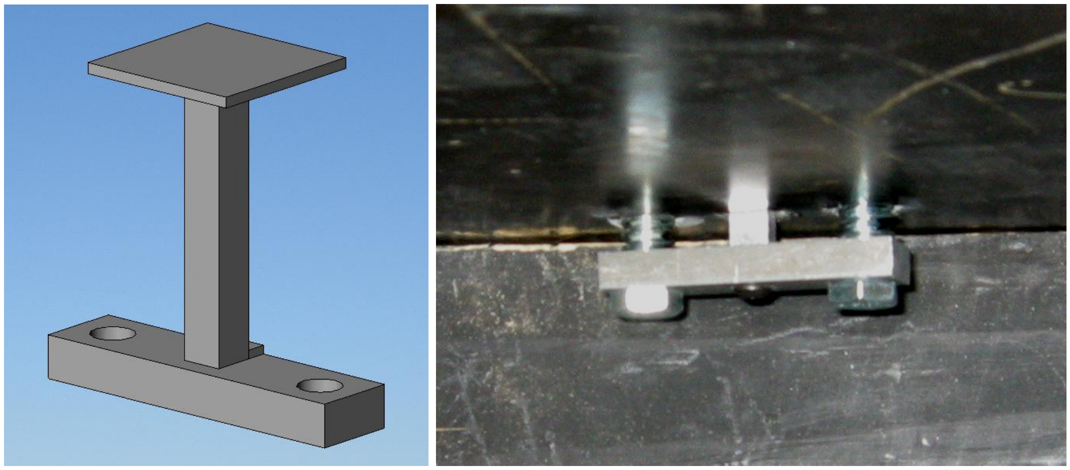


Figure 43 A CAD model of the dog mock up that holds the bottom sheet of fabric to the steel plate (Left). A photo of the mock up underneath the table (Right). Note the springs between on the bolts that provide a constant, adjustable force. By screwing in the bolts, the dog can be used to clamp the fabric against the steel plate.

The third component is a different mock up of the servo dog shown in Figure 44. It replicates the function of the servo dog that controls the top sheet of fabric. It consists of a stepper motor, a mount, two bearing surfaces, a foot mock up and the stepper motor controller attached serially to a PC. The stepper motor used is a Thomson Airpax Mechatronics Digital Linear Actuator with a maximum travel of 2.5” and 0.001” per step. It was chosen based on availability, stroke length, position resolution, and ease of position control. The bearing surfaces were added after it was noticed that the dog did not track straight when moving larger sheets of fabric as the fabric created a force on the dog perpendicular to the motion. The bearing surfaces are two long aluminum pieces seen in Figure 44 that straddle the dog’s foot. The dog has a foot with a 1.5” area face instead of the 1” face on the prototype to permit the addition of a small weight to provide the normal force necessary to reduce the slip between the dog and the fabric. The weight is the brass piece in the figure with a sheet of paper taped to the top for the purpose of reducing noise in the image processed by the vision system. As with the prototype, 220 grit sandpaper was secured to the bottom of the dog to increase its coefficient of friction with the fabric. The controller used for the motor was an All Motion EZ Stepper Controller and Driver that was powered by a 30 Volt power supply.

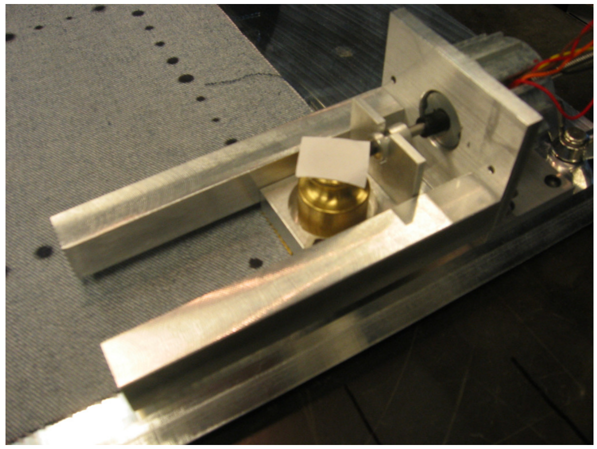


Figure 44 The mock up of the servo dog to control the top sheet of fabric.

The final part of the test bed is the vision system that measures the fabric movement. The camera is a National Instrument's (NI) 1722 Smart Camera and is programmed using NI's Labview with the Machine Vision Toolbox. The program was used first to calibrate the images and then to detect small black dots on the fabric using a threshold in a given bounding box that could be changed by the user in real time. By tracking the position of the dots, a map of the motion and deformation of the fabric could be created. For more on the vision program see Appendix E.

The dots on the fabric were created using an aluminum stencil and were made in different sizes to easily distinguish one from another. The dots were made 2/3" apart in one or two straight lines that were perpendicular to each other. The lines of dots were made perpendicular to record data over an area of the fabric without requiring the measurement of too many dots. The stencil and an example of the dot pattern are shown in Figure 45.

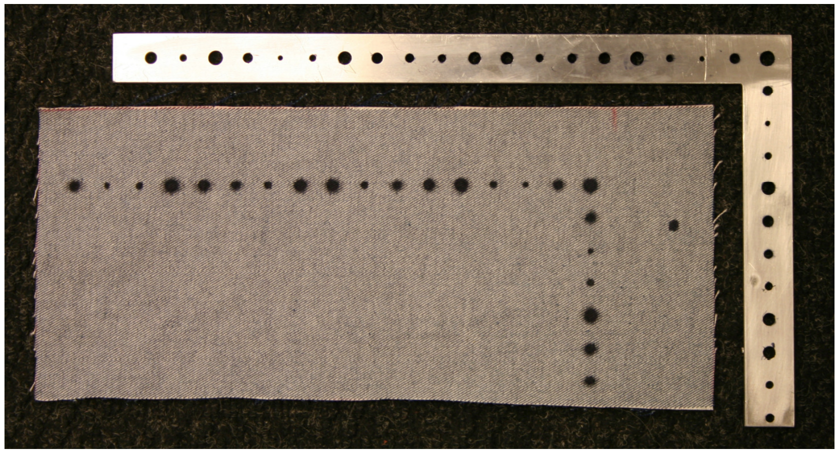


Figure 45 The stencil used to make the dots on the fabric is shown around a sample piece of fabric with the dot pattern. The dot on the far right of the fabric was used to compare the motion of the fabric immediately in front of the dog.

5.3 Experimental Procedure

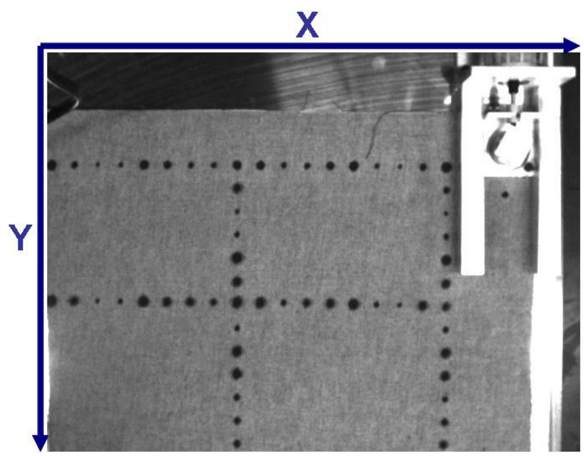


Figure 46 The dog and fabric at the initial position for the first set of tests as seen from the NI Smart Camera. Note that this sheet of fabric is unique in that it has two rows of horizontal and vertical dots. This was the only such test performed. The axis represent the coordinates as perceived by the camera and also the plots used for analysis.

For the first set of experiments, the fabric was translated a given distance and then returned to its original position using the stepper motor dog to move the fabric on the aluminum plate. The dog was placed along one edge of the fabric as shown in Figure 46. The dog was then translated in ½ inch increments four times for a total of 2 inches. Five measurements were taken on the way out, including one at the furthest distance, and four more on the way back. This process was done on a single type of fabric, denim, and completed for several different lengths and widths of fabric. Twelve different tests were performed with fabric having one horizontal row of dots and one vertical row of dots. A final experiment also was performed with two rows of dots in each orientation. A complete list of all the experiments can be found in Appendix G. The large, ½ inch increments were used so that fabric deformations would be easily observable. Using increments on the order of millimeters to move the 2 inches resulted in much larger position errors and resulted in the same types of deformations as those observed for ½ inch increments.

The set of experiments using multiple sheets of fabric was performed in much the same way except that a steel plate was used in place of the aluminum plate. In addition, the fabric sheets were smaller because of the much higher friction forces involved. A single ply was placed a known distance off of the edge of the steel plate and was moved, as with the previous experiments, up to 2 inches out and then back. The experiments and fabric sizes also can be found in Appendix G. This was first done with the sheet hanging off of the steel plate onto the bare epoxy table surface. Then, a second sheet was placed underneath the steel plate with its edges aligned with the top sheet, and was held in place by the mock-up of a dog underneath the plate. The top sheet was moved as before so that the motion of the fabric could be compared with the test performed with the sheet on the epoxy table. In this set of experiments, the fabric was 6 inches long, with varying widths. The distance that the fabric hung off of the steel plate also varied. The detailed experiments and fabric sizes are also in Appendix G.

The final set of experiments tested the hypothesis that there is enough flexibility in the stitch to be able to independently control each sheet of fabric. Two sheets of 4.5 x 9 inch denim were sewn together using a 3 inch stitch along the 9 inch edge in the corner of the fabric. The bottom sheet of fabric was held in place underneath the steel plate using the bottom dog as shown in Figure 47. The top sheet of fabric was first translated 1 mm out, then back to its starting position, and then 1 mm in the opposite direction and back to the starting position. The same cycle was then repeated with 2 mm and 4 mm motions. Each test was performed with the seam placed different distances from the edge of the steel plate.

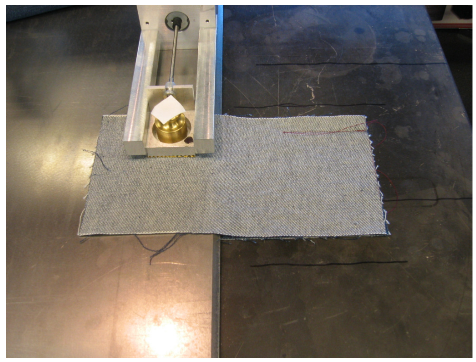
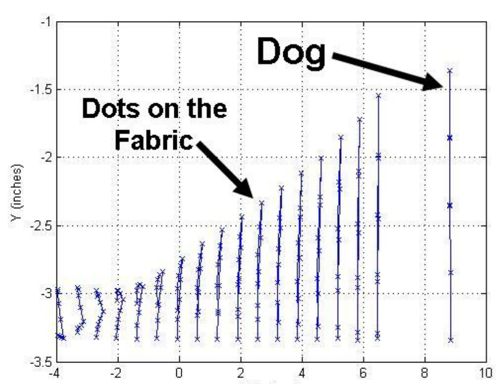


Figure 47 Two sheets of fabric were sewn together 3 inches along an edge as would be done on a standard seam. The top sheet was translated by the top dog while the bottom sheet was held in place by the bottom dog.

The data was analyzed using Matlab to produce meaningful plots. Examples of the code used for the data analysis can be found in Appendix F. A plot of the raw data from the machine vision program can be seen in Figure 48. The data was reordered so that the horizontal and vertical rows of dots could be fitted with a regression curve and a plot was made of the error between the estimated line and the data. A plot was also made of the slopes of the regression lines. Finally, the displacement of each dot was plotted in both the x and y directions.



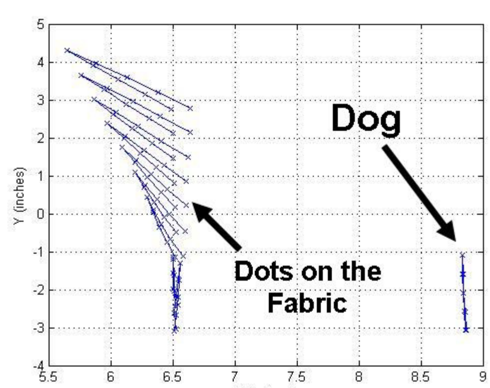


Figure 48 Data of the motion of the horizontal row of dots and the dog (Left). Data of the motion of the vertical row of dots and the dog (Right)

5.4 Results and Discussion

5.4.1 Experiment I: Fabric on Aluminum

A typical motion sequence can be seen in Figure 49. Each test resulted in one of three outcomes: either the fabric buckled at the corner of the dog and continued to buckle as it was further displaced as in Figure 49, or the fabric buckled during the first few displacements and then maintained its shape as it was further displaced, or the fabric moved without deforming through the entire path. In the cases where the fabric did deform, the only significant deformation was at the corner of the dog where the fabric buckled. The rest of the sheet of fabric was not deformed. This was shown in Experiment 13 (see Appendix G).

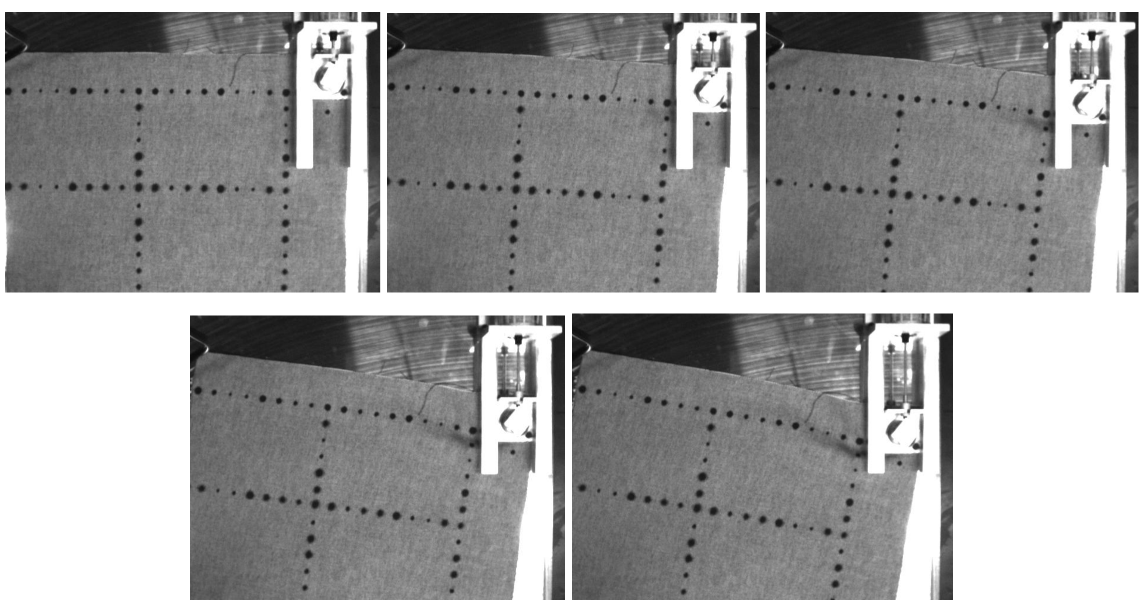


Figure 49 Still shots from the NI smart camera of Experiment 13. The fabric increasingly buckles from the initial position (Top left) to the final position (Bottom right). Images are not shown of the dog returning to the original position.

Experiment 13 used a 10 x 14 inch sheet of fabric with two sets of horizontal and vertical lines as in Figure 49. As the fabric was translated, the angle between the lines did not change significantly. Figure 50 shows a plot of the angle between the horizontal and vertical lines. Notice that the angle between the lines is nearly 90^o at the start of the motion and remains nearly 90^o for the entire motion out and back. The maximum angle change is 0.83^o compared to the angle change of the dot lines, which is about 9.5^o from the starting horizontal and vertical positions. Also, it is worth noting that the angle change is greatest when looking at the angle between Horizontal 1 and Vertical 1 because these are the dot lines closest to the dog. The angle between Horizontal 2 and Vertical 2 remains the same angle. These are the dot lines furthest from the dog. The larger angle change is thus explained by the deformation of the fabric near the dog. As the fabric buckles, the dots near the dog are displaced relative to the rest of the line, changing the angle of the line with respect to the horizontal.

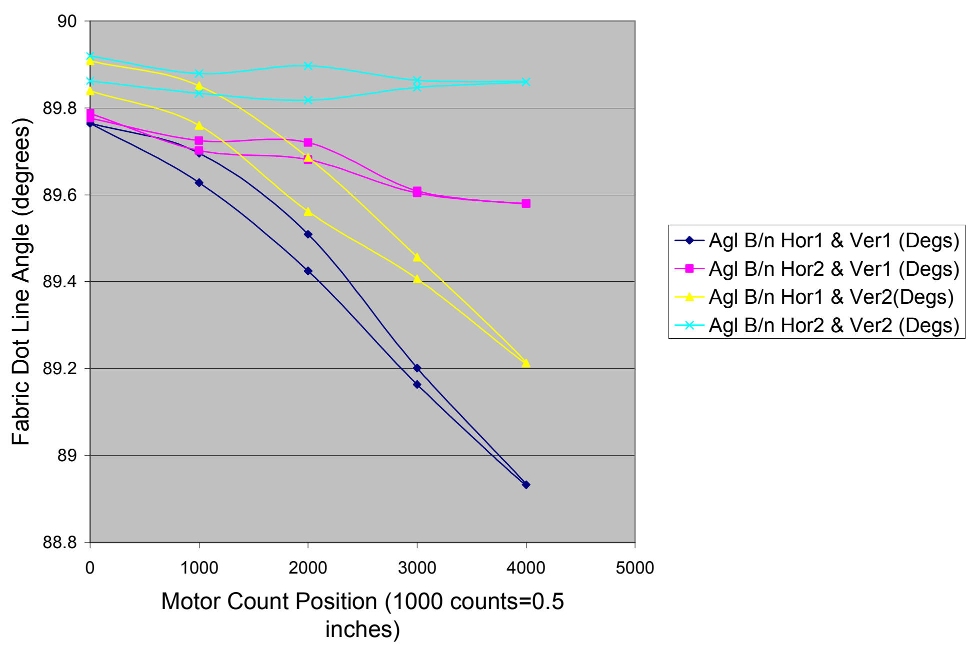


Figure 50 The angle between the rows of dots as the fabric is displaced by the dog. Hor1 and Ver1 correspond to the rows of dots that are beside the dog. Hor2 and Ver2 correspond to the rows of dots that are halfway between the dog and the far edge of the fabric.

In spite of this change, the dot lines, both horizontal and vertical, maintain a linear slope throughout the motion, providing further evidence that the fabric does not measurably deform away from the dog. The profile of both the horizontal lines and vertical lines remains linear even as the fabric deforms. This can be shown by fitting regression lines to the dot values in the x-y plane and by looking at the error in the regression lines. Examples are shown below for the horizontal lines, Figure 51, and for the vertical lines, Figure 52, and others can be found in Appendix G. The maximum error occurs on the dot nearest the dog and at the farthest position, 2 inches, from the initial position, confirming the earlier statement that the buckling is primarily near the dog. This buckling causes the dots near the dog to displace relative to the rest of the dot line. The dots away from the dog remain in a line because the fabric does not deform away from the dog.

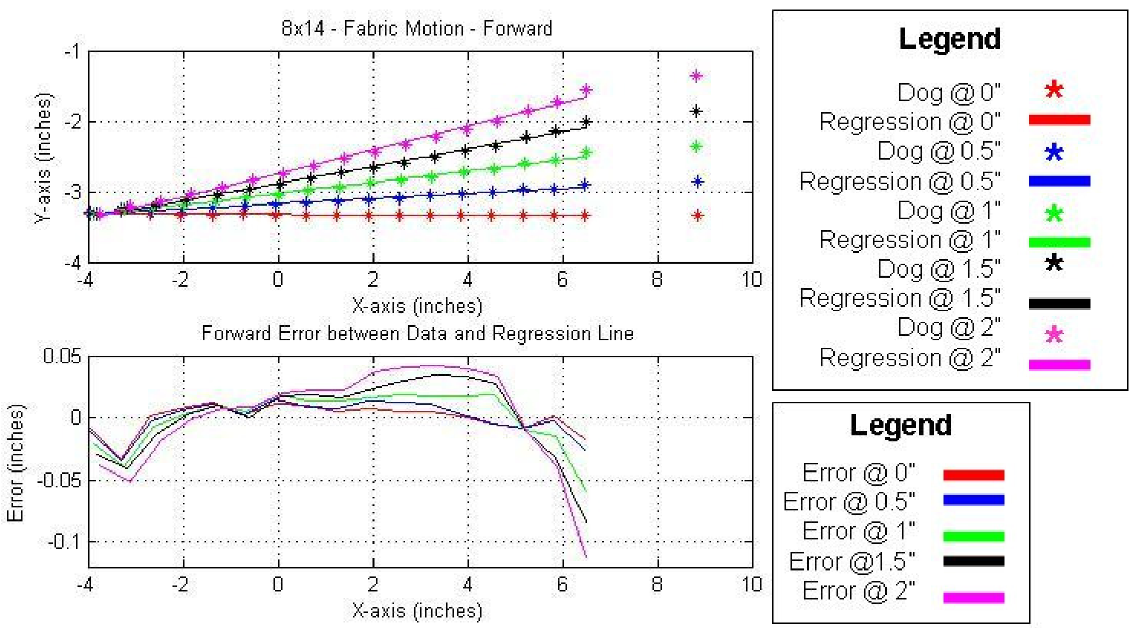


Figure 51 The top graph shows the horizontal row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

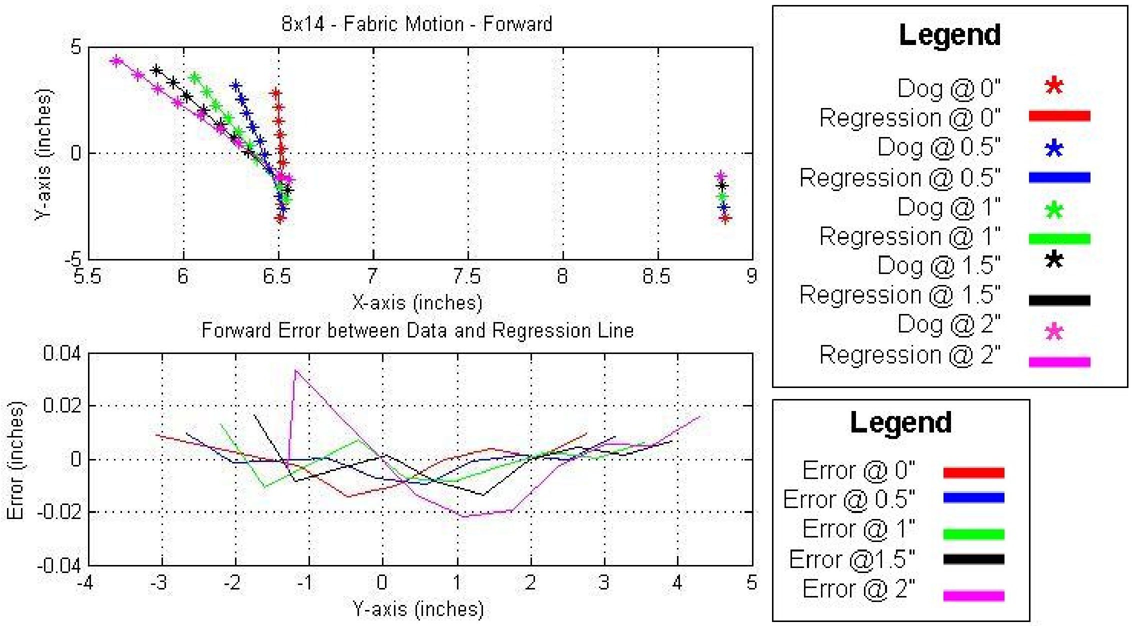


Figure 52 The top graph shows the vertical row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

In addition to linearity, further information can be gained from looking at the slopes of the regression lines. If the slopes of the regression lines are plotted as in Figure 53, a couple of observations can be made. First, the change in the slope of the dot line is linear. In other words, the rate of change of the dots is proportional to a constant. Therefore, for a given dot translation, knowing the slope of the dot line, one can find the position of any point on the fabric along that line. Given a further displacement, one can predict the displacement of any point along the line. This suggests that it would be possible to control a point on the fabric a given distance from the dog for a known size of denim.

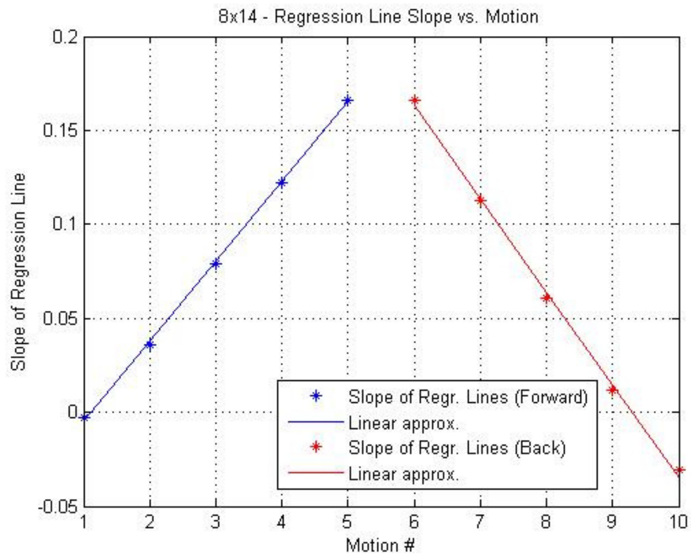


Figure 53 The slopes of the regression lines follow a linear pattern. The blue line represents the motion of the fabric while the dog moves out. The red line represents the motion of the dog moving back to the initial position.

A second observation is that the profile of the slopes is linear both as the fabric is pushed out and as it is brought back. Looking more closely at the slopes of the regression lines of the slopes of the dot lines, or the rate of change of the slopes of the dot lines, reveals that the fabric deforms more quickly as it is pulled back than as it is pushed forward. This is a result of hysteresis in the buckling phenomenon as numerically demonstrated in Table 1. This is an important observation when considering the desired task of flattening fabric when it buckles. If a movement of the dog causes the fabric to buckle, it would be expected that the same movement in the opposite direction should return the fabric to its original position. However, these results show that the movement should be in the opposite direction and should be a shorter displacement in order for the fabric to return to its undeformed position. In other words, fabric buckling demonstrates significant hysteresis that would have to be accounted for in control. Furthermore, note that the linear relationship between the change in the slope of the dot lines and the motions of the dog only occurred in the experiments where the fabric was large enough to cause the fabric to buckle more with each motion.

Other experiments resulted in no change at all in the slope of the regression lines of the dots. As can be seen in Table 1, in these experiments the fabrics were 4.66 inches wide in addition to the 3 x 9.33 inch sheet. If the fabric was narrow enough, then the fabric would not deform at all as it was displaced because the inertial and friction forces that caused the deformation did not place a moment on the fabric large enough to overcome the fabric's stiffness. Experiment 6 provides a good example, shown in Figure 54. Using a 3 x 4.66 inch sheet of fabric, the fabric moves exactly as the dog does, as if it were a rigid body attached to the dog. Therefore, the slope of the dot line does not significantly change as the fabric is translated.

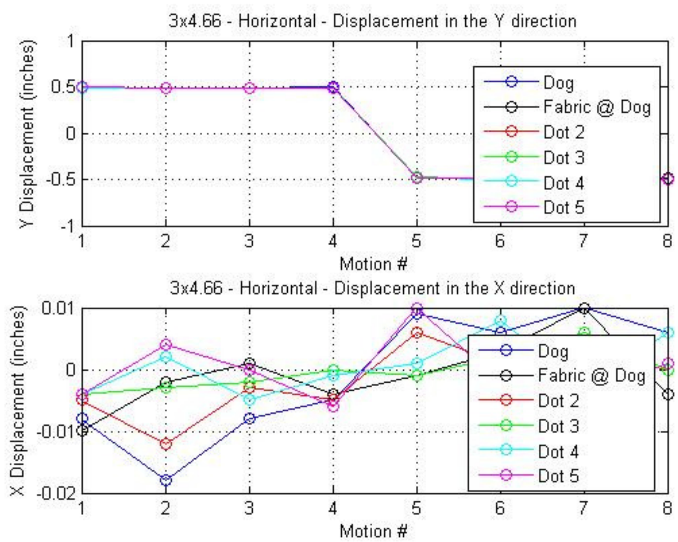


Figure 54 The displacements of the dog and 3x4.66" fabric dots for each motion of the dog. The top graph shows displacements in the y direction. The bottom graph shows displacements in the x direction.

Table 1 The slope of the slopes of the dot lines is listed for both the Horizontal and Vertical dot lines. Notice that the magnitude of the slopes back is greater than the slopes out. NL=Nonlinear Curve; NC=No Change in slopes; NA=Not Available.

		Horizontal		Vertical	
Exp. #	**Fabric Size**	**Slope Out**	**Slope Back**	**Slope Out**	**Slope Back**
1	8x14	0.0424	-0.0495	-0.0391	0.0455
2	8x9.33	NL	NL	NL	NL
3	8x4.66	NC	NC	NC	NC
4	3x14	0.0388	-0.055	NA	NA
5	3x9.33	NC	NC	NA	NA
6	3x4.66	NC	NC	NA	NA
7	6x14	0.0412	-0.0663	NA	0.0491
8	6x9.33	NL	NL	NL	NL

9	6x4.66	NC	NC	NC	NC
10	8x14	0.0407	-0.0484	-0.0399	0.0482
11	8x9.33	NL	NL	NL	NL
12	8x4.66	NC	NC	NC	NC
13a	10x14	0.0418	-0.0468	-0.038	0.0446
13b	10x14	0.0389	-0.0438	-0.0389	0.0454

The more interesting cases are where the fabric deforms slightly. In those cases, experiments 2, 8, and 11, the fabric deformation was not proportional to the dog displacement. This can be seen in Figure 55. However, this was the result of the fabric reaching its maximum deformation for a given force. Notice that the changes in the slopes in Figure 55 are less than 5% of the total displacement of the fabric. The fabric remains mostly horizontal, as seen in Figure 56, but does deform more during the first displacement than during subsequent displacements. The deformation also can be seen in Figure 57. Notice that the displacement of each dot converges to the displacement of the dog as the number of motions increases. This is analogous to pushing a spring attached to a mass. As the spring is pushed, it deflects a certain distance until the spring force is balanced by the kinetic friction force. Similarly, as the fabric deforms, it stiffens and eventually the stiffness of the fabric approaches the friction and inertial forces that cause the deflection, and thus the amount of deformation levels out.

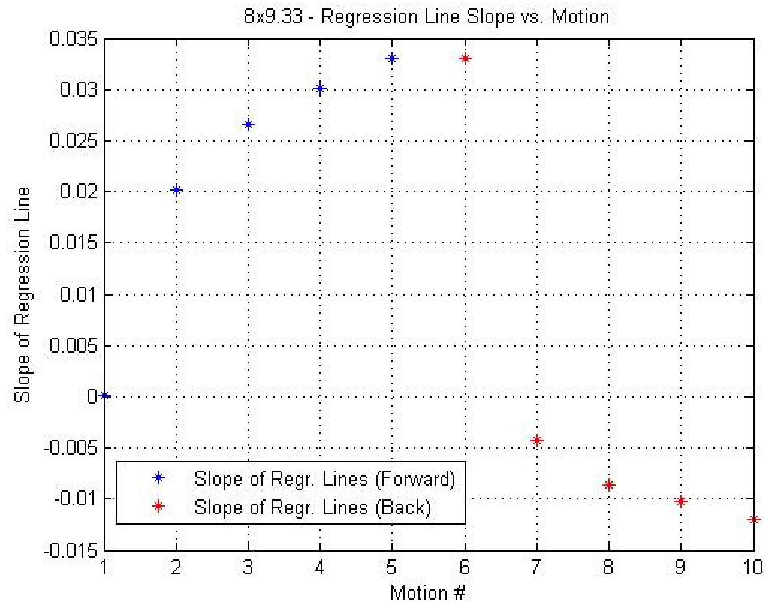


Figure 55 For the fabrics tested that were 9.33" wide with the exception of the 3x9.33" sheet, the relationship between the amount of deflection and the input displacement is nonlinear.

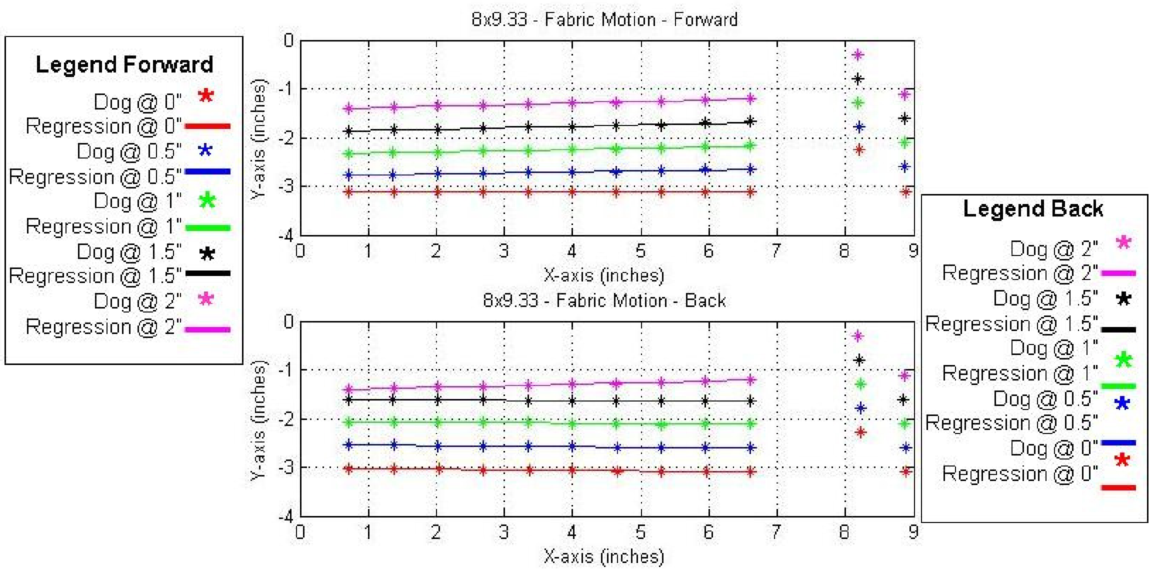


Figure 56 The top graph shows the motion of the fabric being pushed forward. The bottom graph shows the motion of the fabric being pulled back. Notice that during the first motion of each, particularly when being pulled back, the slope of the line of dots changes the most. The later motions do not have as significant an effect on the slope of the lines.

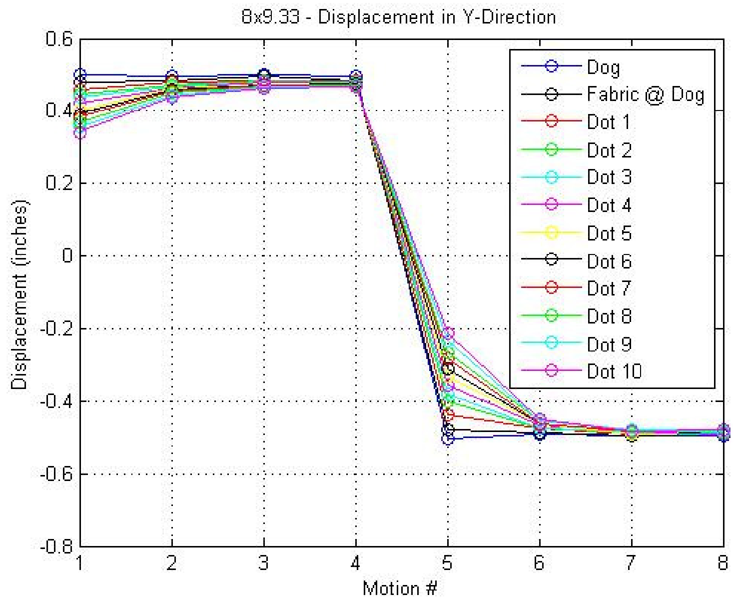


Figure 57 The displacements in the y direction also demonstrate the nonlinear relationship because the magnitude of the displacement of each dot is varied most during the first motion and during the fifth motion, which is the first motion of the fabric being pulled back.

5.4.2 Experiment II: Fabric on Fabric

Each test involving two sheets of fabric also was done with the top sheet placed on the bare table surface. Even with the largest sheet of fabric tested, shown in Figure 58, the fabric did not significantly deform due to the lower coefficient of friction of the epoxy table relative to the aluminum surface used in the first set of experiments. The displacement of the horizontal row of dots in the y direction can be seen in Figure 59. A complete list of the results from the experiments is in Appendix G. Notice that, as in the experiments with the fabric on the aluminum surface, the fabric deforms slightly during the first motion and little during subsequent motions. The other fabric sizes exhibited even less deformation where the fabric was placed on the table surface rather than the aluminum surface. The behavior of the fabric hanging off of the steel plate is the same as the behavior of the fabric on the aluminum plate.

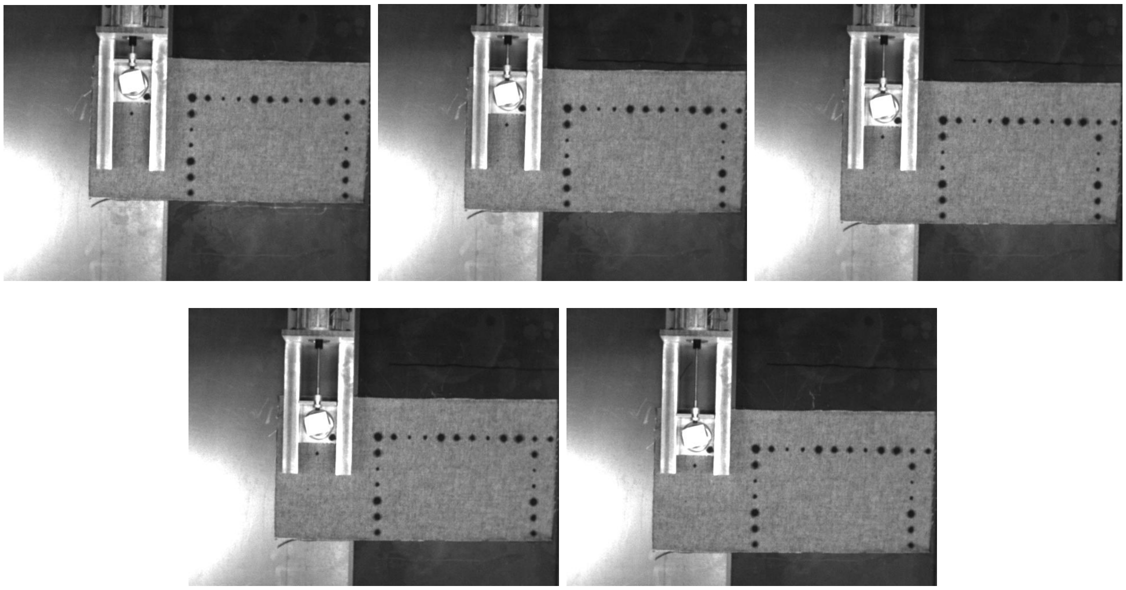


Figure 58 Experiment 14 with the fabric lying on the table resulted in no significant deformation of the fabric from the initial position (Top left) to the outermost position (Bottom Right).

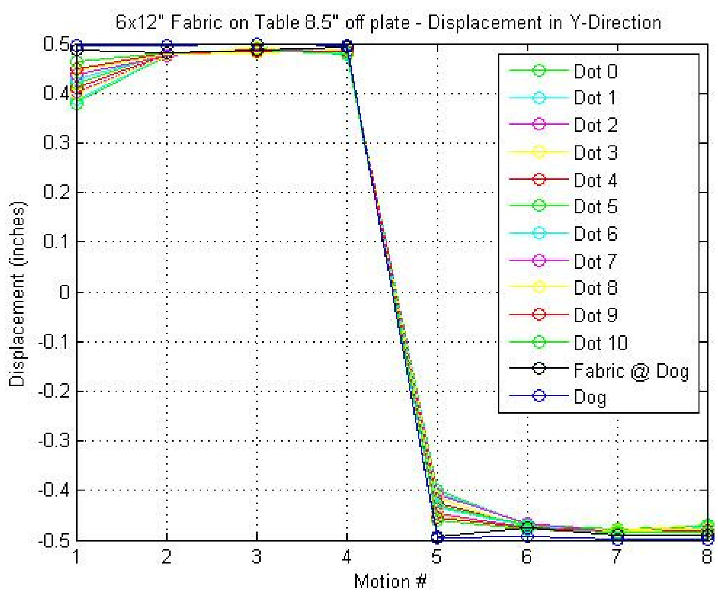


Figure 59 The displacement, in the y direction, of the horizontal row of dots on the fabric being translated while hanging off of the steel plate onto the table.

The experiments conducted with the top sheet of fabric lying on another sheet of fabric that was held by the dog underneath the steel plate showed significant deformation as in Figure 60. In fact, the deformation was much more significant than for the fabric on the aluminum plate described in the first set of experiments. In Figure 60, even as early as the second displacement, a second buckle forms in the fabric at the corner of the dog. This second buckle was not seen in any of the experiments performed on the aluminum plate. Furthermore, the rate of change of the slopes of the dot lines, shown in Table 2, is as much as 60% greater than that of the fabric on the aluminum plate, even for smaller fabric sheets.

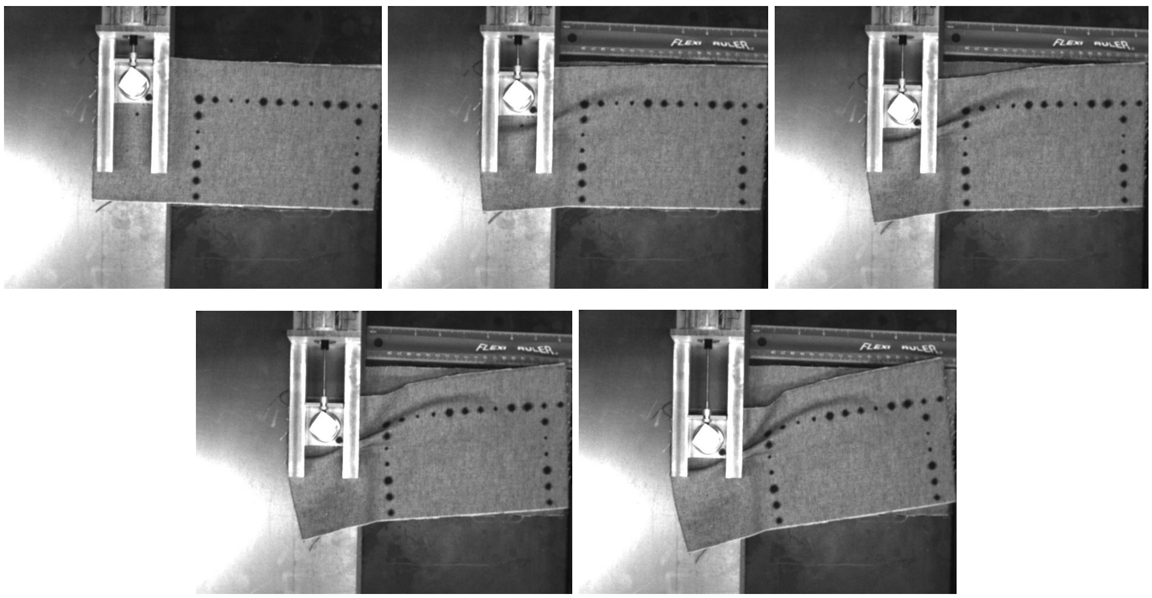


Figure 60 Experiment 14 with the fabric lying on the table resulted in significant deformation of the fabric from the initial position (Top left) to the outermost position (Bottom Right). Also note that the lower sheet of fabric did not displace.

Table 2 The slope of the slopes of the dot lines is listed for both the Horizontal and Vertical dot lines. Notice that the magnitude of the slopes back is not significantly greater than the slopes out. The experiments ending in E are the experiments with fabric lying on the epoxy table. Experiments ending in F are ones in which the fabric lies on a second sheet. 14F1 corresponds to the second row of vertical dots as in Figure 60.
NL=Nonlinear Curve; NC=No Change in slopes; NA=Not Available.

		Horizontal		Vertical	
Exp. #	Fabric Size	Slope Out	Slope Back	Slope Out	Slope Back
14E	6x12	NL	NL	NL	NL
14F	6x12	-0.0607	0.0616	0.051	-0.0512
14F1	6x12	NA	NA	0.0497	-0.034
15E	6x9	NL	NL	NA	NA
15F	6x9	-0.0835	0.0884	NA	NA
16E	6x6	NC	NC	NA	NA
16F	6x6	NL	NL	NA	NA

Other than a much higher rate of deformation and one other key exception, the fabric on fabric experiments deformed in exactly the same way as the fabric on aluminum. The lines of dots remained linear in all cases. The error between the regression lines and the actual data was greater than for the fabric on aluminum but only because the buckle in the fabric was greater and extended further into the rows of dots. For example, comparing the graphs in Figure 61 and Figure 62 readily reveals that the error of the vertical row next to the dog is affected by the buckle in the fabric at the corner of the dog, causing the larger errors between the linear regressions and the data points. However, looking at the vertical row of dots far from the dog, the error is smaller because the buckle in the fabric is only at the corner of the dog and because the fabric does not deform beyond the buckle at the dog.

Other evidence that the fabric does not deform outside of the buckle at the dog is the constant angle between the dot lines. As with the experiments on the aluminum plate, the angle change between the dot lines, as shown in Figure 63, was small relative to the absolute change in the angle of each line. The change was larger than on the aluminum plate, which also suggests that the larger buckle reduced the linearity of the dot lines near the dog.

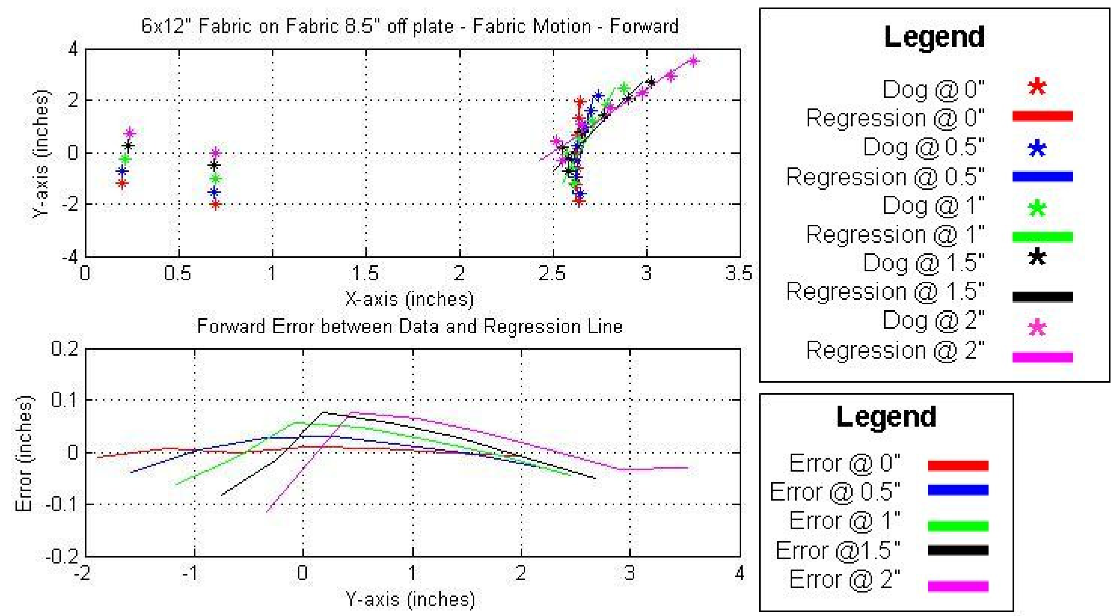


Figure 61 The top graph shows the vertical row of dots that were close to the dog and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

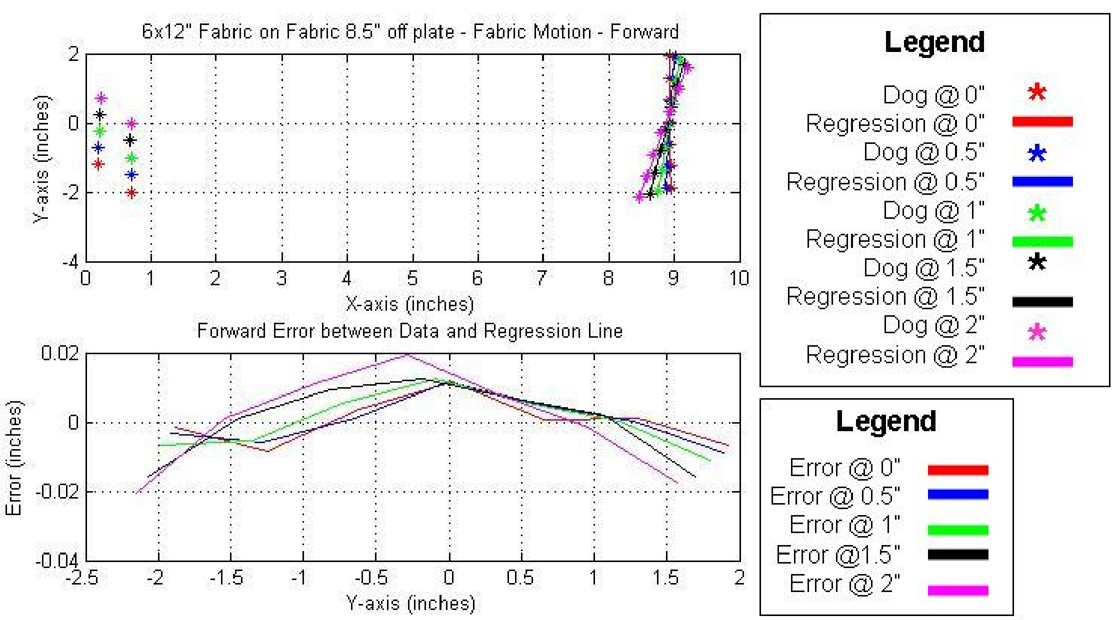


Figure 62 The top graph shows the vertical row of dots that were far from the dog and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. Note the relatively small error in the bottom graph.

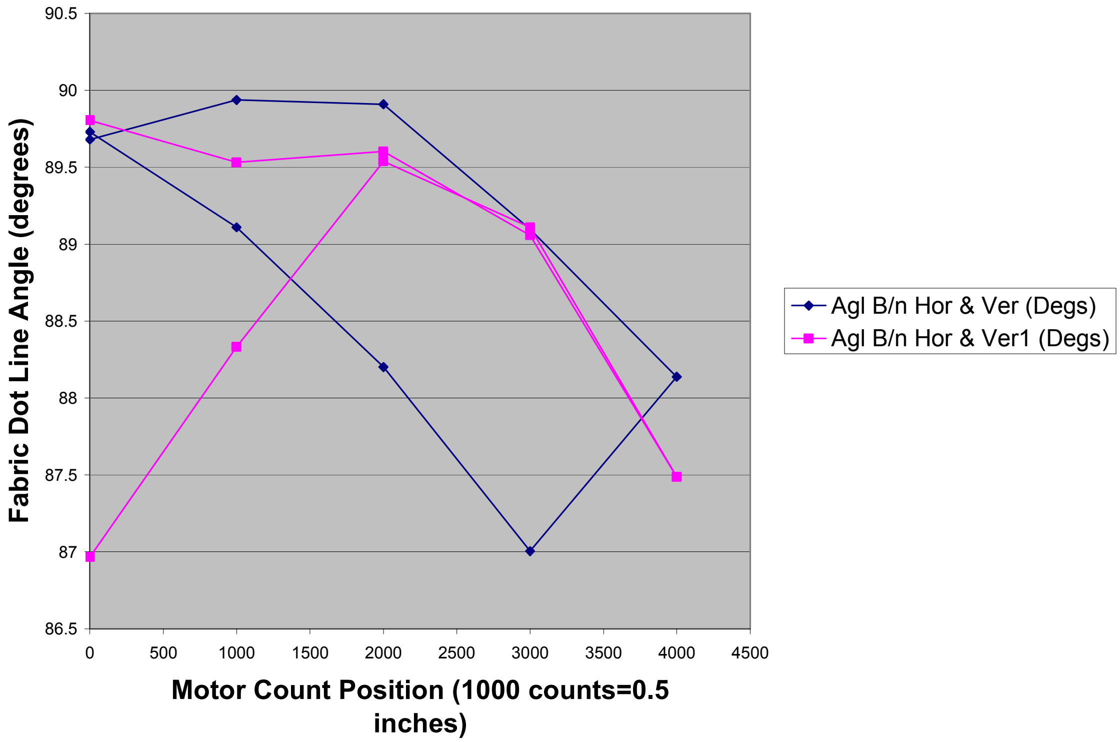


Figure 63 The change in angle between the horizontal row of dots (Hor) and both the vertical row of dots near the dog (Ver) and far from the dog (Ver1).

One of the major differences between the behavior of the fabric on the aluminum table and the placement of fabric on fabric is the rate of change of the slope of the dot lines. When moving on the aluminum surface, the fabric exhibited significant hysteresis, with the horizontal dot lines returning to their undeformed positions more quickly than they deform. This may be seen in the plot of the slopes of the dot lines after each motion in Figure 53 and by comparing the slope of the line going out with the slope of the line coming back in Table 1. If the same comparison is made for the experiments with the fabric lying on fabric, the slope out and the slope back, as shown in Table 2, is not significantly different. A graphical representation can be seen in Figure 64. Comparing this plot to the plot in Figure 53 demonstrates that the fabric on the aluminum plate returned to a 0 slope more quickly than the fabric on fabric.

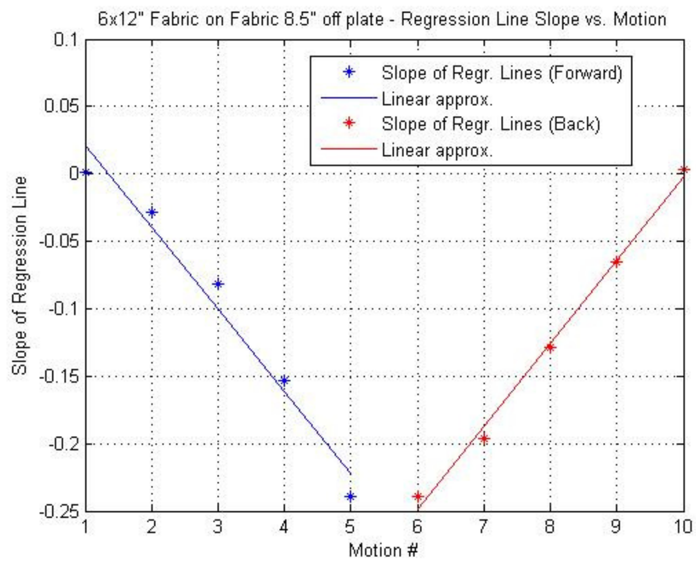


Figure 64 The slopes of the regression lines follow a linear pattern. The blue line represents the motion of the fabric while the dog moves out. The red line represents the motion of the dog moving back to the initial position.

Another important observation from the experiments is that the lower sheet of fabric does not measurably displace or deform, as can be seen in Figure 60 and more closely in Figure 65. In spite of the fact that the displacements of the top sheet are large relative to those used in sewing, and the amount of fabric that is lying on top of another sheet of fabric is greater and is further from the dog than what will likely be designed, the lower sheet of fabric is unaffected by the movement of the upper sheet. This means that the two sheets can be independently controlled by multiple servo controlled dogs when placed on top of one another.

Therefore, the use of a thin plate to separate two sheets of fabric offers a viable method to control both sheets of fabric. Each sheet can be independently controlled without moving the other sheet. In addition, each sheet can be controlled in such a way that if faults are detected, such as buckling, they can be easily remedied.

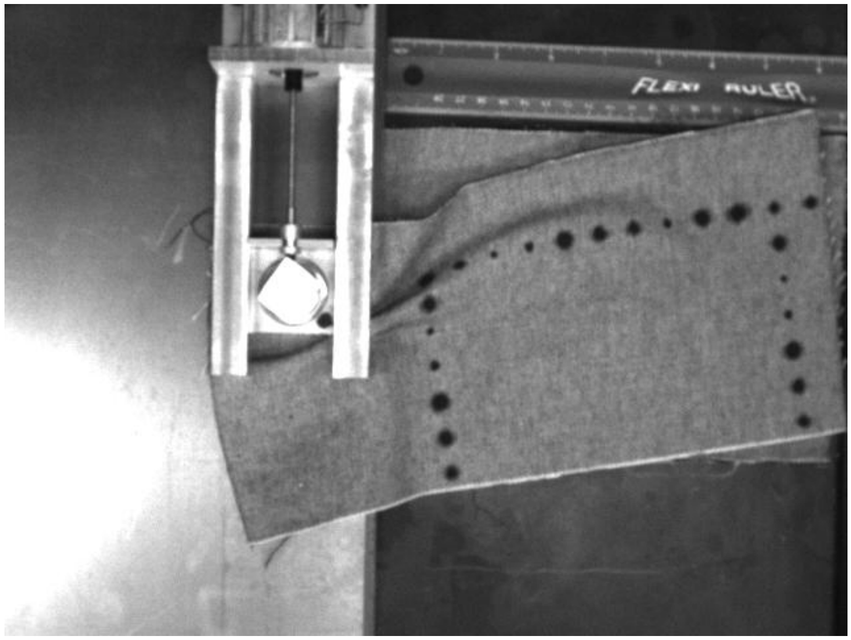


Figure 65 The furthest position from the start position. Note the lower sheet of fabric is undisturbed.

5.4.3 Experiment III: Fabric Stitched to Fabric

The final set of experiments looked at the possibility of relatively controlling the fabric after two sheets were partially sewn together. The test was set up much like the fabric on fabric experiments, but the bottom and top sheets were sewn together as in Figure 47. For these tests, the fabric was translated distances of 2 mm and 4 mm. Even though the distance between the dog and the beginning of the stitch was varied, all of the tests yielded the same general results. Because of the stiffness of the seam, both the bottom and top sheets of fabric buckled out of the plane. In fact, for the larger translations, an entire section of the two fabrics would lift off of the table. In spite of every motion causing some undesirable deformation, moving the dog back to its starting position corrected the deformation. Thus, as before when the sheets were not sewn together, errors can be corrected if they are detected. In addition, the seam helps to keep the two sheets oriented, reducing the need for independent control except in the case of correcting errors.

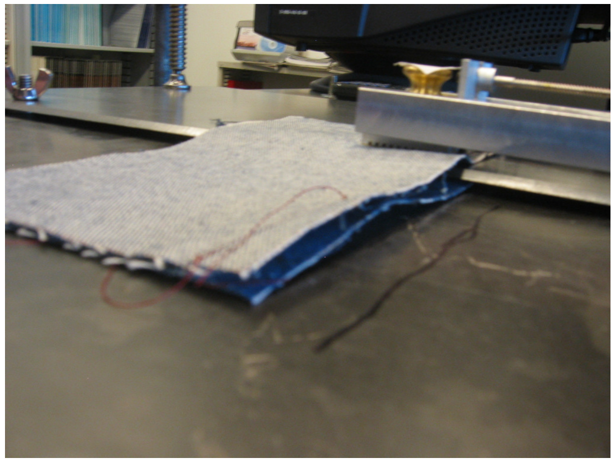


Figure 66 Both sheets of fabric buckle out of the plane even at the slightest disturbance due to the stiffness of the seam between them.

CHAPTER 6

CONCLUSIONS

This project demonstrates a new system for automated fabric control during the sewing process that addresses shortcomings revealed by previous attempts at automation. The design includes an entirely new method of sensing, through the use of fabric threads, and of actuation, using a servo controlled feed dog, placed in the context of a complete automated garment manufacturing system. The continuing challenges presented by automated sewing, particularly due to fabric's mechanical properties, are highlighted. The prototype demonstrates the feasibility of the design, and the experiments identify key behaviors of fabric in response to the new method of actuation.

6.1 Servo Dog Conceptual Design

The servo dog concept is based upon the requirements of sewing. The dogs must be able to move in the vertical direction in order to have incremental contact with the fabric. They must perform this motion 180^{o} out of phase with the sewing needle. Because sewing rates are high, 5,000 stitches per minute, the servo dogs must be able to complete each motion at an equally high rate.

To control fabric on a surface, the dogs have a minimum of two degrees of freedom, and for complete control of the fabric, the dogs must control six degrees of freedom. The servo dog design meets another key requirement by their capability to control two sheets of fabric using a thin plate to separate the two sheets of fabric. This is a vital aspect of sewing that has been largely ignored in previous research.

Finally, the control of the fabric must be accurate and robust with respect to fabric deformation. The thread tracking vision system provides accurate fabric position feedback even in the case of fabric deformation. This is possible because the position of the fabric is based on a coordinate system built into the fabric that deforms with the fabric. The needle, therefore, always makes the stitch through the appropriate spot on the fabric regardless of whether that spot has moved as a result of fabric stretching. Using the vision system with the servo dog offers a technique of fabric control that avoids fabric deformation by using an incremental actuation method.

6.1.1 Recommendations for future work

As a result of this project, numerous research directions would be appropriate to pursue. A key area of research is the integration of the various components. Most important is the integration of the vision system developed at Georgia Tech Research Institute with the servo dog. Adding feedback control to the fabric is a basic requirement of the entire system, which would demonstrate the capabilities of both the vision system and the servo dog. The coordination of the servo dog and the budgers is another important area of study. The budgers offer continuous control, while the servo dog is an incremental controller, and the integration of these two devices would be a valuable task. Further, the coordination of multiple servo dogs in the context of controlling both one and two sheets of fabric should be studied.

Additional research is needed as to the degrees of freedom of control that are required by the sewing process. One would assume that complete fabric control would be necessary for a device with the flexibility needs of a sewing machine, but it would be a significant engineering and economical advantage if it were possible to use fewer degrees of freedom.

6.2 Servo Dog Prototype

The prototype of the servo controlled sewing dog successfully shows the feasibility of the concept of high speed fabric control in time with an industrial sewing machine. While the prototype did not demonstrate fabric control for sewing speeds higher than 500 stitches per minute, the cable drive system with voice coil motors has the ability to achieve high accelerations in multiple degrees of freedom. The components currently inhibiting the performance are computer and computer-amplifier serial communication. The servo dog prototype achieved accelerations of 27 gs, which mechanically allow the device to achieve over 5,000 stitches per minute.

6.2.1 Recommendations for future work

The current prototype has generally fulfilled its purposes, but a number of improvements could be made in the next generation model using the lessons learned here. The largest performance enhancement would result from improving the electrical communication and computational components of the device. The limiting factor that prevented the dog from operating at highest sewing speeds was the processing time for the commands.

To obtain better coordinated control between the dog and sewing machine at high speeds, the communication between the PC and the amplifier should be improved, or the commands should be streamlined in such a way that the time lost in commanding the motor is miniscule relative to the time of the motions. The most obvious solution is to switch from a Windows PC to a real-time operating system or a microcontroller. In addition, the PD gains should be tuned to provide the fastest, most accurate response.

Finally, the position of the optical sensor should be optimized with respect to the stroke of the dog and needle. This is difficult because the speed of the needle bar is not constant throughout its stroke. In fact, the needle bar appears to move much more quickly in the lower half of its stroke than the upper half. Therefore, it appears the sensor should not be placed in the middle of the stroke. To properly place the sensor requires a substantial amount of iteration to ensure that the dog sufficiently contacts the fabric during the entire time that the needle is out of the fabric and is entirely out of contact with the fabric when the needle is stitching. The sensor thus must be placed so that the dog starts its motion at precisely the right instant. Currently, the sensor is placed so that the number of high voltage readings approximately equals the number of low voltage readings as the sewing machine turns. Keeping up with the sewing machine at higher speeds is the first issue that must be addressed, which should be feasible using a different computer and improving the serial communication.

Other improvements could enhance the accuracy of the device. A number of adjustments could be made to reduce the slip between the dog and the fabric. Different foot textures should be tried, such as rubber or plastic and other grits of sandpaper. Adjusting the preload in the spring could yield less slip at the expense of a higher required force from the voice coil motor. Also, adding a thin, low friction plate to the table surface to create a smoother, more even surface would reduce the slip and the directionality of the slip.

The rotational arm could be redesigned to improve the accuracy of the dog in the rotational and translational directions. Currently the rotation arm is wider than it needs to be to fit the endpoints of the cables. Reducing the width of the bar would reduce the nonlinearities due to the geometry of the connection. Also, the rotation arm is presently screwed onto the lower leg of the dog. While it is mounted at the center of rotation of the translational direction, the cables are attached a distance from the center as described in section 3.2.4. Thus, as the dog translates, the points where the cables attach rotate slightly about the translational component's axis. This could be reduced by narrowing the width of the rotation arm, and it could be eliminated entirely by mounting the rotation arm through a bearing with a shoulder screw. When the dog translates the fabric, the rotation bar would remain level.

Additional improvements could increase the acceleration. While the theoretical acceleration for the prototype is greater than 30 gs, the dog actually was measured only up to 27 gs. This is partly due to the added mass of the accelerometer. This discrepancy was most likely due to significant damping in the actuator and pulley system. This could be reduced by simply adding lubrication to the pulleys and the linear bushing on the actuator. However, a better solution would be to replace the aluminum pulleys with bearings and to re-machine the linear brass bushing of the actuators and aluminum shafts that ride on them to a tighter tolerance.

The robustness of the design could be improved with respect to the vibrations of the machine at high sewing rates. In general, slop could be reduced in the mechanical linkage between the sewing needle by adding another bearing surface and in the dog by adding thread lock to the screws, adding an additional bearing surface or re-machining the parts to a tighter tolerance. A more permanent solution, and one that would benefit control, would be to replace the mechanical linkage with a separate actuator that moves the dog vertically. In addition to potentially reducing the effect of vibration on the wear of the components, that would permit the dog to actuate the fabric without the sewing machine running and to make larger motions of the fabric between stitches if necessary.

A final useful change to the prototype would be to re-design the presser foot to move up and down with the needle so that the prototype could stitch the fabric.

6.3 Fabric Behavior

As demonstrated, denim, when translated, will buckle at the point of actuation. The rest of the fabric remains undeformed, and the deformation can be removed by translating the fabric in the opposite direction. Therefore, the position of the fabric a given distance from the point of actuation depends on the magnitude of the buckle for large fabrics. For small widths of fabrics, no deformation occurs and the fabric can be treated as a rigid body. Obviously, other variables are at play, such as the applied acceleration, friction and the stiffness of the fabric. However, if these variables are relatively constant or identified, as they were in previous work, the fabric here demonstrated three different behaviors depending on fabric size: (1) the fabric buckles at the dog and continues to buckle as it is displaced further, causing the fabric to deform only at the point and in a linearly increasing manner; (2) the fabric buckles during the first displacement and maintains its deformation through subsequent displacement, reaching a steady state value; and (3) the fabric does not deform. Furthermore, after deformations have occurred, moving in the opposite direction returns the fabric to its original position more quickly than it was moved to its deformed position.

When fabric is actuated while two sheets are placed on top of one another, its behavior is similar to where the fabric is simply lying on a flat surface. The lower sheet of fabric can be held in place using a dog and the movements of the upper sheet of fabric do not affect the lower sheet. Due to the much higher friction between the fabrics than between the fabric and the aluminum plate, the upper sheet of fabric exhibited much higher deformations. The fabric also did not show any hysteresis with respect to the buckling as it did in the experiments on aluminum.

After two sheets of fabric are sewn together, the loss of relative control has been documented. This does not mean that deformations cannot be eliminated using control; rather, one sheet of fabric cannot be moved relative to the other sheet without deforming the fabric.

6.3.1 Recommendations for future work

As with the model to determine the maximum allowable length of fabric, a useful model would determine the maximum allowable width of fabric during automated sewing. These results suggest that there is a discrete point at which the width of the fabric causes significant deformation. While the deformation can be corrected, it is difficult to sense when it occurs, and so avoiding it all together is a more feasible solution.

Controlling two sheets of fabric has been shown to be possible using a plate to separate the fabric with one dog above the plate and one below it. Control of the upper sheet is possible without affecting the position of the lower sheet. A next step in this area is to examine the optimal dimensions for such a system. How far from the plate should the needle be? How high should the plate be above the table? How far from the edge of the plate should the dog be? All of these questions pertain to the sewing process and to the behavior of fabric being controlled while in contact with another sheet.

APPENDIX A

EXAMPLE OF THREAD-LEVEL VISION MATLAB CODE

```
function Threshold_rotate_and_separate(deg,varargin)

% Find the centroids by dividing the image into 36 regions, threshold
each
% region based on the mean and standard deviation of intensities in
that
% region, reasemble the image, and erode using a line structure
element.
% Time the procedure.

f6 = imread(varargin{1});
f6 = rgb2gray(f6);
tic
siz = size(f6);
warning off
I61 = f6(1:siz(1)/6,1:siz(2)/6);
I62 = f6(1:siz(1)/6,(siz(2)/6)+1:2*siz(2)/6);
I63 = f6(1:siz(1)/6,(2*siz(2)/6)+1:3*siz(2)/6);
I64 = f6(1:siz(1)/6,(3*siz(2)/6)+1:4*siz(2)/6);
I65 = f6(1:siz(1)/6,(4*siz(2)/6)+1:5*siz(2)/6);

. . . . . .

I631 = f6((5*siz(1)/6)+1:siz(1),1:siz(2)/6);
I632 = f6((5*siz(1)/6)+1:siz(1),(siz(2)/6)+1:2*siz(2)/6);
I633 = f6((5*siz(1)/6)+1:siz(1),(2*siz(2)/6)+1:3*siz(2)/6);
I634 = f6((5*siz(1)/6)+1:siz(1),(3*siz(2)/6)+1:4*siz(2)/6);
I635 = f6((5*siz(1)/6)+1:siz(1),(4*siz(2)/6)+1:5*siz(2)/6);
I636 = f6((5*siz(1)/6)+1:siz(1),(5*siz(2)/6)+1:siz(2));

warning on

level61 = mean2(im2double(I61));
stand_dev61 = std2(im2double(I61));
I61 = im2bw(I61,level61-.35*stand_dev61);

level62 = mean2(im2double(I62));
stand_dev62 = std2(im2double(I62));
I62 = im2bw(I62,level62-.35*stand_dev62);

level63 = mean2(im2double(I63));
stand_dev63 = std2(im2double(I63));
I63 = im2bw(I63,level63-.35*stand_dev63);

. . . . . .

level634 = mean2(im2double(I634));
stand_dev634 = std2(im2double(I634));
I634 = im2bw(I634,level634-.35*stand_dev634);
```

```
level635 = mean2(im2double(I635));
stand_dev635 = std2(im2double(I635));
I635 = im2bw(I635,level635-.35*stand_dev635);

level636 = mean2(im2double(I636));
stand_dev636 = std2(im2double(I636));
I636 = im2bw(I636,level636-.35*stand_dev636);

I6 = [I61 I62 I63 I64 I65 I66; I67 I68 I69 I610 I611 I612; I613 I614
I615 I616 I617 I618; I619 I620 I621 I622 I623 I624; I625 I626 I627 I628
I629 I630; I631 I632 I633 I634 I635 I636];
larger_separate_timeb1 = toc;
I6 = imrotate(I6,deg,'bilinear');
tic
I6 = bwareaopen(I6,2000);
L6 = bwlabel(I6);
s6 = regionprops(L6,'Orientation');
orientation6 = cat(1, s6.Orientation);
theta6 = median(orientation6);
se6 = strel('line',40,theta6-67.3582);
I6 = imerode(I6,se6);
L6 = bwlabel(I6);
s6 = regionprops(L6,'Centroid');
centroids6 = cat(1, s6.Centroid);
larger_separate_timeb2 = toc;

% Calculate the outliers, mean, median and standard deviation of the
% minimum distances between all of the centroids.

[separate_6_centroiddiff, larger_separate_outliers] =
centroid_stat_min(centroids6);
% separate_6 = [separate_6_centroiddiff larger_separate_time]

before_error_detection.num_centroids = separate_6_centroiddiff(1);
before_error_detection.num_outliers = separate_6_centroiddiff(2);
before_error_detection.mean_dist = separate_6_centroiddiff(3);
before_error_detection.median_dist = separate_6_centroiddiff(4);
before_error_detection.stand_dev_dist = separate_6_centroiddiff(5);
before_error_detection.time =
larger_separate_timeb1+larger_separate_timeb2;
before_error_detection

% Correct for miss labeled threads.

tic
centroids6b = centroid_stat_error_correct2(centroids6);
[separate_6_centroiddiffb, larger_separate_outliersb] =
centroid_stat_min(centroids6b);
error_correct_time = toc;

after_error_detection.num_centroids = separate_6_centroiddiffb(1);
after_error_detection.num_outliers = separate_6_centroiddiffb(2);
after_error_detection.mean_dist = separate_6_centroiddiffb(3);
after_error_detection.median_dist = separate_6_centroiddiffb(4);
```

```
after_error_detection.stand_dev_dist = separate_6_centroiddiffb(5);
after_error_detection.time =
larger_separate_timeb1+larger_separate_timeb2+...
    error_correct_time;
after_error_detection

% Plot the centroids and outliers over the original image.

f6 = imrotate(f6,deg,'bilinear');
warning off
figure, imshow(f6), title('Fabric Thread Detection')
hold(imgca,'on')
plot(imgca,centroids6(:,1), centroids6(:,2), 'r*')
plot(imgca,larger_separate_outliers(:,1),
larger_separate_outliers(:,2), 'go'), legend('Threads','Errors')
hold(imgca,'off')
figure, imshow(f6), title('after error correction')
hold(imgca,'on')
plot(imgca,centroids6b(:,1), centroids6b(:,2), 'r*')
plot(imgca,larger_separate_outliersb(:,1),
larger_separate_outliersb(:,2), 'go'), legend('centroidsb','outliersb')
hold(imgca,'off')
warning on
```

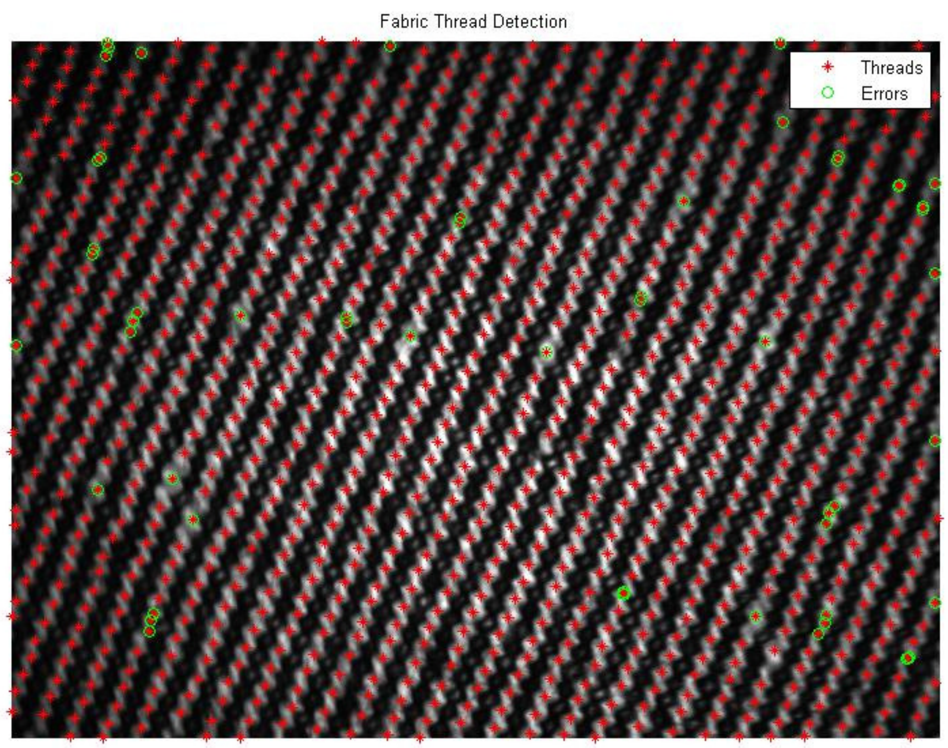


Figure 67 Image of fabric produced using code with threads identified (red) and "error" threads identified (green).

APPENDIX B

CIRCUIT FOR IR SENSOR

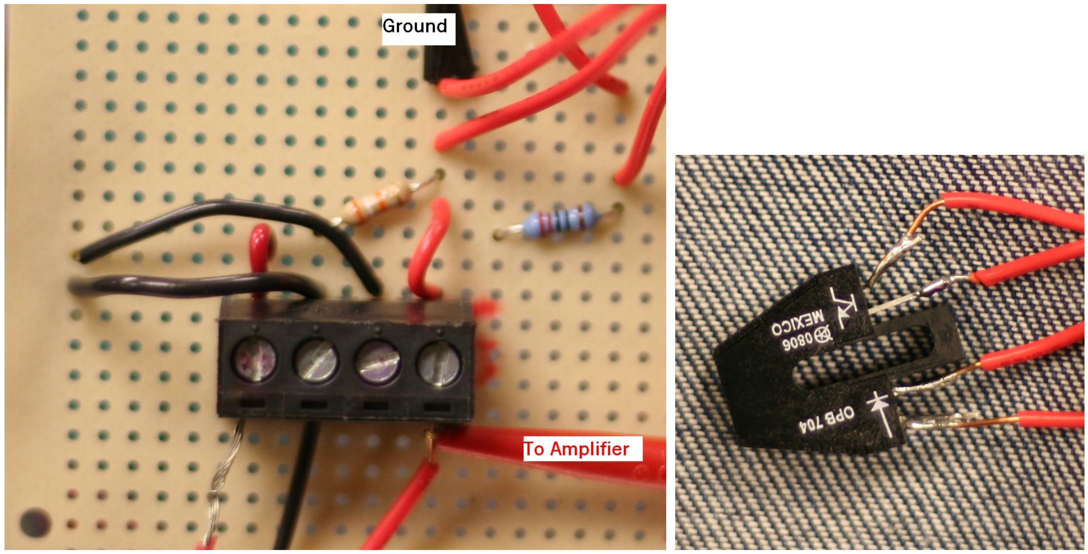


Figure 68 Photo of IR sensor circuit (Left). IR sensor (Right). The 4 wires in the top right of the circuit images connect to the sensor.

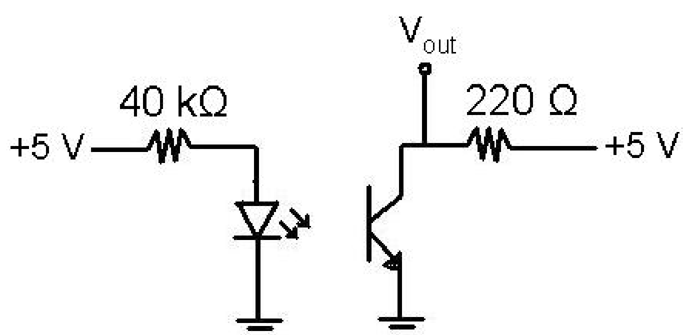


Figure 69 Circuit for the IR sensor. The IR LED would reflect of a shiny surface to the phototransistor.

APPENDIX C

EXAMPLE OF TEXT PROGRAM FOR PROTOTYPE

C.1 Example Program used for Control Tests

```
COM1  the comm port connected to the MEAS 3C20
115200  the baud rate:
110,300,600,1200,2400,4800,9600,14400,19200,38400,56000,57600, or 115200
8      the number of data bits: 4 to 8
0        parity:  0=none, 1=odd, 2=even, 3=mark parity, 4=space parity
0      stop bits: 0=one, 1= one point five, 2=two stop bits
114      number of commands in the script  23 + no. of motions x 10
5.0   minimum number of milliseconds to delay between sending commands
00 MESASTART> 1000.0
00 LS00> 5.0            Send commands to amplifier 01
00 II> 5.0              get ht eboard identification
00 IR> 5.0              get the firmware revision number
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
00 WIA046> 5.0          start of back and forth, #1
00 WI0FA0> 5.0          low word of target position
00 WI0000> 5.0          high word of target position
00 WI8002> 5.0          GO if true
00 WIFFFF> 2000.0
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
00 WIA046> 5.0
00 WI0000> 5.0          low word of target position
00 WI0000> 5.0          high word of target position
00 WI8002> 5.0          GO if true
00 WIFFFF> 2000.0
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
00 WIA046> 5.0          start of back and forth, #2
00 WI0FA0> 5.0          low word of target position
00 WI0000> 5.0          high word of target position
00 WI8002> 5.0          GO if true
00 WIFFFF> 2000.0
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
```

```
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
00 WIA046> 5.0
00 WI0000> 5.0          low word of target position
00 WI0000> 5.0          high word of target position
00 WI8002> 5.0          GO if true
00 WIFFFF> 2000.0
00 WI0022> 5.0          Read encoder position
00 RI> 5.0
00 IR> 5.0              get the firmware revision numberas a check
00 MESASTOP> 10.0
```

C.2 Example Program used for Sewing Machine Run Tests

Note that the commands with comments followed by ******* and commands created by the executable for logical operations pertaining to reading the IR sensor to maintain timing with the sewing needle.

```
COM1  the comm port connected to the MEAS 3C20
115200  the baud rate:
110,300,600,1200,2400,4800,9600,14400,19200,38400,56000,57600, or 115200
8      the number of data bits: 4 to 8
0        parity:  0=none, 1=odd, 2=even, 3=mark parity, 4=space parity
0      stop bits: 0=one, 1= one point five, 2=two stop bits
45       number of commands in the script  23 + no. of motions x 10
5.0    minimum number of milliseconds to delay between sending commands
00 MESASTART> 1000.0
00 LS01> 1000           Send commands to amplifier 01
00 II> 100.0            get ht eboard identification
00 IR> 100.0            get the firmware revision number
00 WI8005> 5.0          To set drive mode to current
00 WIFFFF> 5.0
00 WI8003> 5.0          To set PID enable
00 WIFFFF> 5.0
00 WI8004> 5.0          To enable trapozoidal profile
00 WI0001> 5.0          Use 1
00 WIA03F> 5.0          To set acceleration limit
00 WI4740> 5.0          low word
00 WI06F9> 5.0          high word
00 WIA048> 5.0          To set slew limit
00 WIF9C0> 5.0          low word
00 WI15DF> 5.0          high word
00 WI802B> 5.0          Kd set
00 WI0062> 5.0
00 WI802A> 5.0          Kp set
```

```
00 WI002D> 5.0
00 WIA02D> 5.0       Ki set to zero
00 WI0000> 5.0
00 WI0000> 5.0
00 WIA01C> 5.0       Set home position
00 WI0000> 5.0
00 WI0000> 5.0
00 WI806C> 5.0       Clear counter if true
00 WIFFFF> 5.0
00 WI8070> 5.0       Enable motor
00 WIFFFF> 5.0
00 DH> 5.0           Wait for HIGH from IR sensor        *******
00 WIA046> 2.0            Target Position 1ST MOVE CMD
00 WI0FA0> 2.0            low word
00 WI0000> 2.0            high word
00 WI8002> 2.0            GO if true
00 WIFFFF> 2.0
00 DL> 5.0           Wait for LOW from IR sensor         *******
00 WIA046> 2.0            Target Position 2nd MOVE CMD
00 WI0000> 2.0            low word
00 WI0000> 2.0            high word
00 WI8002> 2.0            GO if true
00 WIFFFF> 2.0
00 CJ0E05> 2.0       Jump 13 commands back and do it 5 time *******
00 IR> 5.0           get the firmware revision numberas a check
00 MESASTOP> 5.0
```

APPENDIX D

RESULTS FROM PERFORMANCE TESTS OF DOGS

D.1 How to Read the Results

Twenty-two tests were done and the data is tabulated here. The tables will be explained here for the convenience of the reader. In each table the encoder position from the actuator is listed first and labeled COUNTS. The counts are listed in hexadecimal and millimeters. The distance of motions is the difference between the positions in the previous column. For rotations, the encoder counts are converted into millimeters first and then to radians and degrees based on the equations discussed in section 3.2.4. Measured values (MSRD) are measurements of the dog in tests 3 and 4 and of the fabric in all other tests. These are done using calipers for translation and by a protractor for rotation. For translation of the fabric, the distance was measured at three points and the distances are averaged. For rotation, the angle change was measured at the left and right edge of the fabric and the two are averaged. The %Diff is the percent difference between the measured distance moved by the fabric and the encoder distance traveled by the actuator.

D.2 Tabulated Results

TEST 1 *Dog in air, move 2mm and back*

COUNTS	COUNTS	MMs	DIST (MMs)	% Error
0	0	0		
0F49	3913	1.957	1.9565	2.175
0F4A	3914	1.957		
00BB	187	0.094	-1.8635	6.825

TEST 2 *Dog in air, move 4mm and back*

COUNTS	COUNTS	MMs	DIST (MMs)	% Error
0	0	0		
1ECB	7883	3.942	3.9415	1.4625
1E9D	7837	3.919		
97	121	0.061	-3.858	3.55

TEST 3 *Dog in air, rotate 13.75 deg and back*

COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	MSRD ANGL (deg)	DIST (deg)	% Diff	% Error wrt CMD
001F	31	0.0155	0.001	0.001	0.053			89.5			
1E1C	7708	3.854	0.152	0.231	13.247	13.194	4.0426	77	-12.5	5.261	9.091
1E26	7718	3.859	0.152	0.232	13.265			77			
01C7	455	0.2275	0.009	0.014	0.782	-12.483	9.2173	89.5	12.5	0.139	9.091

TEST 4 *Dog in air, rotate 6.875 deg and back*

COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	MSRD ANGL (deg)	DIST (deg)	% Diff	% Error wrt CMD
0013	19	0.0095	0.000	0.001	0.033			89.5			
0EB0	3584	1.792	0.071	0.108	6.160	6.127	10.88	83	-6.5	6.088	5.455
0ECF	3791	1.8955	0.075	0.114	6.515			83			
013F	319	0.1595	0.006	0.010	0.548	-5.967	13.205	89	6	0.550	12.727

TEST 5 *Dog on fabric (5x5"), move 4mm and back*

Position of Measurement on Fabric

						0"	2.5"	5"	0"	2.5"	5"			
	COUNTS	COUNTS	MMs	DIST (MMs)	% Error	MSR VALS (MMs)			DIST (MMs)			AVG	% Diff	% Error wrt CMD
	0000	0	0			15.22	17.43	19.65						
FWD	1E3F	7743	3.8715	3.8715	3.213	11.5	14.15	16.69	-3.72	-3.28	-2.96	-3.32	14.245	17.000
	1E73	7795	3.8975			11.5	14.15	16.69						
BCK	0115	277	0.1385	-3.759	6.025	14.89	16.64	18.72	3.39	2.49	2.03	2.637	29.857	34.083

TEST 6 *Dog on fabric (5x5"), move 2mm and back*

Position of Measurement on Fabric

						0"	2.5"	5"	0"	2.5"	5"			
	COUNTS	COUNTS	MMs	DIST (MMs)	% Error	MSR VALS (MMs)			DIST (MMs)			AVG	% Diff	% Error wrt CMD
	0001	1	0.0005			15.02	16.83	18.86						
FWD	0F19	3865	1.9325	1.932	3.400	12.75	15.24	17.79	-2.27	-1.59	-1.07	-1.643	14.941	17.833
	0F23	3875	1.9375			12.75	15.24	17.79						
BCK	018D	397	0.1985	-1.739	13.050	14.17	16.02	18.12	1.42	0.78	0.33	0.843	51.505	57.833

TEST 7 *Same as Test 6 but move in opposite direction*

Position of Measurement on Fabric

						0"	2.5"	5"	0"	2.5"	5"			
	COUNTS	COUNTS	MMs	DIST (MMs)	% Error	MSR VALS (MMs)			DIST (MMs)			AVG	% Diff	% Error wrt CMD
	0EF2	3826	1.913			13.97	16.35	18.6						
FWD	016F	367	0.1835	-1.7295	13.525	14.4	17.44	20.8	0.43	1.09	2.2	1.24	28.303	38.000
	0152	338	0.169			14.4	17.44	20.8						
BCK	0EC7	3783	1.8915	1.7225	13.875	12.59	15.93	19.68	-1.81	-1.51	-1.12	-1.480	14.078	26.000

TEST 8 *Same as Test 5 but move in opposite direction*

Position of Measurement on Fabric

						0"	2.5"	5"	0"	2.5"	5"			
	COUNTS	COUNTS	MMs	DIST (MMs)	% Error	MSR VALS (MMs)			DIST (MMs)			AVG	% Diff	% Error wrt CMD
	1E60	7776	3.888			11.95	14.55	17.47						
FWD	08CD	2253	1.1265	-3.643	8.925	13.96	17.08	21.45	2.01	2.53	3.98	2.84	22.042	29.000
	01EA	490	0.245			13.96	17.08	21.45						
BCK	1E1F	7711	3.8555	3.6105	9.738	10.6	14.48	18.88	-3.36	-2.6	-2.57	-2.843	21.248	28.917

TEST 9 *Dog on fabric (5x5"), rotate 6.875 deg and back*

	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	Position of Measurement on Fabric: MSR VALS (deg) LEFT EDGE	MSR VALS (deg) RIGHT EDGE	DIST (deg) LEFT EDGE	DIST (deg) RIGHT EDGE	AVG	% Diff	% Error wrt CMD
	0000	0	0	0.000	0.000	0.000			89.5	91					
FWD	0EA3	3747	1.8735	0.074	0.112	6.440	6.440	6.330	83	84	-6.5	-7	-6.75	4.817	1.818
	0EA5	3749	1.8745	0.074	0.112	6.443			83	84					
BCK	01FB	507	0.2535	0.010	0.015	0.871	-5.572	18.954	87	88.5	4	4.5	4.25	23.724	38.182

TEST 10 *Dog on fabric (5x5"), rotate 13.75 deg and back*

	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	Position of Measurement on Fabric: MSR VALS (deg) LEFT EDGE	MSR VALS (deg) RIGHT EDGE	DIST (deg) LEFT EDGE	DIST (deg) RIGHT EDGE	AVG	% Diff	% Error wrt CMD
	0001	1	0.0005	0.000	0.000	0.002			89	90					
FWD	1DD2	7634	3.817	0.150	0.229	13.120	13.119	4.593	76.5	78	-12.5	-12	-12.25	6.621	10.909
	1DBE	7614	3.807	0.150	0.228	13.086			76.5	78					
BCK	0155	341	0.1705	0.007	0.010	0.586	-12.500	9.092	87	88.5	10.5	10.5	10.5	15.999	23.636

TEST 11 *Same as Test 10 but rotate in opposite direction*

	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	Position of Measurement on Fabric: MSR VALS (deg) LEFT EDGE	MSR VALS (deg) RIGHT EDGE	DIST (deg) LEFT EDGE	DIST (deg) RIGHT EDGE	AVG	% Diff	% Error wrt CMD
	1DAF	7599	3.7995	0.150	0.228	13.060			89	90					
FWD	019B	411	0.2055	0.008	0.012	0.706	-12.354	10.155	99	101	10	11	10.5	15.005	23.636
	0199	409	0.2045	0.008	0.012	0.703			99	101					
BCK	1854	6228	3.114	0.123	0.187	10.704	10.001	27.266	90	91	-9	-10	-9.5	5.008	30.909

TEST 12 *Same as Test 9 but rotate in opposite direction*

	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	Position of Measurement on Fabric: MSR VALS (deg) LEFT EDGE	MSR VALS (deg) RIGHT EDGE	DIST (deg) LEFT EDGE	DIST (deg) RIGHT EDGE	AVG	% Diff	% Error wrt CMD
	0EA2	3746	1.873	0.074	0.112	6.438			90	91					
FWD	0215	533	0.2665	0.010	0.016	0.916	-5.522	19.679	93	94	3	3	3	45.672	56.364
	0204	516	0.258	0.010	0.015	0.887			93	94					
BCK	0DA2	3490	1.745	0.069	0.105	5.998	5.111	25.654	90	91	-3	-3	-3	41.306	56.364

TEST 13 *Dog on fabric (5x5"), move 12mm and back using 2mm steps*

OUT					BACK				
COUNTS	COUNTS	MMs	DIST (MMs)	% Error	COUNTS	COUNTS	MMs	DIST (MMs)	% Error
1	1	0.0005			006D	109	0.0545		
0F08	3848	1.924			0F65	3941	1.9705	1.916	4.200
00BB	187	0.0935	-1.8305	8.475	0070	112	0.056		
0EF0	3824	1.912			0F70	3952	1.976	1.92	4.000
00E0	224	0.112	-1.8	10.000	006B	107	0.0535		
0EF1	3825	1.9125			0F80	3968	1.984	1.9305	3.475
011F	287	0.1435	-1.769	11.550	0068	104	0.052		
0EF0	3824	1.912			0F70	3952	1.976	1.924	3.800
010C	268	0.134	-1.778	11.100	006E	110	0.055		
0EEB	3819	1.9095			0F73	3955	1.9775	1.9225	3.875
00F7	247	0.1235	-1.786	10.700	0062	98	0.049		
0EEE	3822	1.911			0F74	3956	1.978	1.929	3.550
00D3	211	0.1055	-1.8055	9.725	0059	89	0.0445		
		TOTAL	-10.769	10.258			**TOTAL**	11.542	3.817

Position of Measurement on Fabric

	0"	2.5"	5"	0"	2.5"	5"			
	MSR VALS (MMs)				DIST (MMs)		AVG	% Diff	% Error wrt CMD
	20.14	20.95	22.14						
OUT	24.14	28.52	33.84	4	7.57	11.7	7.757	27.972	35.361
BACK	13.78	21.5	28.66	-10.36	-7.02	-5.18	-7.520	34.847	37.333

TEST 14 *Same as Test 13 but rotate in opposite direction*

OUT					BACK				
COUNTS	COUNTS	MMs	DIST (MMs)	% Error	COUNTS	COUNTS	MMs	DIST (MMs)	% Error
FFE7	-25	-0.0125			0072	114	0.057		
0F76	3958	1.979	1.9915	0.425	0F24	3876	1.938		
0038	56	0.028			00D0	208	0.104	-1.834	8.300
0F89	3977	1.9885	1.9605	1.975	0F15	3861	1.9305		
0046	70	0.035			00FF	255	0.1275	-1.803	9.850
0F7C	3964	1.982	1.947	2.650	0F2A	3882	1.941		
0048	72	0.036			00D8	216	0.108	-1.833	8.350
0F79	3961	1.9805	1.9445	2.775	0F22	3874	1.937		
0045	69	0.0345			010C	268	0.134	-1.803	9.850
0F7D	3965	1.9825	1.948	2.600	0F21	3873	1.9365		
004F	79	0.0395			00F4	244	0.122	-1.8145	9.275
0F78	3960	1.98	1.9405	2.975	0F1C	3868	1.934		
0042	66	0.033			010F	271	0.1355	-1.7985	10.075
		TOTAL	11.732	2.233			**TOTAL**	-10.886	9.283

Position of Measurement on Fabric

	0"	2.5"	5"	0"	2.5"	5"			
	MSR VALS (MMs)				DIST (MMs)		AVG	% Diff	% Error wrt CMD
	25.66	26.43	27.39						
OUT	13.2	17.16	22.24	-12.46	-9.27	-5.15	-8.960	23.628	25.333
BACK	17.24	24.91	34.31	4.04	7.75	12.07	7.953	26.940	33.722

TEST 15 *Dog on fabric (5x5"), move 12mm and back using 4mm steps*

OUT					BACK				
COUNTS	COUNTS	MMs	DIST (MMs)	% Error	COUNTS	COUNTS	MMs	DIST (MMs)	% Error
0001	1	0.0005			009B	155	0.0775		
1E95	7829	3.9145			1EDC	7900	3.95	3.8725	3.188
0119	281	0.1405	-3.774	5.650	0073	115	0.0575		
1EA7	7847	3.9235			1EFA	7930	3.965	3.9075	2.313
00F2	242	0.121	-3.8025	4.937	0066	102	0.051		
1EAF	7855	3.9275			1EFC	7932	3.966	3.915	2.125
012B	299	0.1495	-3.778	5.550	0053	83	0.0415		
		TOTAL	-11.3545	5.379			**TOTAL**	11.695	2.542

Position of Measurement on Fabric

	0"	2.5"	5"	0"	2.5"	5"			
	MSR VALS (MMs)				DIST (MMs)		AVG	% Diff	% Error wrt CMD
	19.05	20.76	22.27						
OUT	26.06	29.9	34.07	7.01	9.14	11.8	9.317	17.947	22.361
BACK	14.7	19.87	25.16	-11.36	-10.03	-8.91	-10.100	13.638	15.833

TEST 16 *Same as Test 15 but rotate in opposite direction*

OUT					BACK				
COUNTS	COUNTS	MMs	DIST (MMs)	% Error	COUNTS	COUNTS	MMs	DIST (MMs)	% Error
0001	1	0.0005			0077	119	0.0595		
1ECC	7884	3.942	3.9415	1.463	1E86	7814	3.907		
004D	77	0.0385			0127	295	0.1475	-3.7595	6.013
1EDB	7899	3.9495	3.911	2.225	1E85	7816	3.908		
003E	62	0.031			0108	264	0.132	-3.776	5.600
1EF5	7925	3.9625	3.9315	1.713	1E83	7811	3.9055		
0092	146	0.073			0117	279	0.1395	-3.766	5.850
		TOTAL	11.784	1.800			**TOTAL**	-11.3015	5.821

Position of Measurement on Fabric

	0"	2.5"	5"	0"	2.5"	5"			
	MSR VALS (MMs)				DIST (MMs)		AVG	% Diff	% Error wrt CMD
	22.68	23.45	24.67						
OUT	12.34	14.87	17.89	-10.34	-8.58	-6.78	-8.567	27.303	28.611
BACK	19.15	24.19	29.83	6.81	9.32	11.94	9.357	17.209	22.028

TEST 17 *Dog on fabric (5x5"), rotate 41.25 deg and back using 13.75 deg steps*

OUT								BACK							
COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error
0000	0	0	0.000	0.000	0.000			013D	317	0.1585	0.006	0.010	0.545		
1E25	7717	3.8585	0.152	0.231	13.263			1DF2	7666	3.833	0.151	0.230	13.175	12.630	8.142
0166	358	0.179	0.007	0.011	0.615	-12.648	8.017	014E	334	0.167	0.007	0.010	0.574		
1DED	7661	3.8305	0.151	0.230	13.167			1DF7	7671	3.8355	0.151	0.230	13.184	12.610	8.292
0178	376	0.188	0.007	0.011	0.646	-12.520	8.942	0165	357	0.1785	0.007	0.011	0.614		
1DE9	7657	3.8285	0.151	0.230	13.160			1DE7	7655	3.8275	0.151	0.230	13.156	12.543	8.780
017F	383	0.1915	0.008	0.011	0.658	-12.502	9.080	0159	345	0.1725	0.007	0.010	0.593		
					TOTAL	-37.670	8.680						**TOTAL**	37.783	8.405

Position of Measurement on Fabric

	LEFT	RIGHT	LEFT	RIGHT			
	MSR VALS (deg)		DIST (deg)		AVG	% Diff	% Error wrt CMD
	89.5	90					
OUT	118	119	28.5	29	28.75	23.678	30.303
BACK	82.5	83.5	-35.5	-35.5	-35.5	6.042	13.939

TEST 18 *Same as Test 17 but rotate in opposite direction*

OUT								BACK							
COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error
FFF4	-12	-0.006	0.000	0.000	-0.021			0148	328	0.164	0.006	0.010	0.564		
1E13	7699	3.8495	0.152	0.231	13.232	13.253	3.618	1DD2	7634	3.817	0.150	0.229	13.120		
012A	298	0.149	0.006	0.009	0.512			01DB	475	0.2375	0.009	0.014	0.816	-12.304	10.517
1DF0	7664	3.832	0.151	0.230	13.172	12.660	7.930	1E38	7736	3.868	0.152	0.232	13.296		
012E	302	0.151	0.006	0.009	0.519			01E5	485	0.2425	0.010	0.015	0.834	-12.462	9.367
1DFB	7675	3.8375	0.151	0.230	13.191	12.672	7.842	1E2A	7722	3.861	0.152	0.232	13.271		
0141	321	0.1605	0.006	0.010	0.552			024D	589	0.2945	0.012	0.018	1.012	-12.259	10.842
					TOTAL	38.584	6.463						**TOTAL**	-37.025	10.242

Position of Measurement on Fabric

	LEFT	RIGHT	LEFT	RIGHT			
	MSR VALS (deg)		DIST (deg)		AVG	% Diff	% Error wrt CMD
	90	91					
OUT	53.5	54.5	-36.5	-36.5	-36.5	5.401	11.515
BACK	84	83.5	30.5	29	29.75	19.649	27.879

TEST 19 *Same as Test 20 but rotate in opposite direction*

OUT								BACK							
COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error
0001	1	0.0005	0.000	0.000	0.002			0118	280	0.14	0.006	0.008	0.481		
0EA3	3747	1.8735	0.074	0.112	6.440	6.438	6.355	0E80	3712	1.856	0.073	0.111	6.380		
00EE	238	0.119	0.005	0.007	0.409			01C9	457	0.2285	0.009	0.014	0.785	-5.594	18.629
0EA6	3750	1.875	0.074	0.112	6.445	6.036	12.205	0E83	3715	1.8575	0.073	0.111	6.385		
00F9	249	0.1245	0.005	0.007	0.428			01D5	469	0.2345	0.009	0.014	0.806	-5.579	18.854
0EA0	3744	1.872	0.074	0.112	6.435	6.007	12.630	0E6A	3690	1.845	0.073	0.111	6.342		
011B	283	0.1415	0.006	0.008	0.486			019C	412	0.206	0.008	0.012	0.708	-5.634	18.054
0E9D	3741	1.8705	0.074	0.112	6.430	5.943	13.555	0E65	3685	1.8425	0.073	0.111	6.333		
0107	263	0.1315	0.005	0.008	0.452			01F9	505	0.2525	0.010	0.015	0.868	-5.465	20.504
0E98	3736	1.868	0.074	0.112	6.421	5.969	13.180	0E75	3701	1.8505	0.073	0.111	6.361		
0147	327	0.1635	0.006	0.010	0.562			01EA	490	0.245	0.010	0.015	0.842	-5.519	19.729
0E97	3735	1.8675	0.074	0.112	6.419	5.857	14.805	0E68	3688	1.844	0.073	0.111	6.338		
011A	282	0.141	0.006	0.008	0.485			01FC	508	0.254	0.010	0.015	0.873	-5.465	20.504
					TOTAL	36.250	12.121						**TOTAL**	-33.256	19.379

Position of Measurement on Fabric

	LEFT	RIGHT	LEFT	RIGHT			
	MSR VALS (deg)		DIST (deg)		AVG	% Diff	% Error wrt CMD
	89	90					
OUT	57	58	-32	-32	-32	11.724	22.424
BACK	77	78	20	20	20	39.861	51.515

TEST 20 *Dog on fabric (5x5"), rotate 41.25 deg and back using 6.875 deg steps*

OUT								BACK							
COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error	COUNTS	COUNTS	MMs	INCHES	ANGLE (rads)	ANGLE (deg)	DIST (deg)	% Error
0000	0	0	0.000	0.000	0.000			0135	309	0.1545	0.006	0.009	0.531		
0E73	3699	1.8495	0.073	0.111	6.357			0E6C	3692	1.846	0.073	0.111	6.345	5.814	15.429
0198	408	0.204	0.008	0.012	0.701	-5.656	17.729	013B	315	0.1575	0.006	0.009	0.541		
0E59	3673	1.8365	0.072	0.110	6.313			0E7F	3711	1.8555	0.073	0.111	6.378	5.837	15.105
018E	398	0.199	0.008	0.012	0.684	-5.629	18.129	0122	290	0.145	0.006	0.009	0.498		
0E68	3688	1.844	0.073	0.111	6.338			0E64	3684	1.842	0.073	0.111	6.332	5.833	15.155
0183	387	0.1935	0.008	0.012	0.665	-5.673	17.479	0122	290	0.145	0.006	0.009	0.498		
0E53	3667	1.8335	0.072	0.110	6.302			0E6C	3692	1.846	0.073	0.111	6.345	5.847	14.955
01B2	434	0.217	0.009	0.013	0.746	-5.556	19.179	011F	287	0.1435	0.006	0.009	0.493		
0E72	3698	1.849	0.073	0.111	6.356			0E7E	3710	1.855	0.073	0.111	6.376	5.883	14.430
01B7	439	0.2195	0.009	0.013	0.754	-5.601	18.529	0126	294	0.147	0.006	0.009	0.505		
0E62	3682	1.841	0.072	0.110	6.328			0E6F	3695	1.8475	0.073	0.111	6.350	5.845	14.980
01AF	431	0.2155	0.008	0.013	0.741	-5.587	18.729	0128	296	0.148	0.006	0.009	0.509		
					TOTAL	-33.703	18.296						**TOTAL**	35.059	15.009

Position of Measurement on Fabric

	LEFT	RIGHT	LEFT	RIGHT			
	MSR VALS (deg)		DIST (deg)		AVG	% Diff	% Error wrt CMD
	89.5	90.5					
OUT	108.5	109.5	19	19	19	43.625	53.939
BACK	78.5	79.5	-30	-30	-30	14.430	27.273

TEST 22 *Dog is set to home position and moved vertically, encoder position is read at peaks*

	TRANSL					ROT			
	Cycle #	COUNTS	COUNTS	MMs		Cycle #	COUNTS	COUNTS	MMs
U	1	0000	0	0	U	1	0000	0	0
D	2	FFD7	-41	-0.0205	D	2	FFFF	-1	-0.0005
U	3	0025	37	0.0185	U	3	0000	0	0
D	4	FFE3	-29	-0.0145	D	4	FFFE	-2	-0.001
U	5	0028	40	0.02	U	5	0000	0	0
D	6	FFE6	-26	-0.013	D	6	FFFE	-2	-0.001
U	7	002A	42	0.021	U	7	0001	1	0.0005
D	8	FFE7	-25	-0.0125	D	8	FFFE	-2	-0.001
U	9	002A	42	0.021	U	9	0000	0	0
D	10	FFE1	-31	-0.0155	D	10	FFFE	-2	-0.001
U	11	002B	43	0.0215	U	11	0000	0	0
D	12	FFE6	-26	-0.013	D	12	FFFE	-2	-0.001

APPENDIX E

MACHINE VISION FOR FABRIC EXPERIMENTS

For tracking the dots on the fabric, a machine vision system was set up using a National Instrument's (NI) 1722 Smart Camera. The programs were written in Labview making use of the Machine Vision Toolbox. In order to convert the camera's pixel coordinates to coordinates in inches, a calibration program, shown in Figure 70, was created that used Labview's Create Calibration Image and Template block to create a calibrated image that could then be used to calibrate images of the fabric to provide data in inches instead of pixels. The calibration image can be seen in Figure 71.

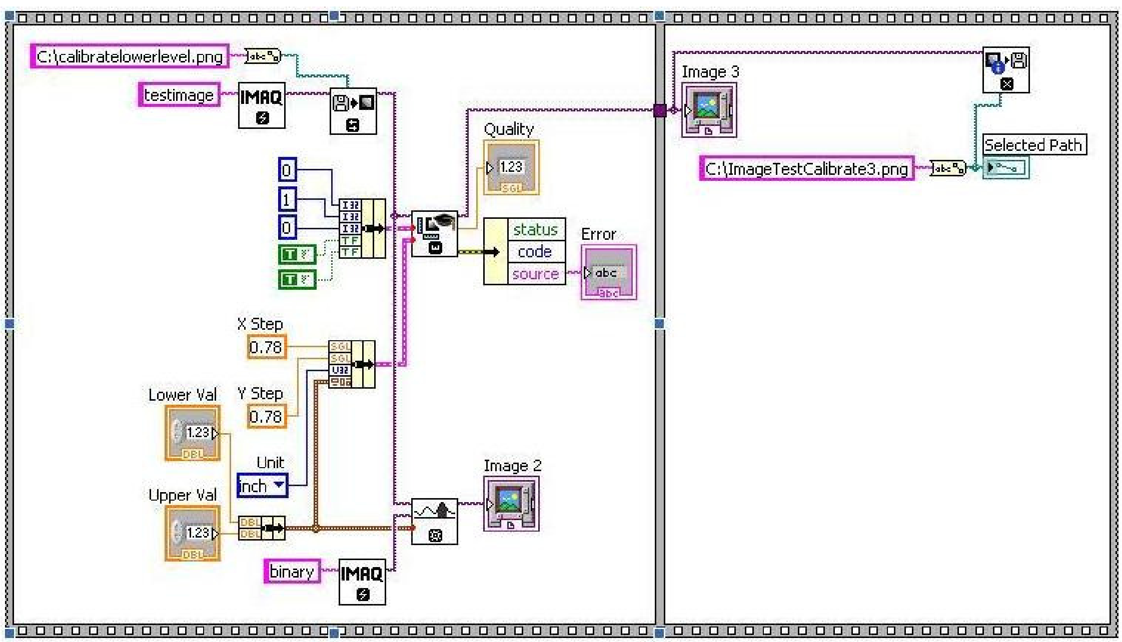


Figure 70 The calibration program takes an image containing a uniform grid of dots and the distances between them and creates an image that contains the conversion of pixel coordinates to real world coordinates in inches.

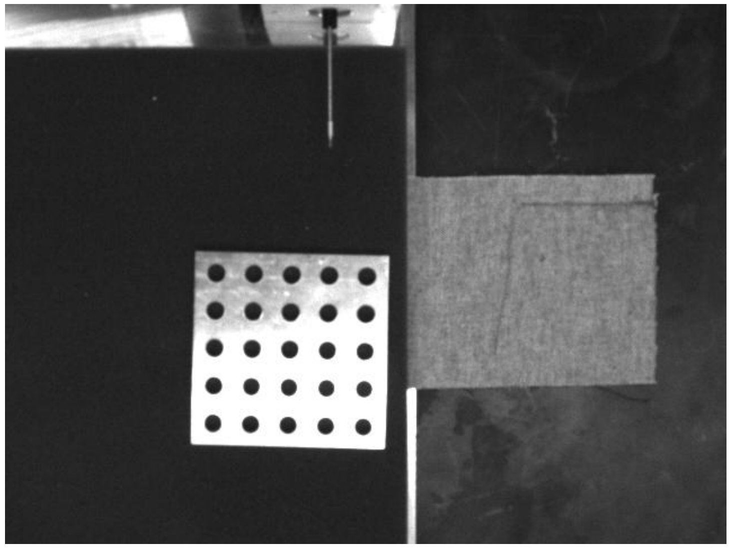


Figure 71 The calibrated image contains the conversion information in the file. The template is machined aluminum with dots 0.78 inches apart.

Using the calibrated image, another program was created to find the dots on the fabric and record their position. The program created three bounding boxes that could be adjusted by the user while running the program. The image could be converted to a black and white image using a different threshold level for each bounding box. This allowed for the dots to be found without worrying about image noise outside of the area immediately surrounding the dots. In addition, as the dots are brought out using a threshold, they are located using another built-in Labview function to find objects. The pixel coordinates of the dots are then inputted into a block that uses the calibrated image to convert them to real world coordinates in inches. The coordinates are then outputted as an xls file each time the user clicks on the "Take Data" button. The program can be seen in Figure 72 through Figure 74.

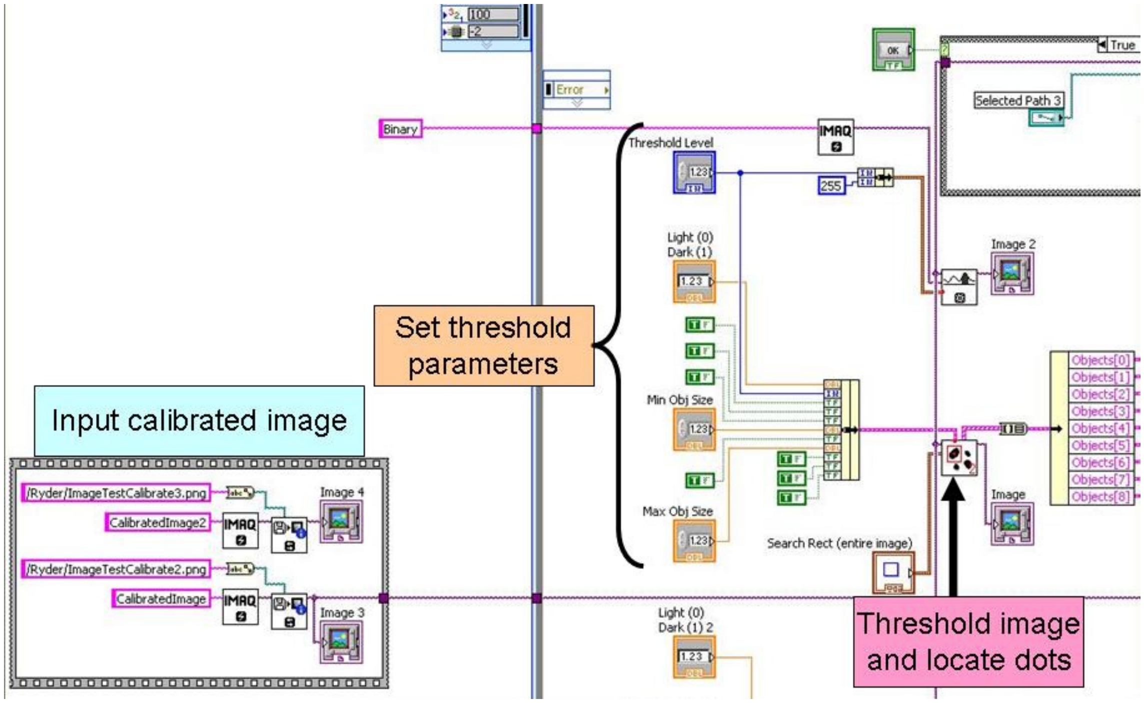


Figure 72 The experiment program takes a calibrated image and uses a threshold to locate dots inside a bounding box.

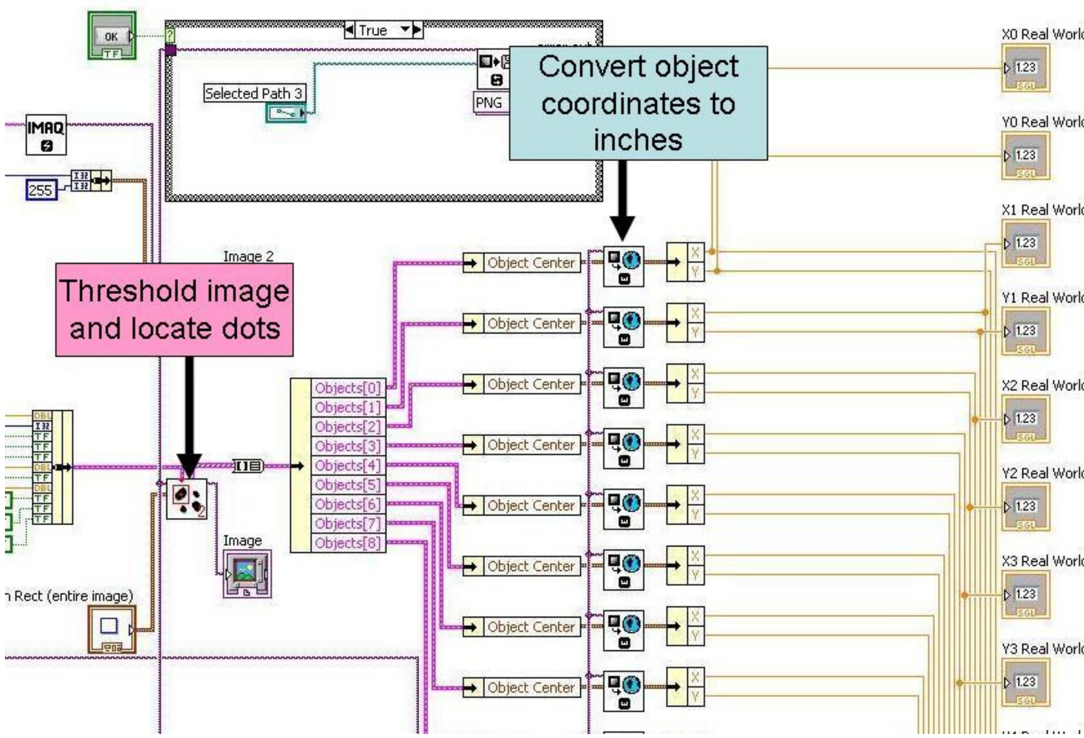


Figure 73 The located objects' coordinates are convert to inches using the loaded calibrated image.

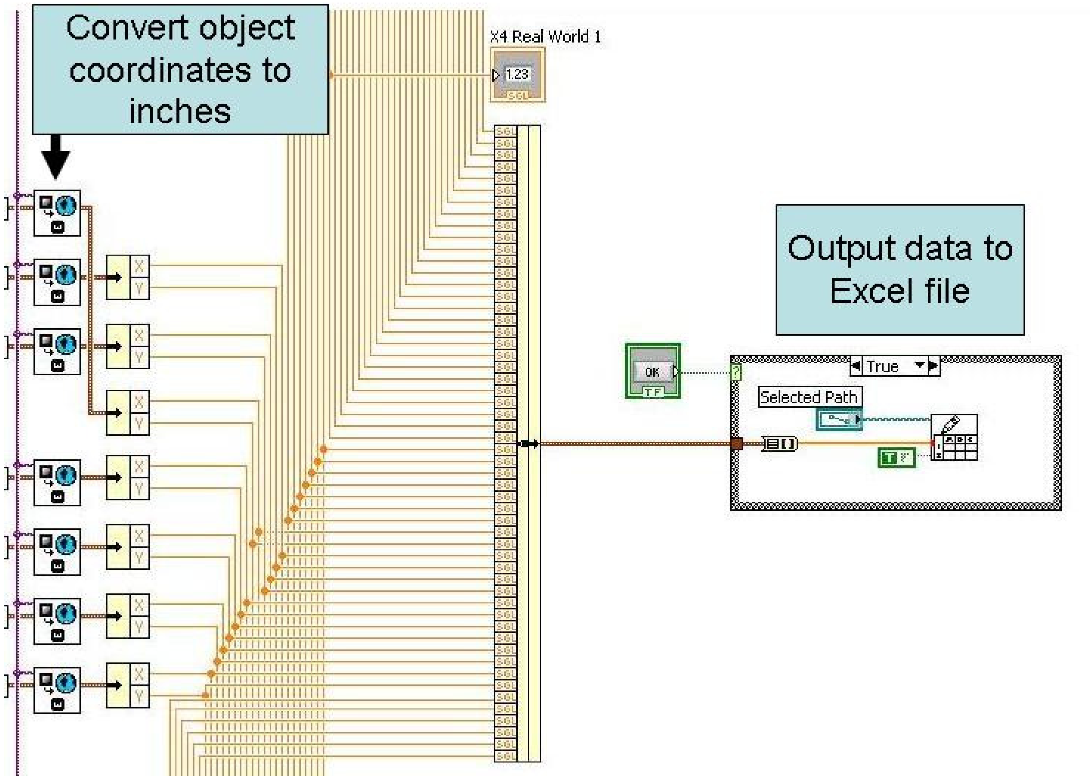


Figure 74 The converted images are exported as a .xls file.

During the experiment, the locations, sizes and orientations of the three bounding boxes can be changed. The threshold levels of the bounding boxes can also be changed. Each coordinate of detected object is also outputted to the screen in pseudo-real-time. When the user wants to record the object coordinates, he or she simply clicks the "Take Data" button to add the data to an Excel file. A portion of the main screen is shown in Figure 75.

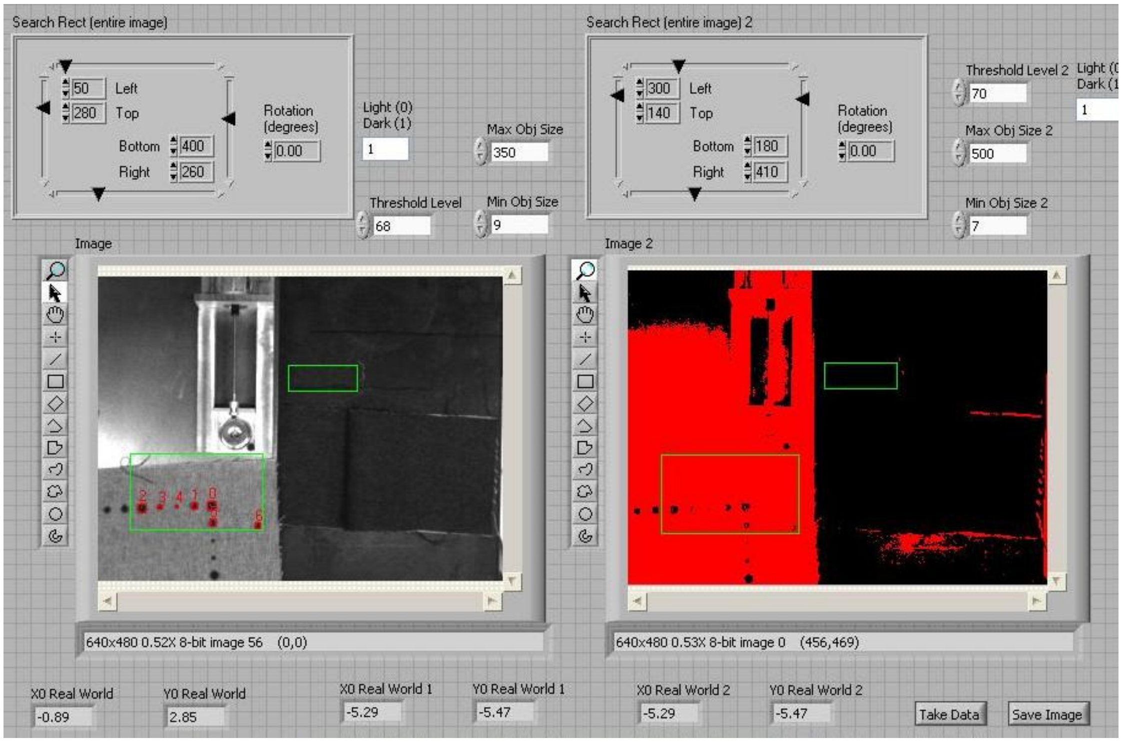


Figure 75 The main screen used to collect data during the fabric experiments.

APPENDIX F

EXAMPLE MATLAB CODE FOR DATA ANALYSIS

```
clear all

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%Experiment 1%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Load data and get data size
Data=load('dataHor.txt');
Dsize=size(Data);

% Find the length of motions in the x & y directions

for j=1:2:(Dsize(2)-1)
    place=1;
    for i = 2:1:Dsize(1)
        dogdiff(place,j)=Data(i,j)-Data(i-1,j);
        dogdiff(place,j+1)=Data(i,j+1)-Data(i-1,j+1);
        place=place+1;
    end
end
diffsize=size(dogdiff);     %get size of created matrix

% Create a vector represent each step
T = zeros(diffsize(1),1);
for i=1:diffsize(1)
    T(i,1)=i;
end

% Plot the length of movement y dir.
figure
plot(T(:,1),dogdiff(:,36),'bo-'),grid on, hold on
plot(T(:,1),dogdiff(:,34),'ko-')
plot(T(:,1),dogdiff(:,32),'ro-')
plot(T(:,1),dogdiff(:,30),'go-')
plot(T(:,1),dogdiff(:,28),'co-')
plot(T(:,1),dogdiff(:,26),'mo-')
plot(T(:,1),dogdiff(:,24),'yo-')
plot(T(:,1),dogdiff(:,22),'ko-')
plot(T(:,1),dogdiff(:,20),'ro-')
plot(T(:,1),dogdiff(:,18),'go-')
plot(T(:,1),dogdiff(:,16),'co-')
plot(T(:,1),dogdiff(:,14),'mo-')
plot(T(:,1),dogdiff(:,12),'yo-')
plot(T(:,1),dogdiff(:,10),'ko-')
plot(T(:,1),dogdiff(:,8),'ro-')
plot(T(:,1),dogdiff(:,6),'go-')
plot(T(:,1),dogdiff(:,4),'co-')
plot(T(:,1),dogdiff(:,2),'mo-'),hold off
title('8x14 - Displacement in Y-Direction')
xlabel('Motion #')
```

```
ylabel('Displacement (inches)')
legend('Dog','Dot 0','Dot 1','Dot 2','Dot 3','Dot 4','Dot 5'...
    ,'Dot 6','Dot 7','Dot 8','Dot 9','Dot 10','Dot 11','Dot 12'...
    ,'Dot 13','Dot 14','Dot 15','Dot 16','Dot 17')

% Plot the length of movement x dir.
figure
plot(T(:,1),dogdiff(:,35),'bo-'),grid on, hold on
plot(T(:,1),dogdiff(:,33),'ko-')
plot(T(:,1),dogdiff(:,31),'ro-')
plot(T(:,1),dogdiff(:,29),'go-')
plot(T(:,1),dogdiff(:,27),'co-')
plot(T(:,1),dogdiff(:,25),'mo-')
plot(T(:,1),dogdiff(:,23),'yo-')
plot(T(:,1),dogdiff(:,21),'ko-')
plot(T(:,1),dogdiff(:,19),'ro-')
plot(T(:,1),dogdiff(:,17),'go-')
plot(T(:,1),dogdiff(:,15),'co-')
plot(T(:,1),dogdiff(:,13),'mo-')
plot(T(:,1),dogdiff(:,11),'yo-')
plot(T(:,1),dogdiff(:,9),'ko-')
plot(T(:,1),dogdiff(:,7),'ro-')
plot(T(:,1),dogdiff(:,5),'go-')
plot(T(:,1),dogdiff(:,3),'co-')
plot(T(:,1),dogdiff(:,1),'mo-'),hold off
title('8x14 - Displacement in X-Direction')
xlabel('Motion #')
ylabel('Displacement (inches)')
legend('Dog','Dot 0','Dot 1','Dot 2','Dot 3','Dot 4','Dot 5'...
    ,'Dot 6','Dot 7','Dot 8','Dot 9','Dot 10','Dot 11','Dot 12'...
    ,'Dot 13','Dot 14','Dot 15','Dot 16','Dot 17')

% Plot the fabric movement
figure
for j=1:2:(Dsize(2)-1)
    plot(Data(:,j),Data(:,j+1),'x-'),hold on,grid on
    xlabel('X (inches)')
    ylabel('Y (inches)')
end
hold off

% Find Fabric Mvmt
% Forward
place2=1;
N=5;
for j=1:N
    place=1;
    for i=1:Dsize(2)/2
        P(i,place2)=Data(j,place);
        place=place+1;
        P(i,place2+1)=Data(j,place);
        place=place+1;
    end
    place2=place2+2;
end
```

```
% Back
place2=1;
N=5;
for j=N:9

    place=1;
    for i=1:Dsize(2)/2
        Q(i,place2)=Data(j,place);
        place=place+1;
        Q(i,place2+1)=Data(j,place);
        place=place+1;
    end
    place2=place2+2;
end

%%%%%%%%%%%%%%%%%%%%

% Find regression lines

for i=1:1:length(P)-1
    P2(i,:)=P(i,:);
end

F(1,:)=polyfit(P2(:,1),P2(:,2),1)
F1=polyval(F(1,:),P2(:,1));
F(2,:)=polyfit(P2(:,3),P2(:,4),1)
F2=polyval(F(2,:),P2(:,3));
F(3,:)=polyfit(P2(:,5),P2(:,6),1)
F3=polyval(F(3,:),P2(:,5));
F(4,:)=polyfit(P2(:,7),P2(:,8),1)
F4=polyval(F(4,:),P2(:,7));
F(5,:)=polyfit(P2(:,9),P2(:,10),1)
F5=polyval(F(5,:),P2(:,9));

for i=1:1:length(Q)-1
    Q2(i,:)=Q(i,:);
end

F(6,:)=polyfit(Q2(:,1),Q2(:,2),1)
G1=polyval(F(6,:),Q2(:,1));
F(7,:)=polyfit(Q2(:,3),Q2(:,4),1)
G2=polyval(F(7,:),Q2(:,3));
F(8,:)=polyfit(Q2(:,5),Q2(:,6),1)
G3=polyval(F(8,:),Q2(:,5));
F(9,:)=polyfit(Q2(:,7),Q2(:,8),1)
G4=polyval(F(9,:),Q2(:,7));
F(10,:)=polyfit(Q2(:,9),Q2(:,10),1)
G5=polyval(F(10,:),Q2(:,9));

figure
subplot(2,1,1), plot(P(:,1),P(:,2),'r*'),hold on, grid on
plot(P2(:,1),F1,'r')
plot(P(:,3),P(:,4),'b*')
plot(P2(:,3),F2,'b')
plot(P(:,5),P(:,6),'g*')
```

```
plot(P2(:,5),F3,'g')
plot(P(:,7),P(:,8),'k*')
plot(P2(:,7),F4,'k')
plot(P(:,9),P(:,10),'m*')
plot(P2(:,9),F5,'m')
hold off
title('8x14 - Fabric Motion - Forward')
xlabel('X-axis (inches)')
ylabel('Y-axis (inches)')
legend('Position 0 Data','Position 0 Regr.','Position 1 Data','Position
1 Regr.',...
    'Position 2 Data','Position 2 Regr.','Position 3 Data','Position 3
Regr.',...
    'Position 4 Data','Position 4 Regr.')

% Regression Error
FE1=F1-P2(:,2);
FE2=F2-P2(:,4);
FE3=F3-P2(:,6);
FE4=F4-P2(:,8);
FE5=F5-P2(:,10);

subplot(2,1,2), plot(P2(:,1),FE1,'r'),hold on, grid on
plot(P2(:,3),FE2,'b')
plot(P2(:,5),FE3,'g')
plot(P2(:,7),FE4,'k')
plot(P2(:,9),FE5,'m')
hold off
title('Forward Error between Data and Regression Line')
xlabel('X-axis (inches)')
ylabel('Error (inches)')
axis([-4 10 -.12 .05])
legend('Position 0 Error','Position 1 Error',...
    'Position 2 Error','Position 3 Error',...
    'Position 4 Error')

figure
subplot(2,1,1), plot(Q(:,1),Q(:,2),'m*'),hold on, grid on
plot(Q2(:,1),G1,'m')
plot(Q(:,3),Q(:,4),'k*')
plot(Q2(:,3),G2,'k')
plot(Q(:,5),Q(:,6),'g*')
plot(Q2(:,5),G3,'g')
plot(Q(:,7),Q(:,8),'b*')
plot(Q2(:,7),G4,'b')
plot(Q(:,9),Q(:,10),'r*')
plot(Q2(:,9),G5,'r')
hold off
title('8x14 - Fabric Motion - Back')
xlabel('X-axis (inches)')
ylabel('Y-axis (inches)')
legend('Position 4 Data','Position 4 Regr.','Position 5 Data','Position
5 Regr.',...
    'Position 6 Data','Position 6 Regr.','Position 7 Data','Position 7
Regr.',...
    'Position 8 Data','Position 8 Regr.')
```

```
% Regression Error
GE1=G1-Q2(:,2);
GE2=G2-Q2(:,4);
GE3=G3-Q2(:,6);
GE4=G4-Q2(:,8);
GE5=G5-Q2(:,10);

subplot(2,1,2), plot(Q2(:,1),GE1,'m'),hold on, grid on
plot(Q2(:,3),GE2,'k')
plot(Q2(:,5),GE3,'g')
plot(Q2(:,7),GE4,'b')
plot(Q2(:,9),GE5,'r')
hold off
title('Back Error between Data and Regression Line')
xlabel('X-axis (inches)')
ylabel('Error (inches)')
axis([-4 10 -.12 .05])
legend('Position 4 Error','Position 5 Error',...
    'Position 6 Error','Position 7 Error',...
    'Position 8 Error')

% Index
for i=1:length(F)
    Index(i,1)=i
end

Slope=polyfit(Index(1:5,1),F(1:5,1),1)
Slope1=polyval(Slope,Index(1:5,1));
Slopeb=polyfit(Index(6:length(F),1),F(6:length(F),1),1)
Slopeb1=polyval(Slopeb,Index(6:length(F),1));

figure
plot(Index(1:5,1),F(1:5,1),'b*'), grid on, hold on
plot(Index(1:5,1),Slope1,'b-')
plot(Index(6:length(F),1),F(6:length(F),1),'r*')
plot(Index(6:length(F),1),Slopeb1,'r-')
hold off
title('8x14 - Regression Line Slope vs. Motion')
xlabel('Motion #')
ylabel('Slope of Regression Line')
legend('Slope of Regr. Lines (Forward)','Linear approx.',...
    'Slope of Regr. Lines (Back)','Linear approx.')
```

APPENDIX G

RESULTS FROM FABRIC EXPERIMENTS

The results will be presented in three sections corresponding to the three types of fabric behavior.

G.1 Fabric Buckling with Linear Increase in Slope

The following chart shows all of the experiments that resulted in large deformations of fabric. These experiments exhibited a linear rate of change of the slope of the lines of dots. An example case, Experiment 10, will also be shown graphically.

Table 3 The slope of the slopes of the dot lines is listed for both the Horizontal and Vertical dot lines. Notice that the magnitude of the slopes back is greater than the slopes out only for the Fabric on Aluminum cases. 13a and 14F1, and 13b and 14F1 represent the dot lines near the dog and far from the dog respectively. The F stands for fabric on fabric as opposed to the table. NA=Not Available.

	Fabric on Aluminum	Horizontal		Vertical	
Exp. #	**Fabric Size**	**Slope Out**	**Slope Back**	**Slope Out**	**Slope Back**
1	8x14	0.0424	-0.0495	-0.0391	0.0455
4	3x14	0.0388	-0.055	NA	NA
7	6x14	0.0412	-0.0663	NA	0.0491
10	8x14	0.0407	-0.0484	-0.0399	0.0482
13a	10x14	0.0418	-0.0468	-0.038	0.0446
13b	10x14	0.0389	-0.0438	-0.0389	0.0454
Fabric on Fabric					
14F	6x12	-0.0607	0.0616	0.051	-0.0512
14F1	6x12	NA	NA	0.0497	-0.034
15F	6x9	-0.0835	0.0884	NA	NA

G.1.1 Experiment 10 Horizontal Row of Dots

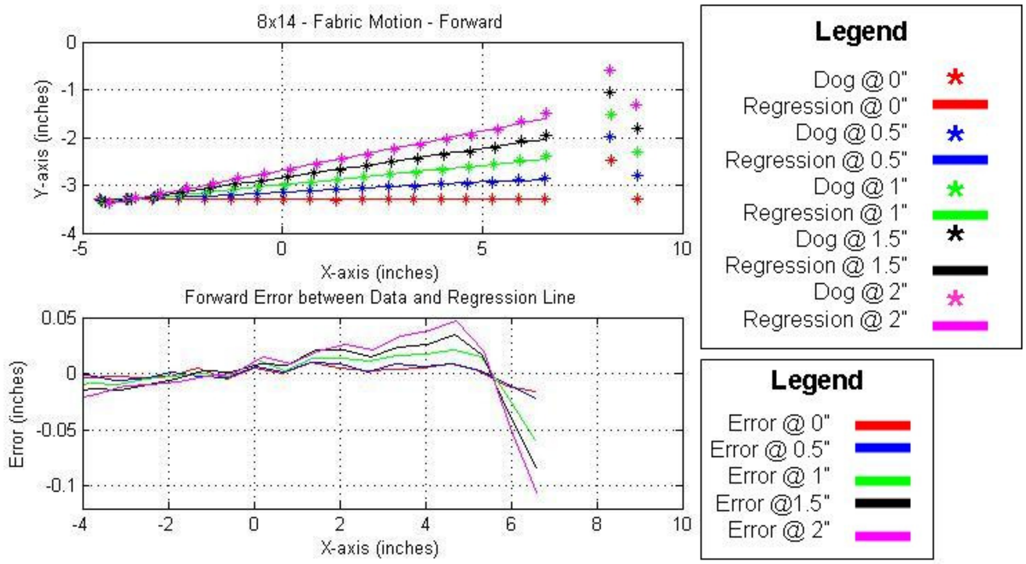


Figure 76 The top graph shows the horizontal row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

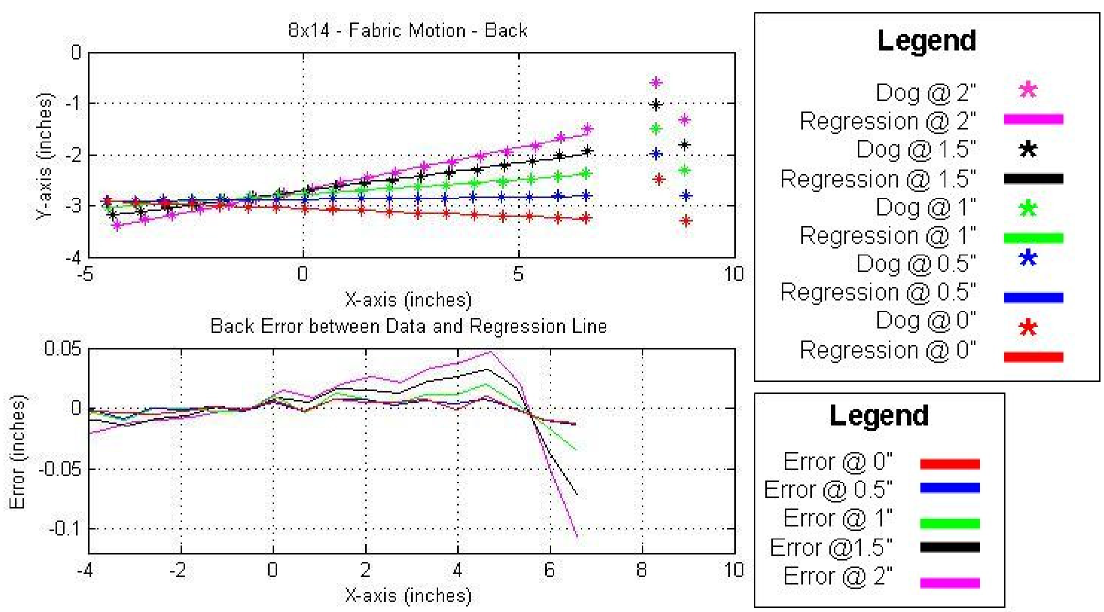


Figure 77 The two graphs are exactly the same as Figure 76 except that the graphs represent the positions as the dog returns to its starting position. Therefore, it is starting at 2" with the fabric deformed and moving to 0", removing the buckle in the fabric.

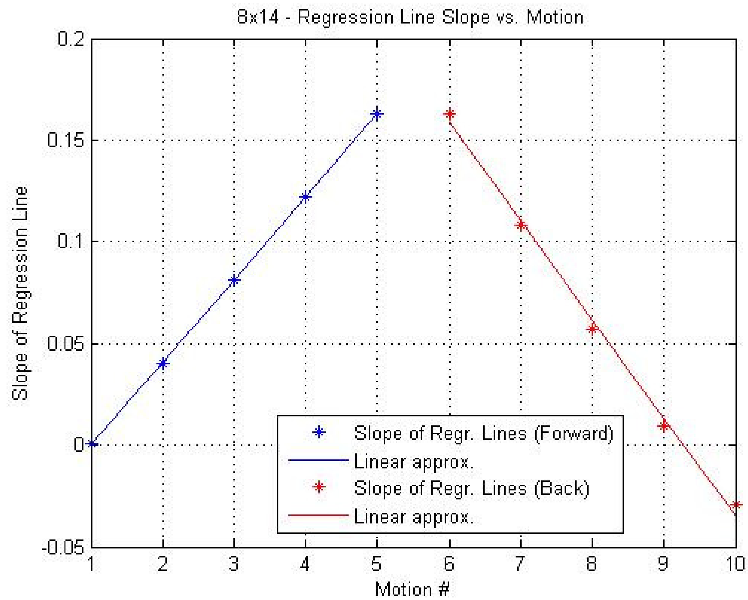


Figure 78 The slopes of the regression lines follow a linear pattern. The blue line represents the motion of the fabric while the dog moves out. The red line represents the motion of the dog moving back to the initial position.

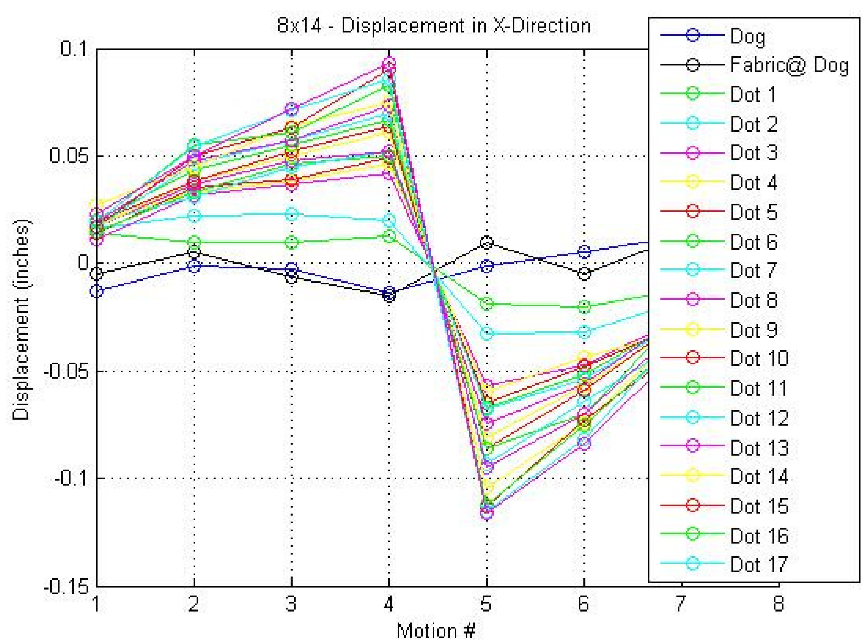


Figure 79 The displacements in the x direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

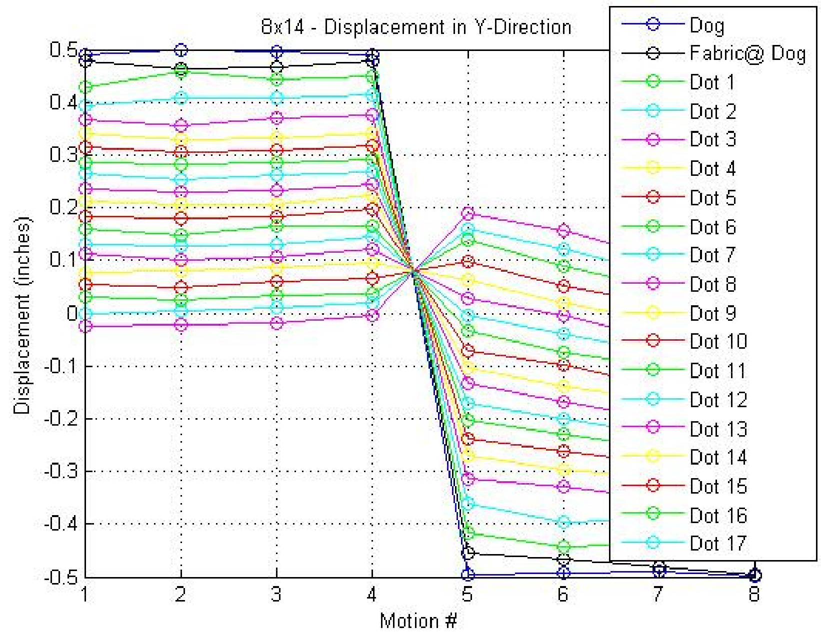


Figure 80 The displacements in the y direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

G.1.2 Experiment 10 Vertical Row of Dots

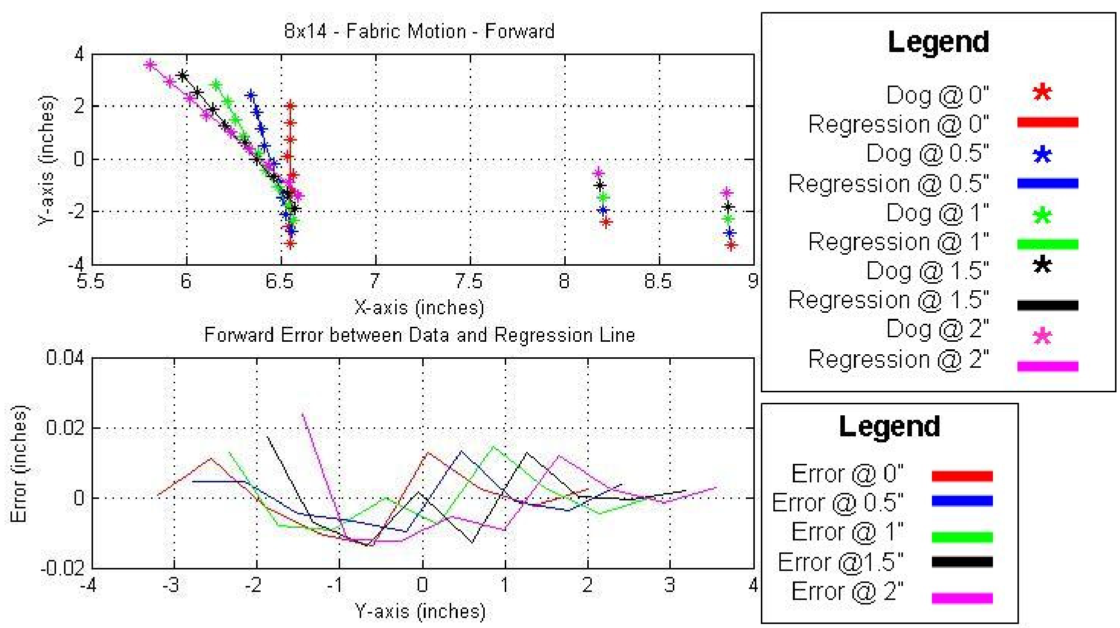


Figure 81 The top graph shows the vertical row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

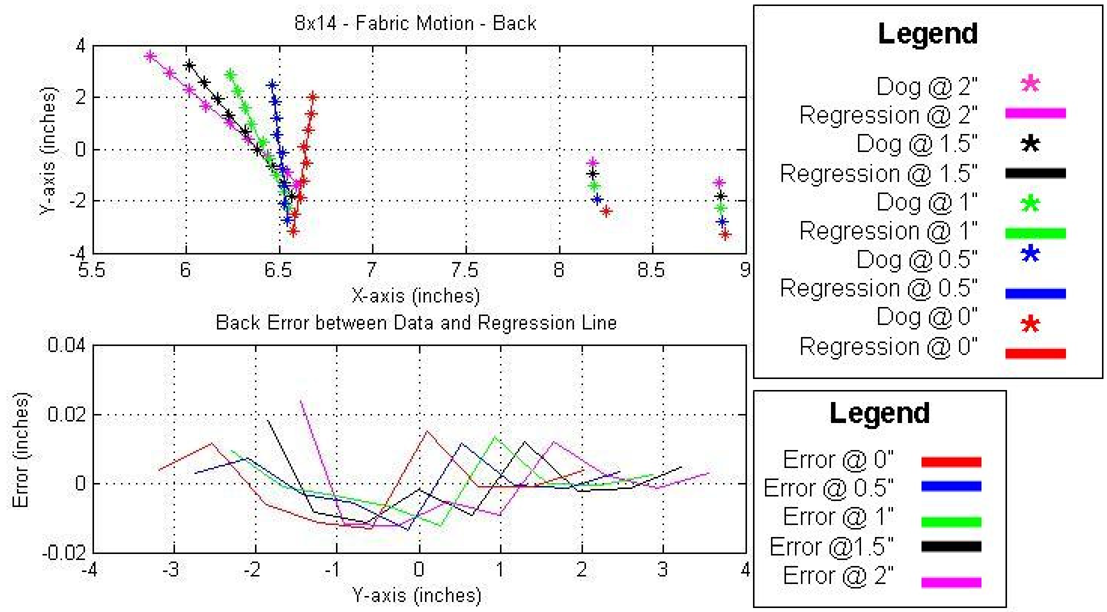


Figure 82 The two graphs are exactly the same as Figure 81 except that the graphs represent the positions as the dog returns to its starting position. Therefore, it is starting at 2" with the fabric deformed and moving to 0", removing the buckle in the fabric.

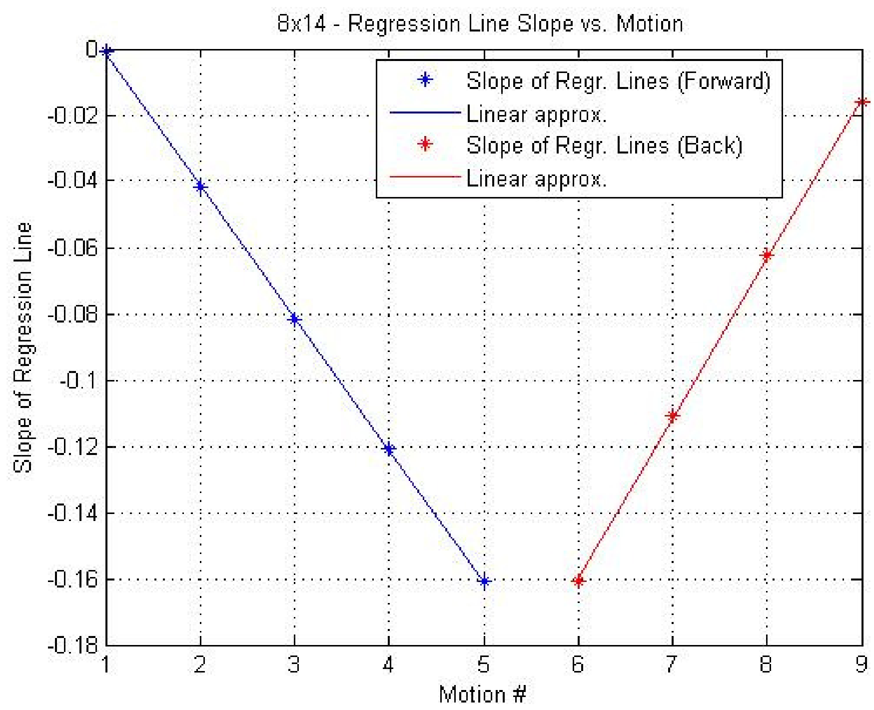


Figure 83 The slopes of the regression lines follow a linear pattern. The blue line represents the motion of the fabric while the dog moves out. The red line represents the motion of the dog moving back to the initial position.

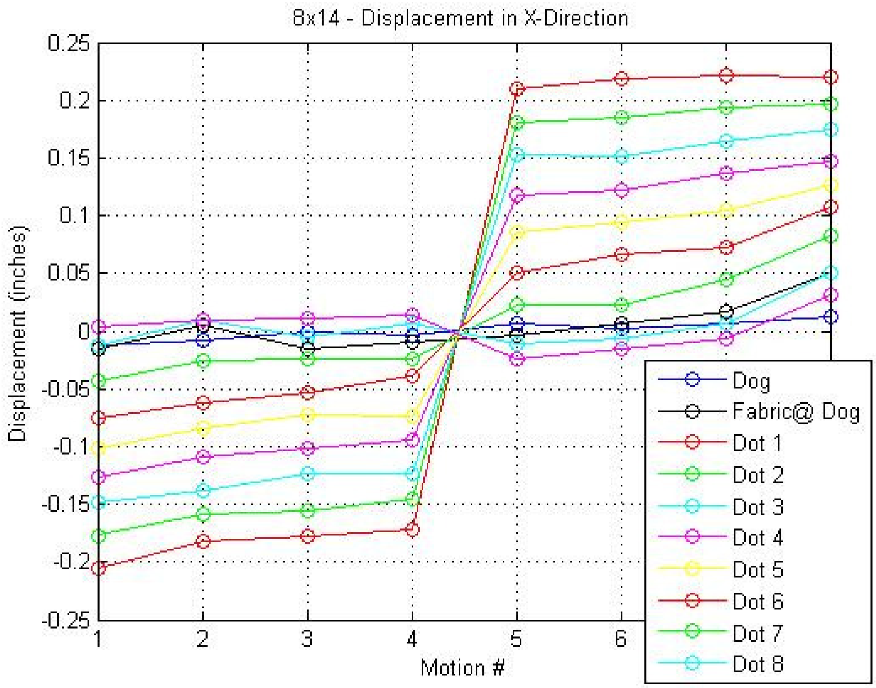


Figure 84 The displacements in the x direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

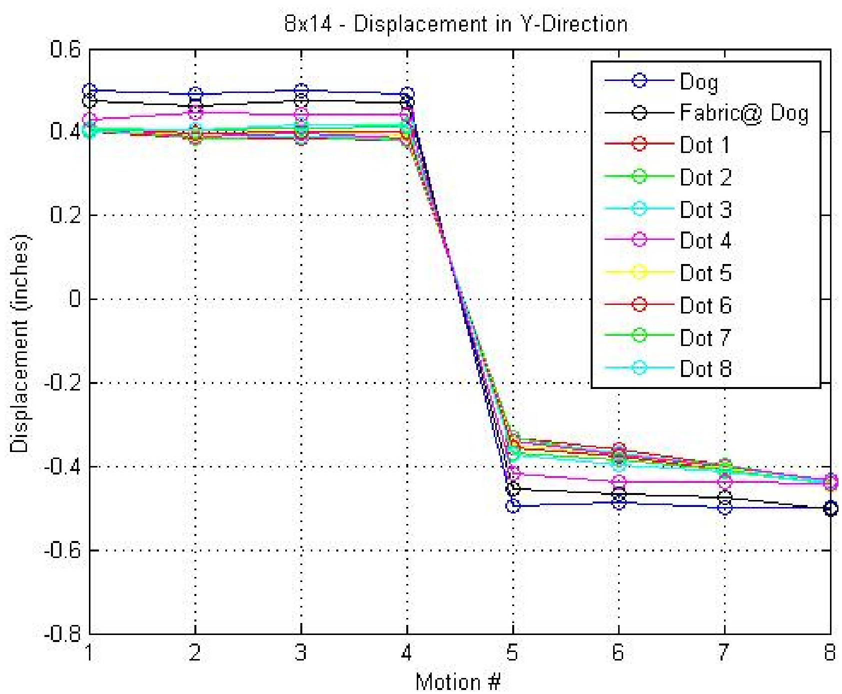


Figure 85 The displacements in the y direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

G.2 Fabric Buckling with Nonlinear Increase in Slope

The following chart shows all of the experiments that resulted in small deformations of fabric. These experiments exhibited a nonlinear rate of change of the slope of the lines of dots. An example case, Experiment 8, will also be shown graphically.

Table 4 The slope of the slopes of the dot lines is listed for both the Horizontal and Vertical dot lines. Note the smaller fabric widths relative to Table 3. 14E and 15E are tests of fabric lying on the table. NL=Nonlinear Curve; NA=Not Available.

		Horizontal		Vertical	
Exp. #	Fabric Size	Slope Out	Slope Back	Slope Out	Slope Back
Fabric on Aluminum					
2	8x9.33	NL	NL	NL	NL
8	6x9.33	NL	NL	NL	NL
11	8x9.33	NL	NL	NL	NL
Fabric on Fabric					
14E	6x12	NL	NL	NL	NL
15E	6x9	NL	NL	NA	NA
16F	6x6	NL	NL	NA	NA

G.2.1 Experiment 8 Horizontal Row of Dots

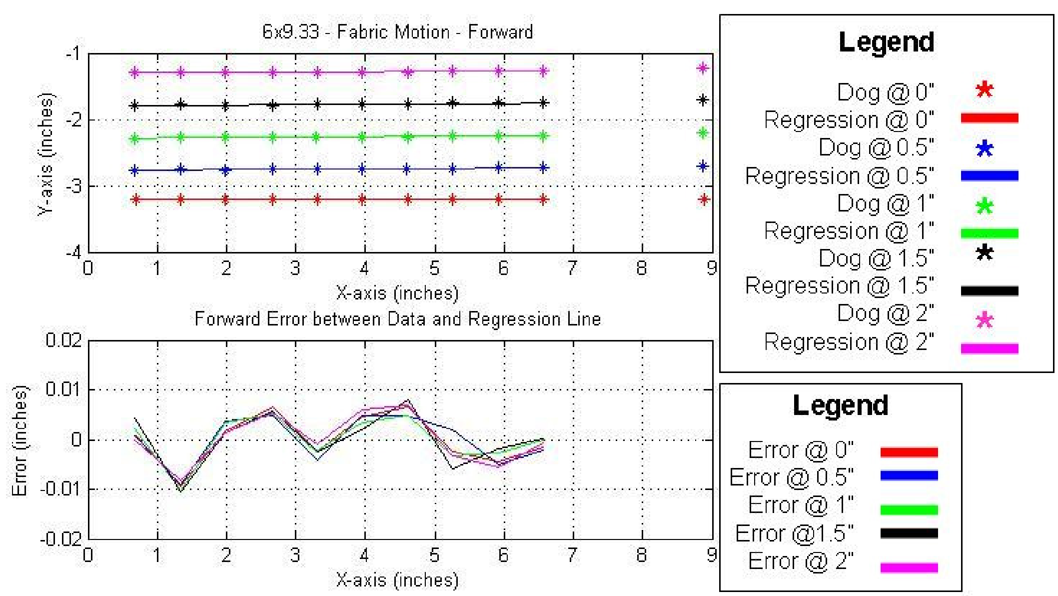


Figure 86 The top graph shows the horizontal row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

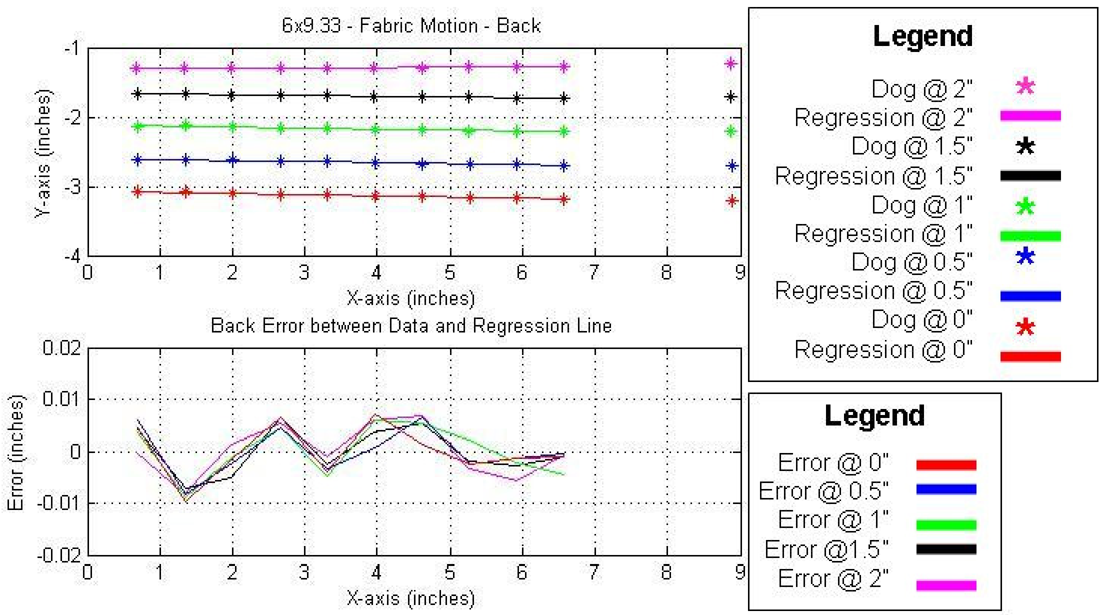


Figure 87 The two graphs are exactly the same as Figure 86 except that the graphs represent the positions as the dog returns to its starting position. Therefore, it is starting at 2" with the fabric deformed and moving to 0", removing the buckle in the fabric.

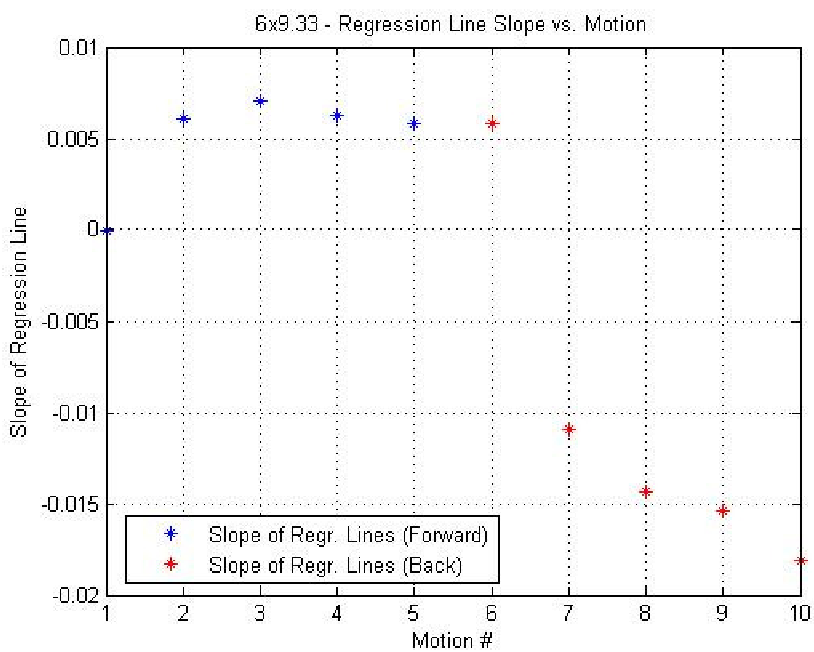


Figure 88 For fabrics that deformed slightly, there is a nonlinear relationship between the dog displacement and the slope of the dot line. Note that the slope approaches a steady state value.

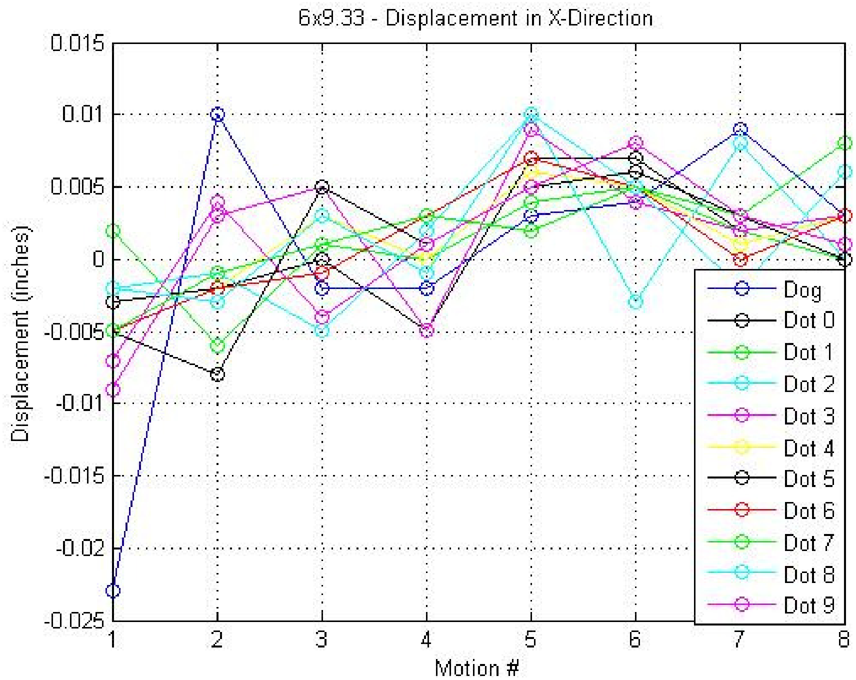


Figure 89 The displacements in the x direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

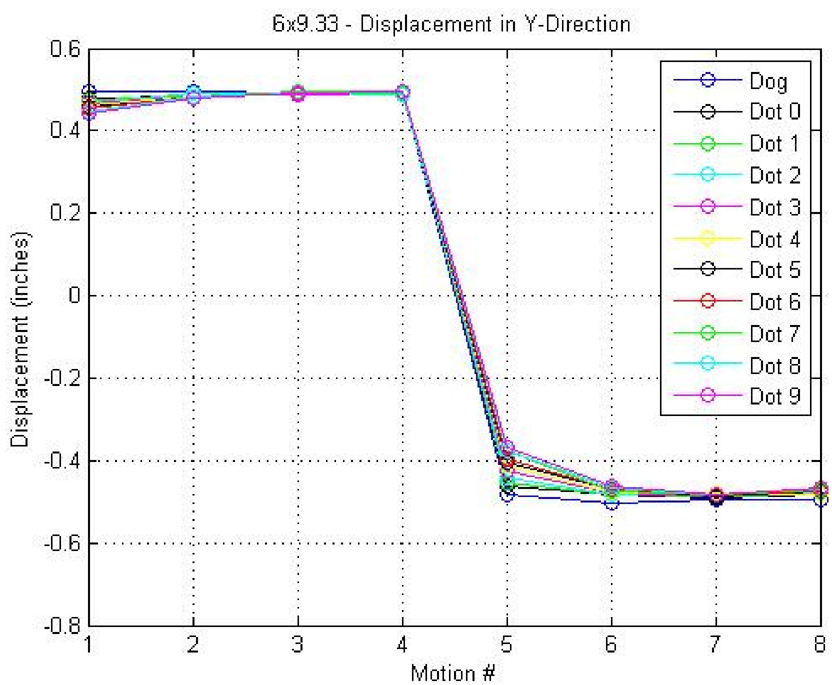


Figure 90 The displacements in the y direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

G.2.2 Experiment 8 Vertical Row of Dots

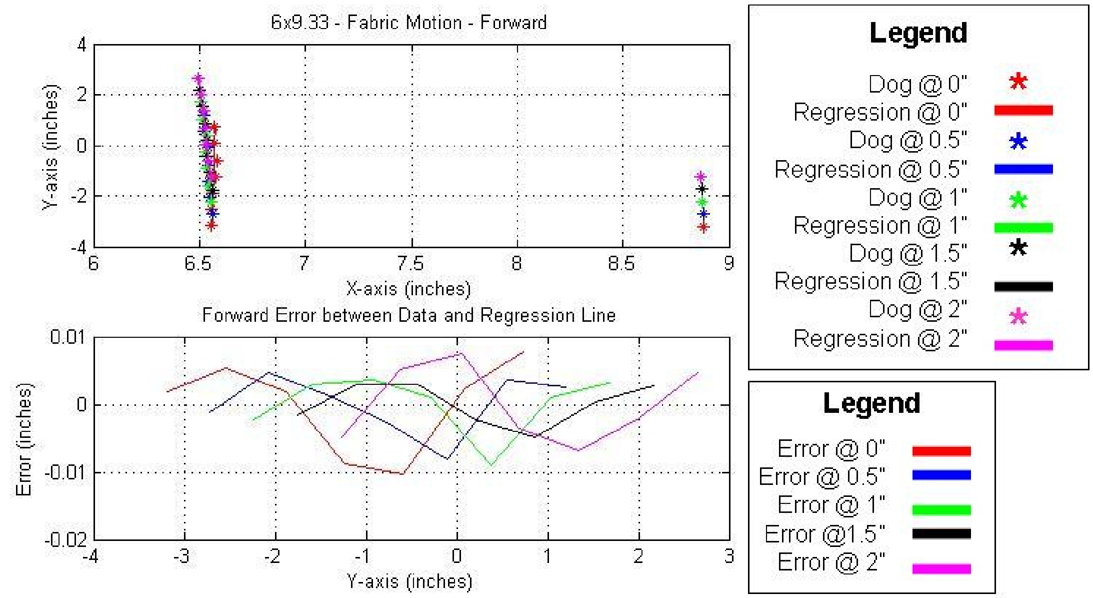


Figure 91 The top graph shows the vertical row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

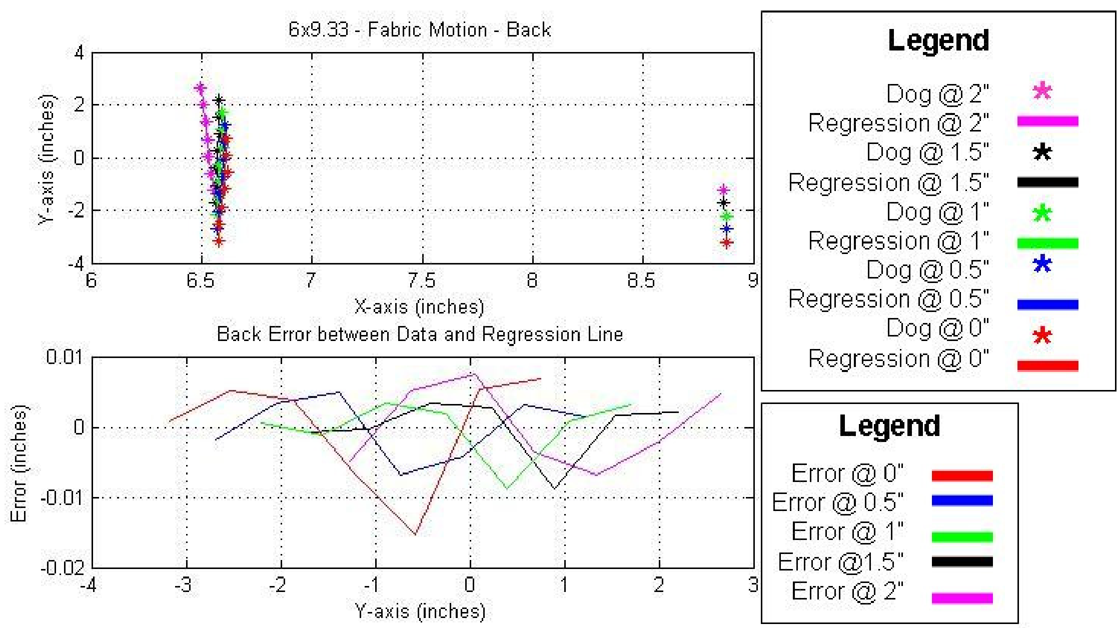


Figure 92 The two graphs are exactly the same as Figure 81 except that the graphs represent the positions as the dog returns to its starting position. Therefore, it is starting at 2" with the fabric deformed and moving to 0", removing the buckle in the fabric.

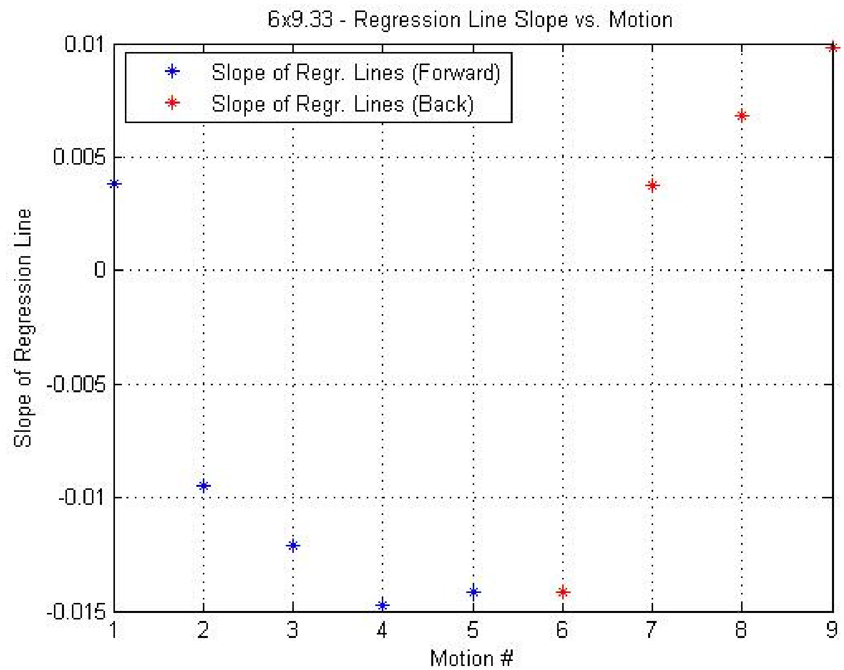


Figure 93 For fabrics that deformed slightly, there is a nonlinear relationship between the dog displacement and the slope of the dot line. Note that the slope approaches a steady state value.

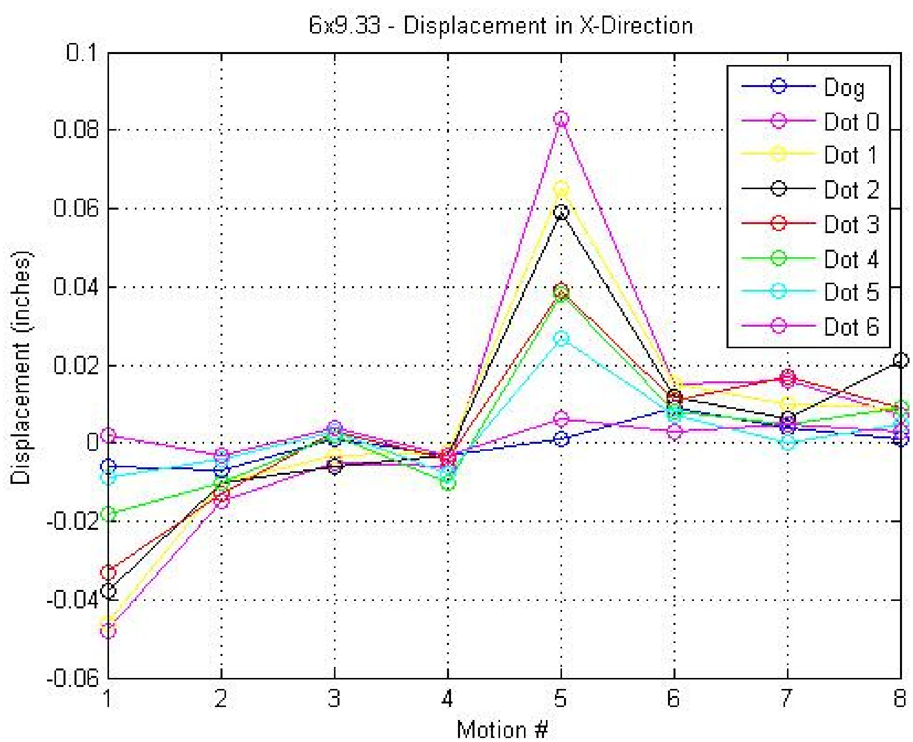


Figure 94 The displacements in the x direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

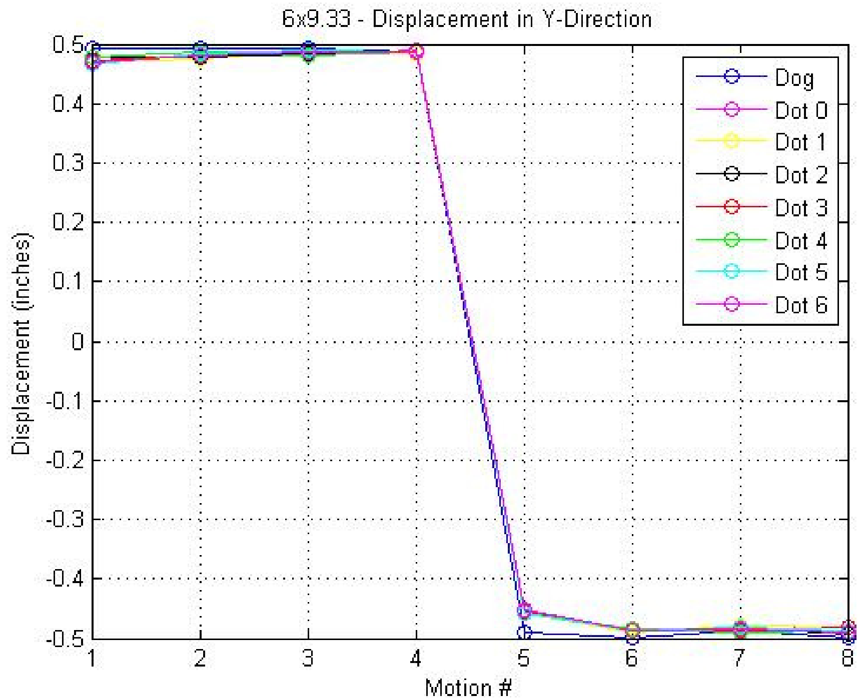


Figure 95 The displacements in the y direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

G.3 Fabric that does not Significantly Deform

The following chart shows all of the experiments that resulted in essentially no deformation of the fabric. These experiments showed that the fabric can be actuated using a dog without buckling if the width is small enough. An example case, Experiment 9, will also be shown graphically.

Table 5 The slope of the slopes of the dot lines is listed for both the Horizontal and Vertical dot lines. Note the smaller fabric widths relative to Table 3 and Table 4. 16E is a test of fabric on the table. NC=No Change in slopes; NA=Not Available.

	Fabric on Aluminum	Horizontal		Vertical	
Exp. #	Fabric Size	Slope Out	Slope Back	Slope Out	Slope Back
3	8x4.66	NC	NC	NC	NC
5	3x9.33	NC	NC	NA	NA
6	3x4.66	NC	NC	NA	NA
9	6x4.66	NC	NC	NC	NC
12	8x4.66	NC	NC	NC	NC
Fabric on Fabric					
16E	6x6	NC	NC	NA	NA

G.3.1 Experiment 9 Horizontal Row of Dots

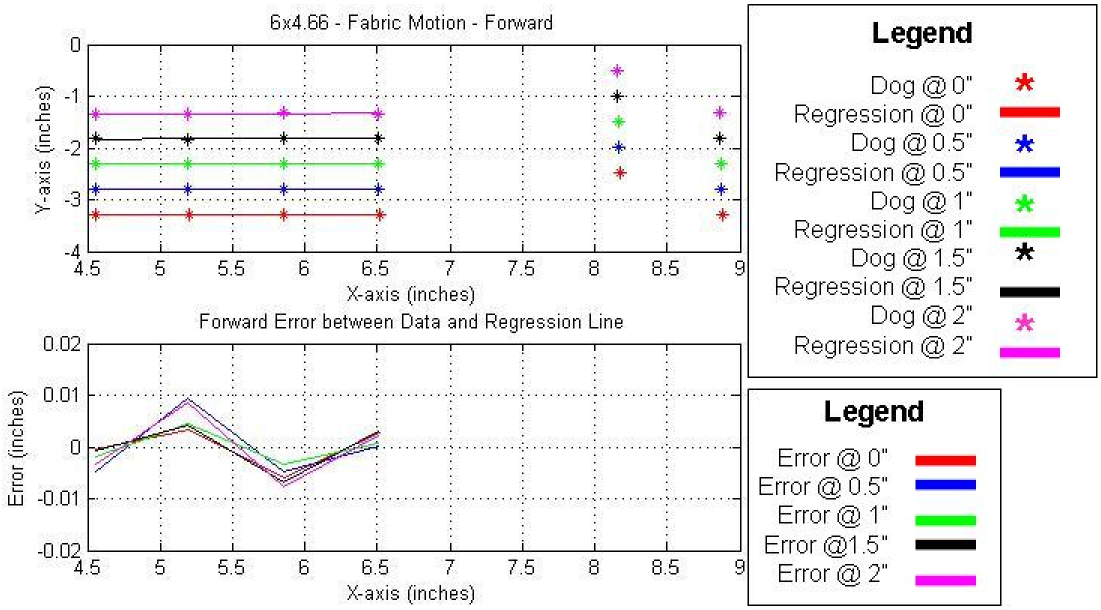


Figure 96 The top graph shows the horizontal row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

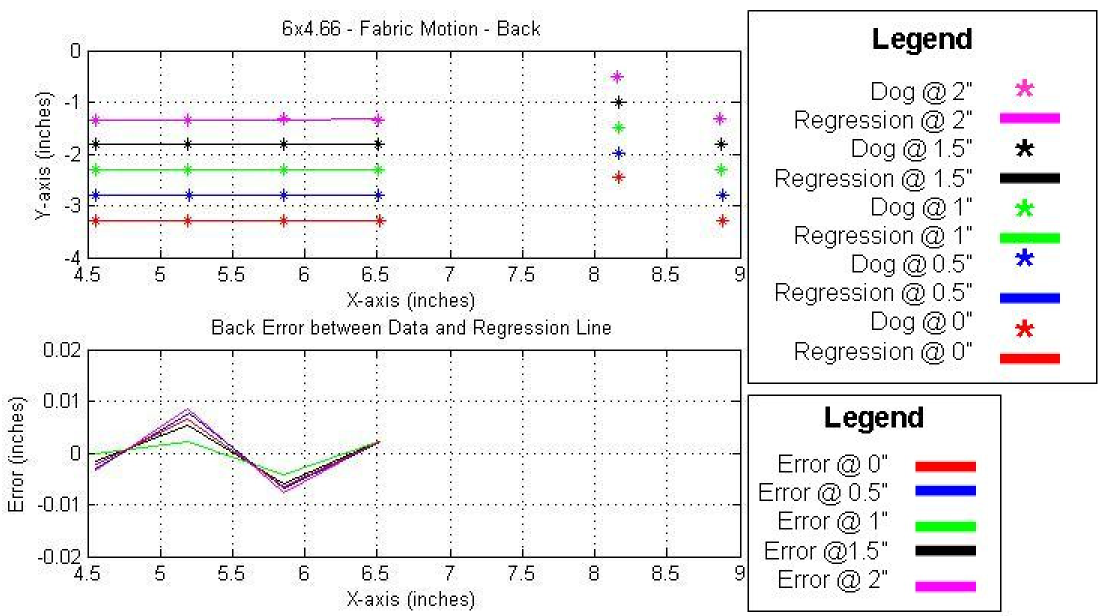


Figure 97 The two graphs are exactly the same as Figure 86 except that the graphs represent the positions as the dog returns to its starting position. Therefore, it is starting at 2" with the fabric deformed and moving to 0", removing the buckle in the fabric.

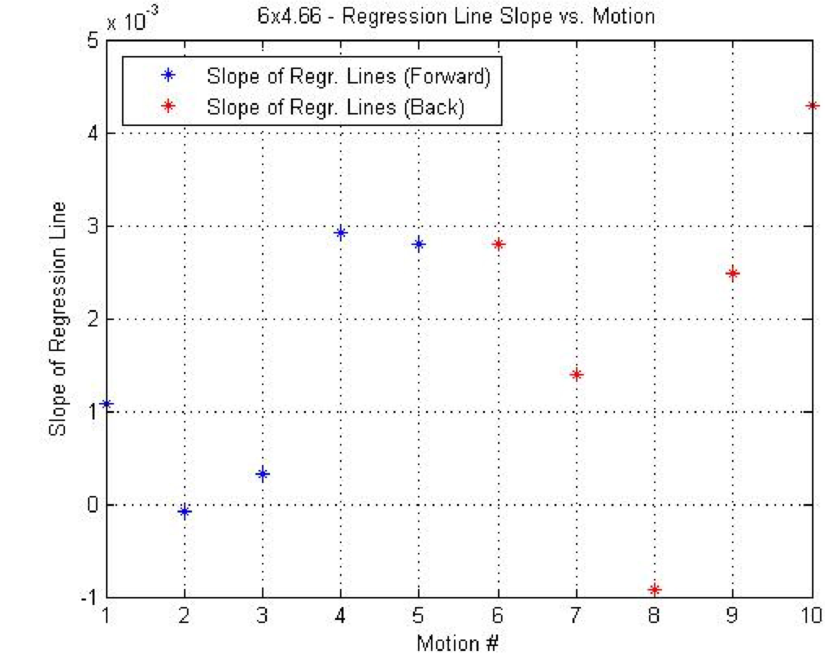


Figure 98 The smallest fabrics showed basically no change in slope.

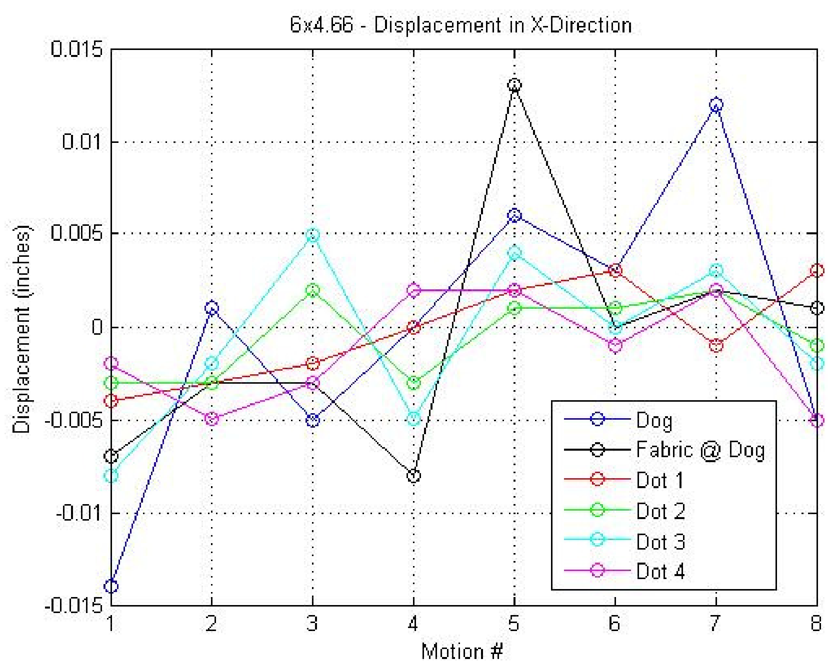


Figure 99 The displacements in the x direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

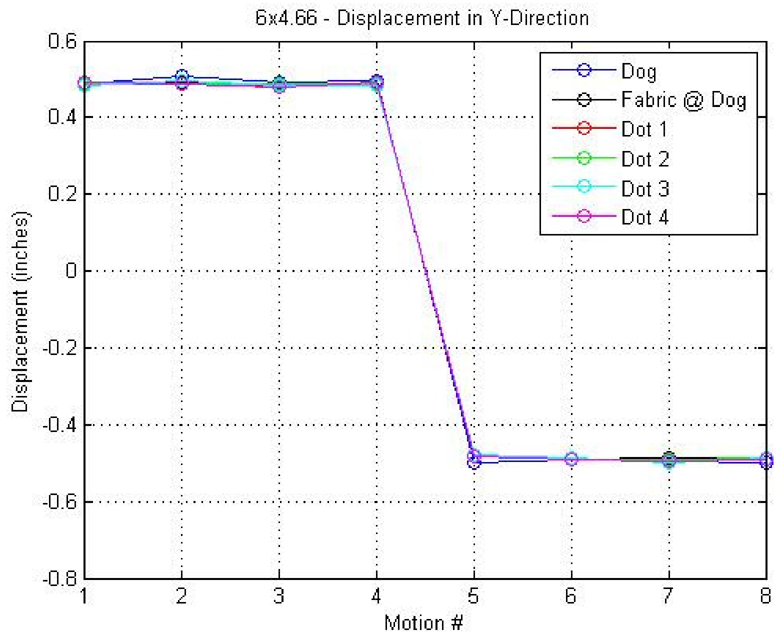


Figure 100 The displacements in the y direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

G.3.2 Experiment 9 Vertical Row of Dots

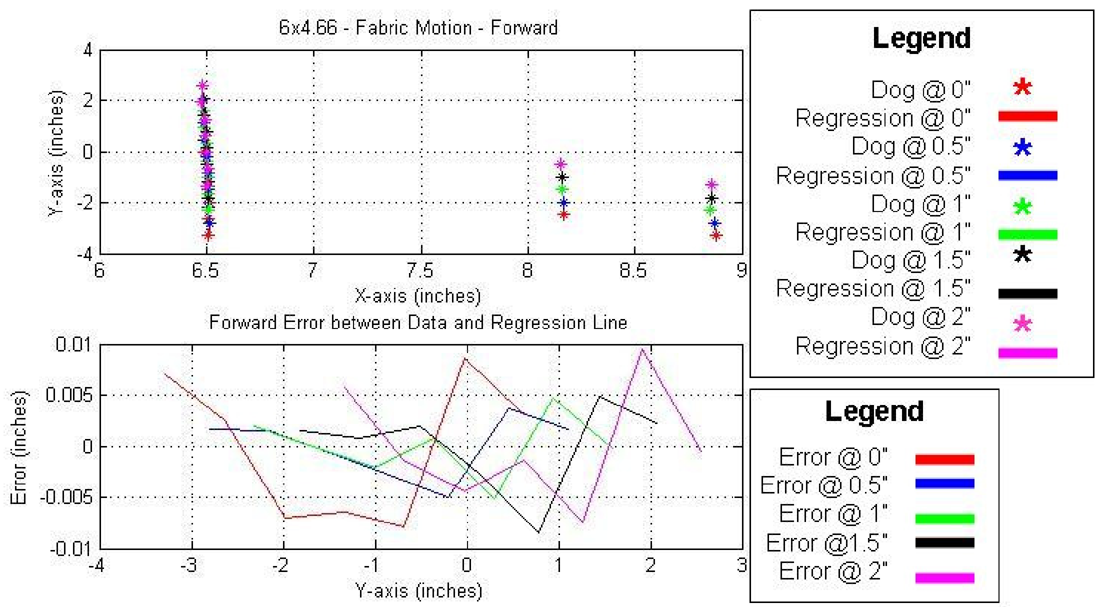


Figure 101 The top graph shows the vertical row of dots and the regression lines. The dots on the right side of the graph are the dog and a dot placed on the fabric immediately in front of the dog. Each color represents the position after a move. The bottom plot shows the error between the dots and the linear regression.

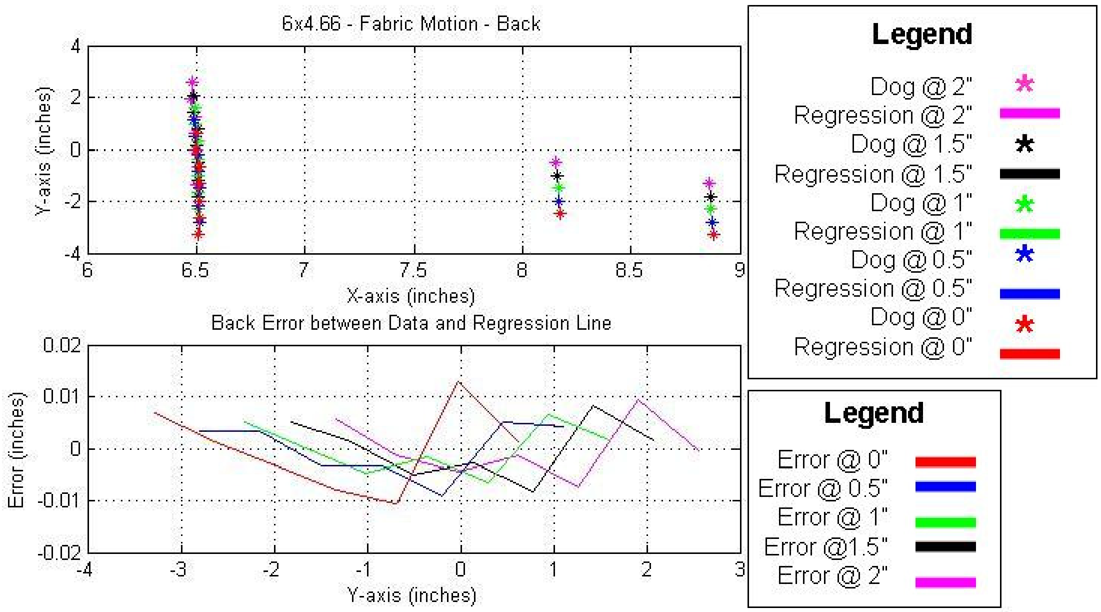


Figure 102 The two graphs are exactly the same as Figure 81 except that the graphs represent the positions as the dog returns to its starting position. Therefore, it is starting at 2" with the fabric deformed and moving to 0", removing the buckle in the fabric.

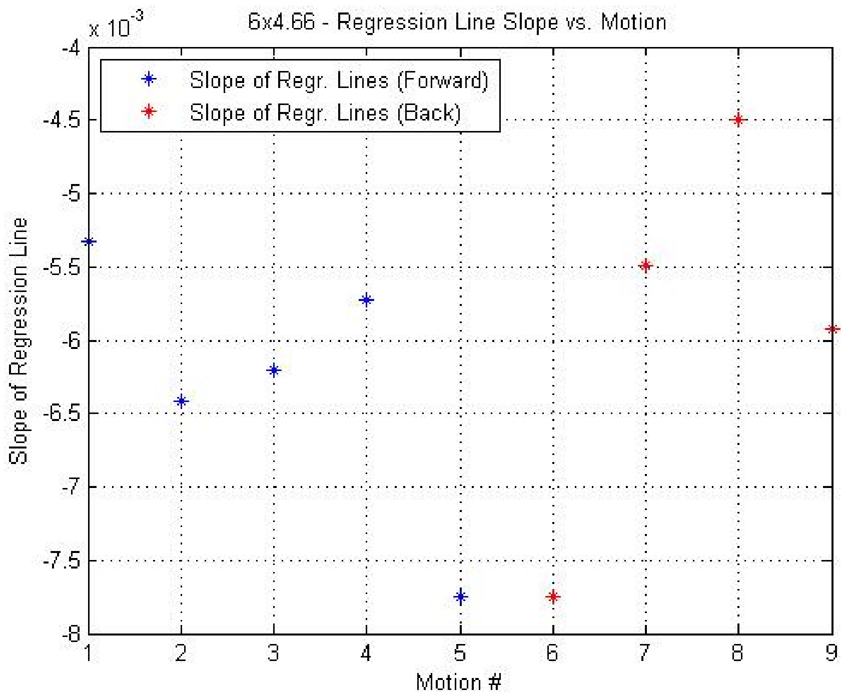


Figure 103 The smallest fabrics showed basically no change in slope.

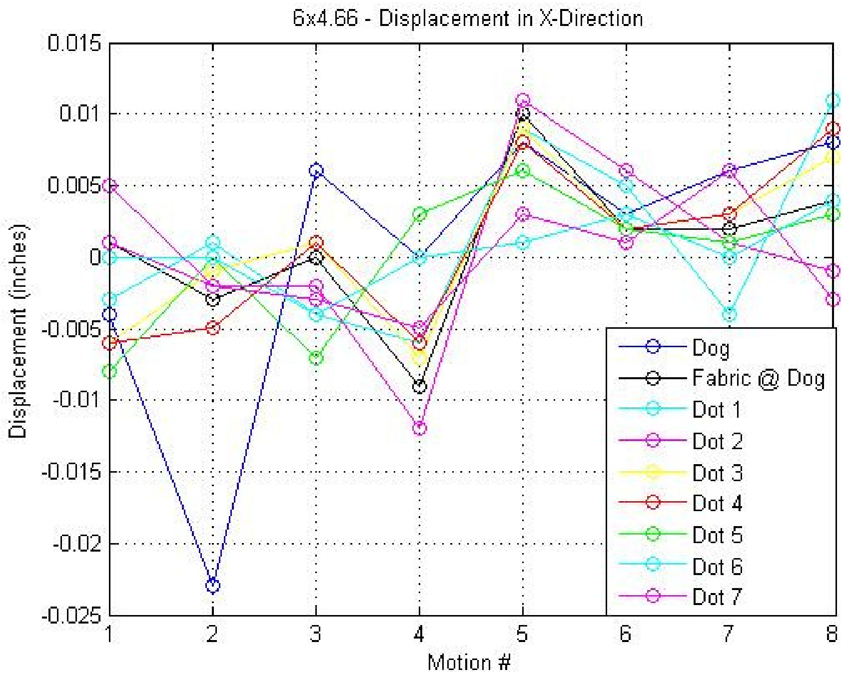


Figure 104 The displacements in the x direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

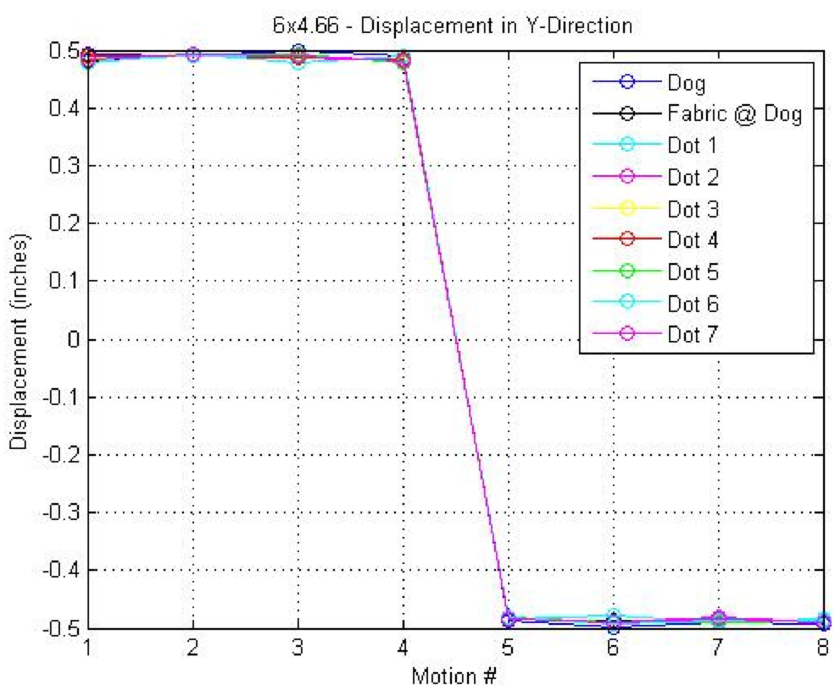


Figure 105 The displacements in the y direction of the dog and the fabric dots for each motion of the dog. The x axis of the graph represents the motions of the dog. Motion 5 is when the dog begins to move back to its initial position.

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