Design, development, and fabrication of a vibration detecting robotic foot-pad using embedded PVDF strips

by

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Abstract

This thesis shows the design, fabrication, and early characterization process of a slip-sensing foot-pad made from PVDF strips embedded in a rubber molded structure. What follows suggests a proof-of-concept for a design that can be used to detect vibrations on the edges of a teethed structure. The ability to detect localized vibrations in the embedded PVDF sensors in this foot-pad can be used in future studies to measure the contact-patch area and investigate the relationship between the change in such area and incipient slip. The future iterations of the proposed foot-pad can be used to integrate with current foot-pads worn by legged robots such as MIT Cheetah to enable them to predict slippage. An experimental procedure was used to find the effect of a localized stress on the embedded sensors' data. Three iterations of the foot-pad were designed and fabricated. Furthermore, a custom slippage tester was designed and built for future studies. The experimental results suggested that the effect of triggering on the foot-pad was highly localized since it did not affect neighboring sensors. This behavior can be used to measure changes in the contact-patch area since loss of contact between the ground and foot-pad introduces vibrations on the edges of the pad. Though further data collection and mapping should be conducted for this foot-pad to be able to predict slippage, the experimental results suggest that usage of urethane embedded PVDF sensors can be a viable and promising approach in achieving this goal by detecting the localized vibrations induced by the slip incident.

Thesis Supervisor: Sangbae Kim
Title: Associate Professor

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Chapter 1

Introduction

Biologists think that the pattern, shape, size, and spacing in people's fingerprints is used as an asset to detect vibrations during incipient slip. This idea suggests that placement of vibration detection sensors as well as addition of ridges be deemed useful in robotic fingers to enable detection of incipient slip [2, 6]. This thesis is part of an effort to try implementing a similar idea in foot-pads worn by legged robots. According to [7], piezoelectricity, Greek for "pressure" electricity, was discovered by the Curie brothers more than 100 years ago. They found that quartz changed its dimensions when subjected to an electrical field,and conversely, generated electrical charge when mechanically deformed. One of the applications of Piezoelectric polyvinylidene fluoride (PVDF) film is detection of vibration and stretch by change in the output voltage across the metalized electrodes[7]. The design of the foot-pad presented in the following chapters was inspired by the MIT Cheetah's foot-pad [9, 10, 4]. According to [8], the current MIT Cheetah's foot-pad as seen in figure 1-1 is a monolithic composite structure composed of an array of sensors embedded in a polyurethane rubber layer. This foot-pad is capable of measurement of the normal and shear forces in the foot-pad using the stress distribution picked up by sensors from deformation of the rubber layer [8].In the presented experiments PVDF sensors were placed in ridges of rubber molded footpads to detect vibration. This can later be used to measure the contact patch area and to predict slippage. This work is intended to be an addition to the already existing foot-pad in order to enable it to predict slippage in the future generations of foot-pads. The experimental setup in this thesis was partially inspired by [5] .

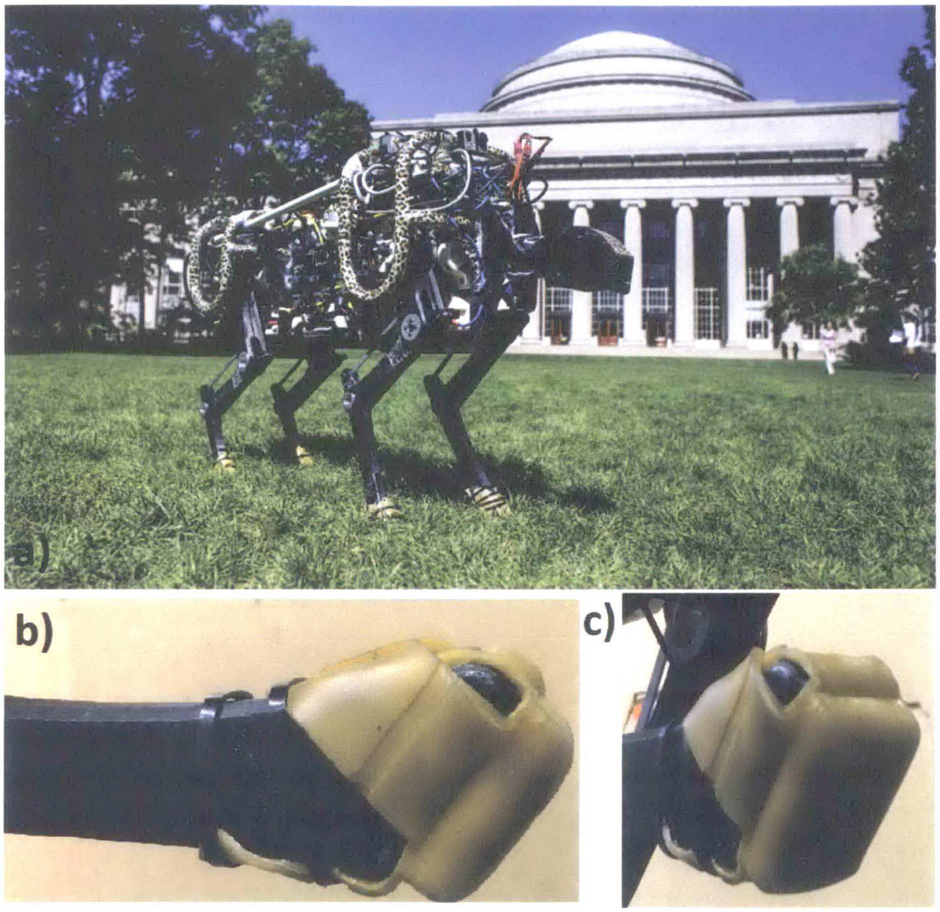

Figure 1-1: a) MIT Cheetah [8] b,c)Cheetah's current footpad design

Chapter 2

Design and Fabrication

2.1 Footpad Design

The sensor integrated foot-pad presented in this section uses the piezoelectric effect to detect changes in shape and vibrations on its edges caused by loss of contact with ground or a similar type of distress. The PVDF stripes are embedded in the teeth-shaped edges of the molded foot-pad and pick up vibrations in the teeth by outputting a voltage difference value. The foot-pad featured in this work is a prototype used to evaluate the ability of PVDF sensors to predict slippage and detect changes in the contact-patch. This foot-pad was enlarged for ease of experimenting and analysis. Future iterations of the footpad will likely focus on having sensors only on the edges so that force and shear sensors could be used in the middle (and could also be fabricated in smaller sizes).

2.1.1 Challenges and Iterations

One of the main challenges of making the molded foot-pads was achieving consistency in location and orientation of PVDF senors. As it can be seen in figure 2-1, the molding procedure sometimes moved the sensors from their initial vertical orientation.

This could lead to inconsistency in data readings from foot-pad to foot-pad. Furthermore, such errors might even result in a variation in data readings in different

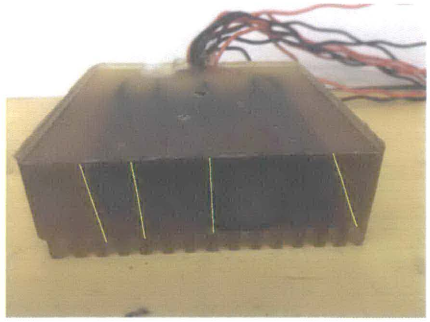

Figure 2-1: Slanted sensors due to motion during the molding procedure

locations on one single foot-pad and hence should be avoided. In order to avoid such variations, a comb-shaped part that can be inserted into the foot-pad was designed and 3D printed as shown in figure 2-2.

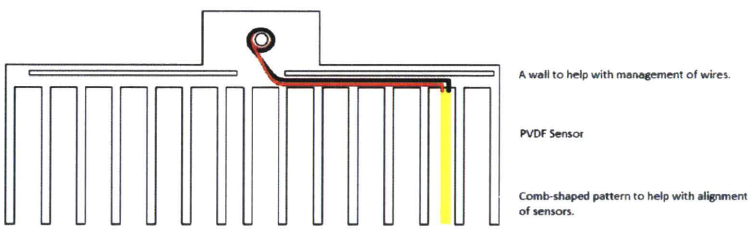

Figure 2-2: 3D printed part used for alignment of sensors

Even though the 3D printed part helped with alignment of sensors it was still not perfect. As a result, clay was used to provide further support for the PVDF strips as seen in 2-3. These two additions significantly improved the issue of variation in sensors' angle.

Better consistency in alignment of sensors was achieved using the above techniques, and a new foot-pad shown in figure 2-4 was molded.

Even though the usage of clay and the comb-shaped piece improved the problem of angle variations, the location of strips with respect to the clay's edge was still varied from teeth to teeth. This was specially problematic since the sensor wires sometimes got pulled during the molding process resulting in further variation than the initial case. Hence, in the next iteration, a multi-step molding procedure was

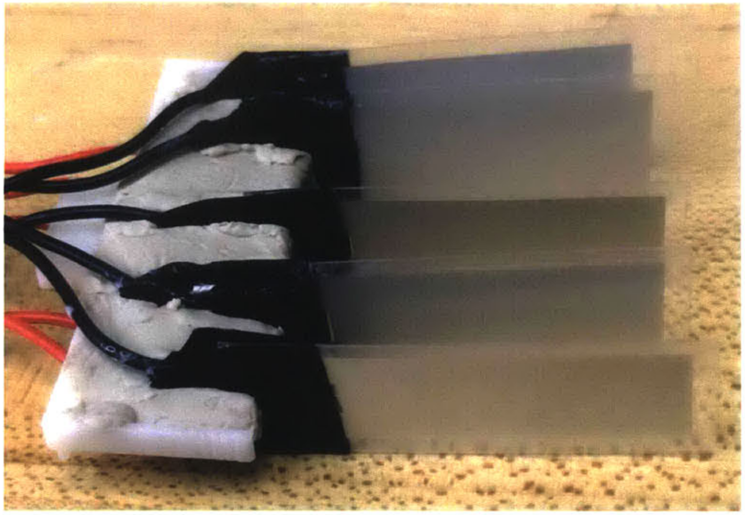

Figure 2-3: Clay used as an adhesive and for further support.

implemented. Two suggested solutions for this problem were: 1) Molding the teeth parts with PVDF sensors inside them separately and fabricating the final foot-pad by placing the already molded teeth in the mold (a sample molded tooth is shown in figure 2-5). 2) Molding a spacer piece and sandwiching the sensors between the spacers. Later, placing the sandwich inside the final mold and fabricating the final foot-pad.

Early testings suggested that the second solution seemed more promising and hence was used for the fabrication of the new foot-pad. This procedure was such that first the spacer between the sensors was molded. Then, the sensors were attached to the spacers using a primer. Later, the adhered pieces were placed in the bottom mold and the bottom half of the footpad was molded without using the top mold piece. This allowed the experimenter to observe the footpads and make sure they were perfectly oriented. The steps of this procedure are shown in figure 2-6 for further clarity.

One of the challenges of this method was perfect attachment of spacers and sensors together using a primer. This was specially difficult since the working time for primer was about 5 minutes, and an attempt to move the sensor after that time resulted in separation of sensor's layers as shown in figure 2-7. Incidents like this not only ruin a sensor but also the spacer since there is a risk that the residue PVDF might affect the voltage reading and ruin the measurements if another sensor is attached on top

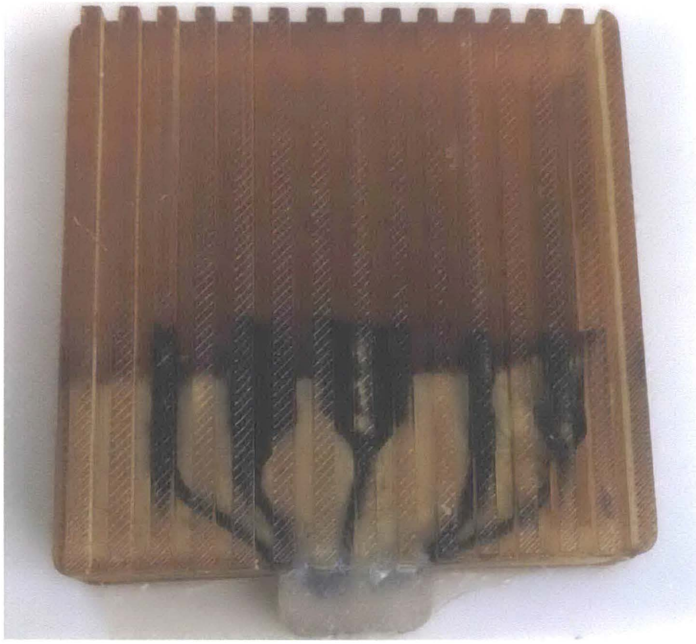

Figure 2-4: Second version foot-pad.

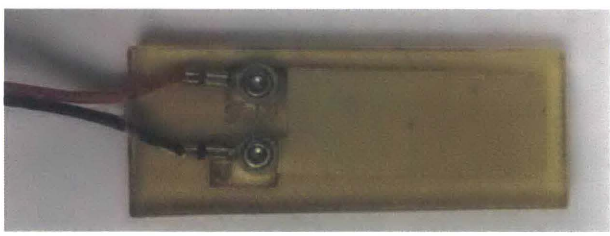

Figure 2-5: One sensor molded in the shape of a teeth

of the spacer. To avoid this problem, extra attention was given while attaching the parts and primer mixing was done separately for each sensor and spacer.

Another change in this model was usage of Vytaflex 60 instead of Vytaflex 20. Since the focus of data collection was measurement of the peak-to-peak voltage and not the frequency of the signal, having stiffer material is not going to cause problems. Furthermore, the advantage of using stiffer material was that the footpad slipped more easily and was better for experimenting. The teeth height was also changed from 4 mm to 2 mm to further facilitate slippage.

2.2 Fabrication Process

For the fabrication of these foot-pads, urethane was mixed and degassed in a vacuum chamber. In the final step sensors and parts were placed inside the 3D printer mold shown in figure 2-8, and the wires were taken out of the mold using the hole on the top piece.

2.3 Future Work: Slip Test Setup Design

For further study of slippage, it is suggested that a foot-like shape assembled from 80/20 parts be built. Furthermore, it is suggested that a structure similar to the one shown in Fig.2-9 be built and attached to a step motor. Using G-code, the step motor can rotate to per-determined angles, and the readings from the sensors can be analyzed during the process until the slippage starts. Using springs to hold the foot as shown in the figure, it is assured that the force applied to the foot is constant at different angles hence the ratio between the normal and shear force can be calculated at each angle. In order to measure the force exerted by the footpad on the ground during this experiment, a force sensor can be placed on the bottom the footpad, as shown.

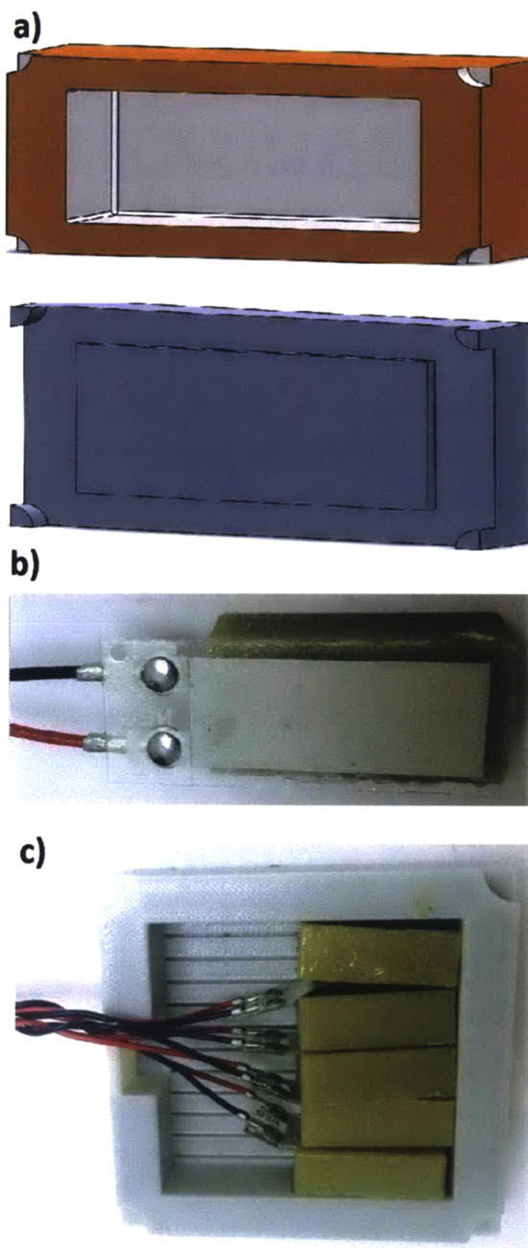

Figure 2-6: (a)CAD of the spacer mold. (b) Sensor attached to the spacer using a primer. (c) Spacers and sensors placed in the Footpad mold.

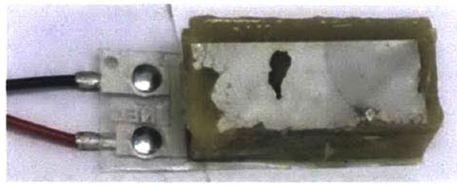

Figure 2-7: The residue of PVDF material after an attempt to detach the sensor from the spacer.

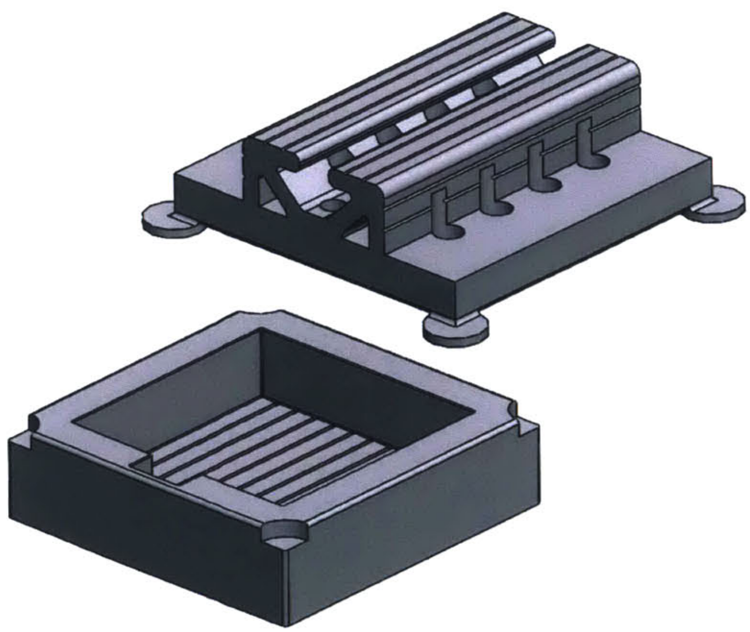

Figure 2-8: Final Footpad's mold CAD

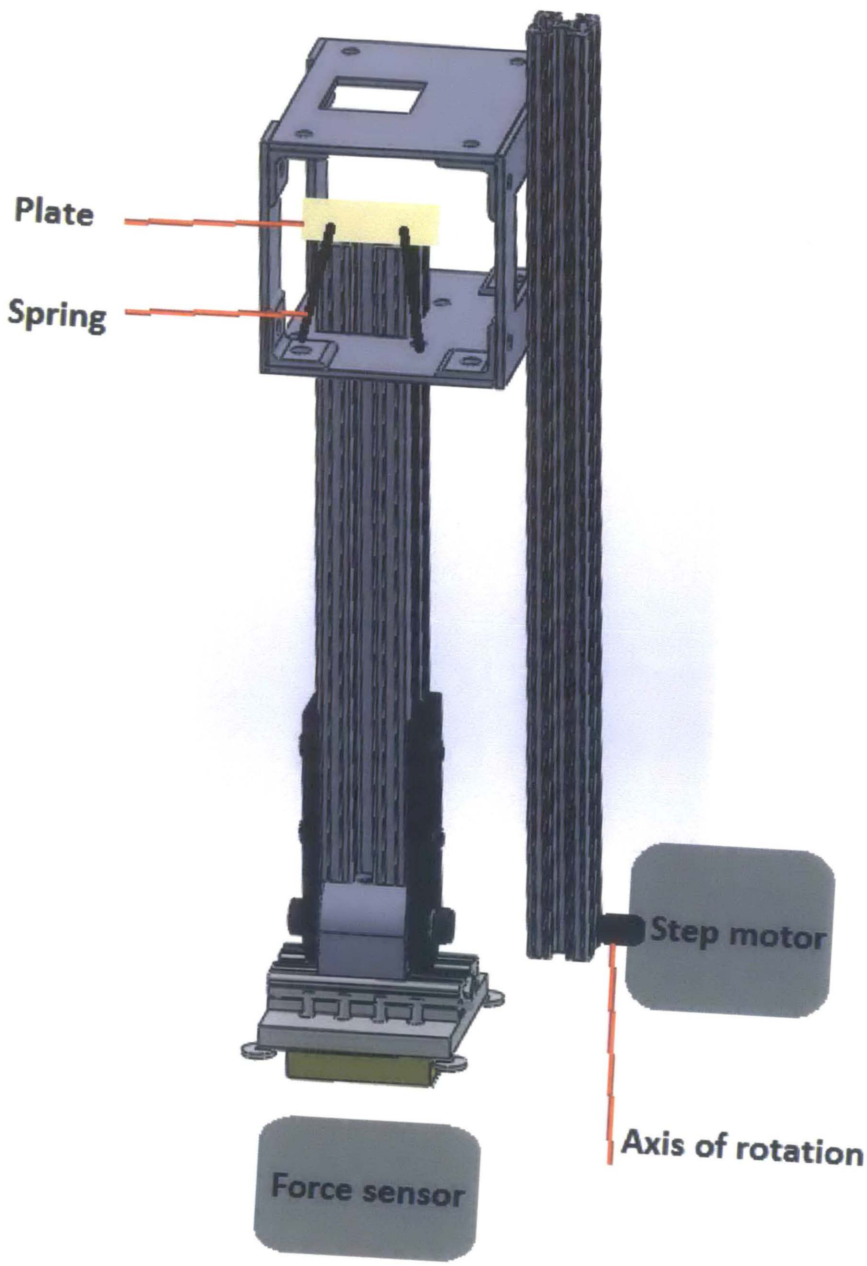

Figure 2-9: CAD of the slip test structure (CAD of the 80/20 parts are taken from [1])

Chapter 3

Experimental Procedure

3.1 Studying the effect of stress on sensors' data

In order for the sensors in the foot-pad to give a correct estimation of the contact-patch, their ability to detect a localized stress change should first be evaluated. Having this capability is important because it enables the detection of changes in the area when one of the edges of the foot-pad looses contact with the ground. Later, one can further study whether there is a direct relationship between the contact-patch and incipient slip using the designed foot-pad. To study the sensitivity of the foot-pad to a localized stress, an experiment was conducted to measure the magnitude of the voltages change in the sensors due to vibration in one teeth. This procedure was repeated for 4 different sensors placed in a variety of teeth locations on the foot-pad. The data suggested that the effect of distress in one teeth was highly localized to the readings from the sensor located inside that teeth and did not show a significant change in readings from the neighboring sensors.

3.1.1 Producing vibration in one teeth using a CNC milling machine

To determine the effect of distress in one teeth on all the embedded sensors, five PVDF stripes were placed at multiple locations inside the foot-pad as shown in figure

3-1. Data from the vibrations of each one of these teeth on sensors' output was analyzed and recorded. To stimulate vibration in one teeth, a thin rod was attached to a desktop Micro Mill DSLS 3000 machine. Using this CNC milling machine, the rod was moved from one side of a teeth to the other only introducing vibration in that teeth while the output voltage of the sensors were being recorded using an oscilloscope. Since the available oscilloscope only had 2 probes, the procedure was repeated 4 times while the data from two sensors were recorded each time. In this experiment, the value of the average peak-to-peak voltage change was used as a measure of vibration detection, and the WaveForms Diligent program was used for recording and analysis. Data suggested that the peak-to-peak values are consistent and repeatable within 2.1% variation (n=5).The second version of the foot-pad design was used in the following experiments.

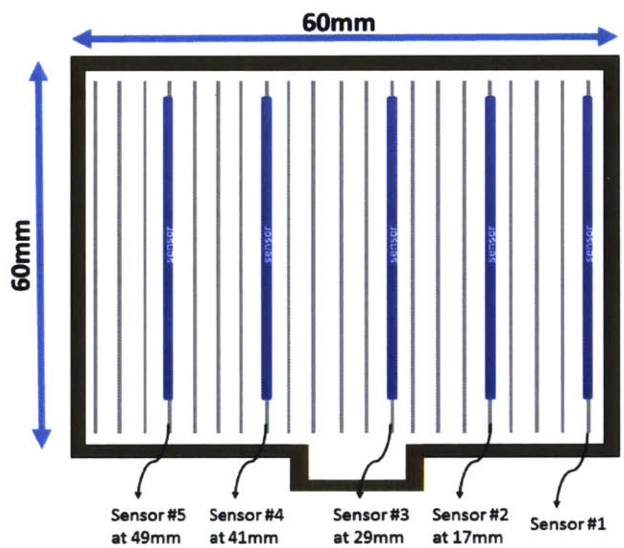

Figure 3-1: Senors placement inside the rubber molded foot-pad. This experiment was conducted to measure the magnitude of voltage change in the sensors due to induced vibrations.

To improve the accuracy and repeatability of the experiment, the measurements were conducted by securing the foot-pad to the machine's XY table using an acrylic platform and screws. G-code was used to produce the desired linear motion in the rod moving through the teeth edge. Sensor 1 was moved from its original position during the molding process. As a result, the vibration test was only conducted over sensors 2, 3, 4, and 5. The motion was repeated over each of the teeth at 5 different locations of Y= 20, 30, 40, 50, 59, and the procedure was repeated 4 times for each teeth (two probes at a time). Each case was repeated five times for further accuracy of data.

In each case one sensor was triggered using the desktop CNC milling machine. The procedure was designed such that a thin rod was attached to the mill and the machine was programmed to move the rod up between two teeth without touching the neighboring teeth. The average of data from several sensors in different trials were used to obtain a general mapping of footpad response at different locations. The experimental setup is shown in figure 3-2.

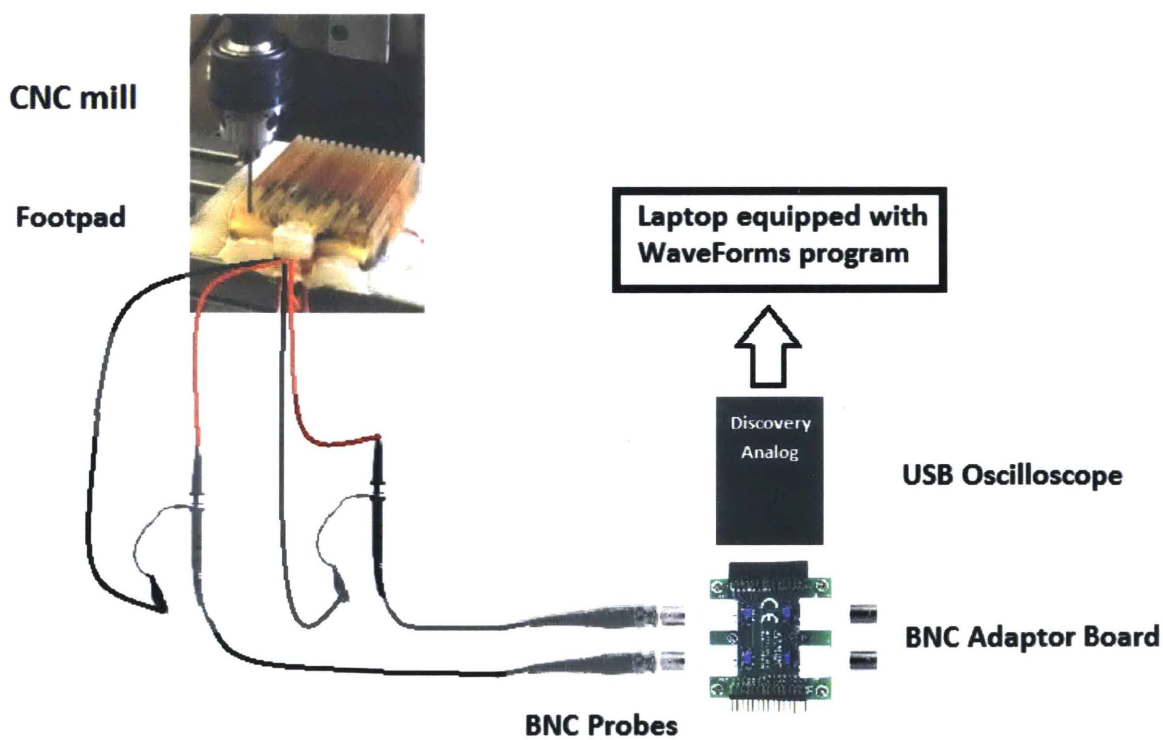

Figure 3-2: Photographic diagram of the experimental setup. Images from [3].

Chapter 4

Experimental Results and Discussion

4.1 Output signals of PVDF sensors embedded in a rubber molded foot-pad

The output signal from the PVDF was found to have a variation of 2.1%, showing good repeatability on the data. Furthermore, the data suggested that the effect of a vibration in one teeth is localized to the sensor located in that teeth. These findings suggested that the magnitude of the peak-to-peak voltage value of multiple sensors can be used to detect the location of vibration. Since it is hypothesized that the teeth might start vibrating when they first loose contact with the ground, such finding can be found useful in finding the number of teeth touching the ground at any instance and hence give an estimation of the contact-patch. These data suggest that placement of PVDF stripes on edges of legged robots' footpads might result in better evaluation of the configuration of the foot at any instant. Fig. 4-1 indicates a sample data set of recorded voltage signal values and the measurement of peak-to-peak voltages. These signals were outputs of sensors 4 and 5 when the teeth with sensor 5 was being triggered at a distance of 40 mm from the foot-pad's edge.

The measurements for the sample data showed that the change in voltage output was very dependent on the location of distress. As shown in figure 4-1 the effect of such triggering on sensor 5 resulted in a peak-to-peak value of 1.7 Volts while in the next

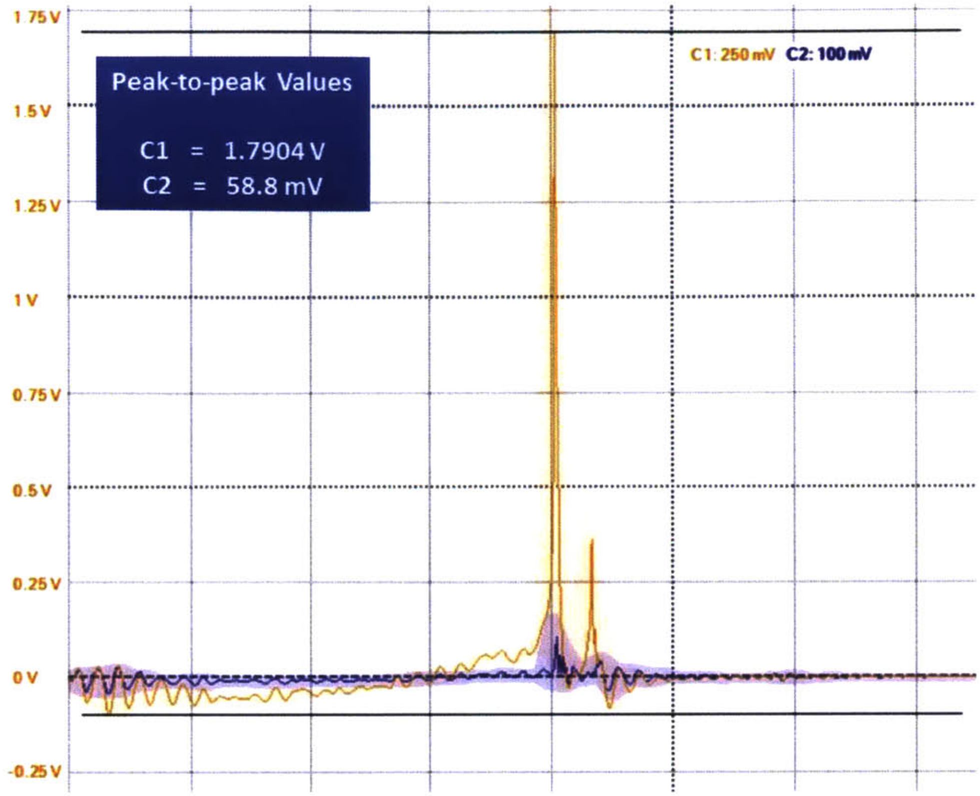

Figure 4-1: Example voltage output of two PVDF stripes C1= Sensor5 (triggered teeth) C2=Sensor4

neighboring sensor it only resulted in a signal with a peak-to-peak magnitude of about 60 mV. A similar experiment was conducted on different locations of sensors 2 through 5. The results of those experiments are shown in figure 4-2. The data confirmed what was seen in the sample data and suggested that the effect is mostly noticeable and significant in the neighboring area of the distress. Another observation was that the range of the data values differed from a) to d) in the figure. The graphs for these data were not normalized to suggest that such variation might provide us with further information about the incipient slippage and should be further investigated. To investigate the source of variation in the data two possible hypothesis were formed. The first hypothesis was that the variation was caused by the slight inconsistency in the position of sensors since they were held and lined up by clay. This idea suggests that since the stripes slightly moved during the molding process from their initial location and are not at the exact same distance from the clay's edge, they experience different triggering. The second hypothesis suggested that the teeth number itself might affect the vibration characteristics. In order to evaluate these hypothesis a foot-pad using the two-step molding design mentioned in the design chapter was fabricated. The location of the PVDF sensors in the new foot-pad are more consistent from teeth to teeth and hence further testings can be conducted to investigate the effect of teeth number. If the deviation in the range from sensor to sensor is caused by the clamping position of the strip no variation in the range is expected to be seen in the new foot-pad. However, if the collected data still indicate a variation, more testings should be done to validate the second hypothesis.

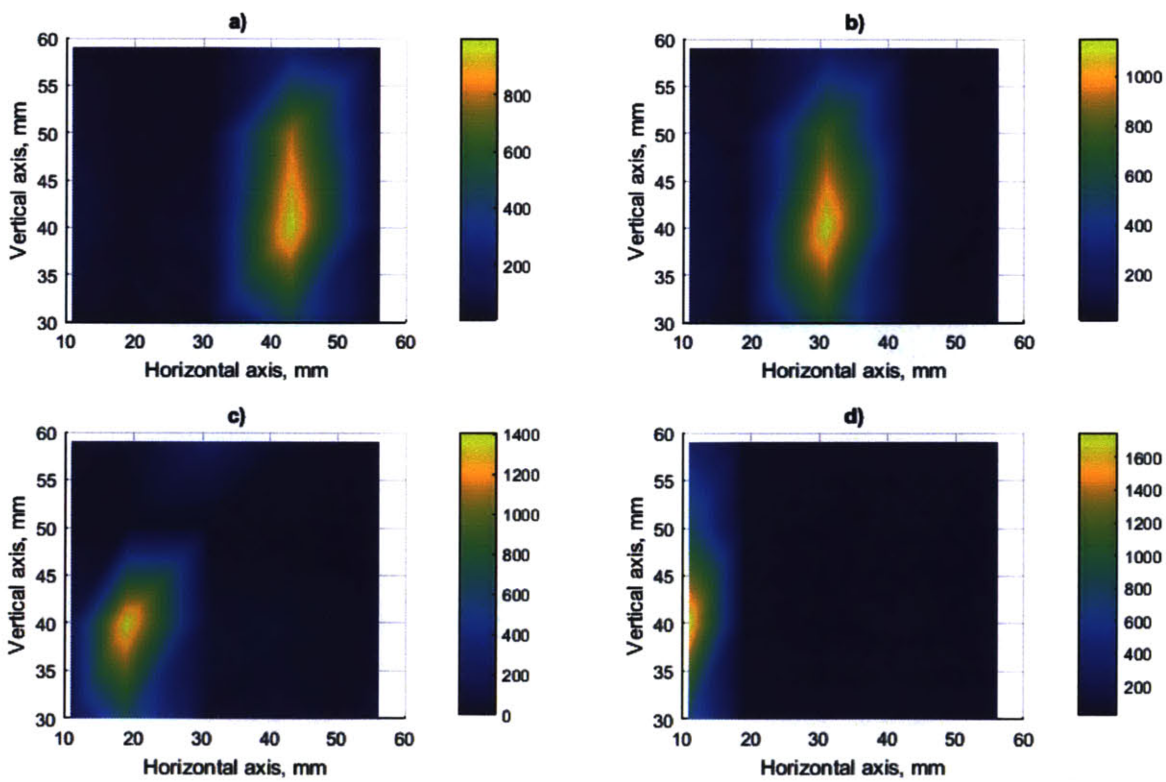

Figure 4-2: Sensors readings when a) Sensor2 b)Sensor3 c)Sensor4 d)Sensor5 was being triggered. All units in mV.

Chapter 5

Conclusion

This thesis presented a proof-of-concept, vibration detecting foot-pad with embedded PVDF strips. Design, fabrication, and early characterization process of three iterations of such foot-pad were presented along with the design of a test setup possible for usage in future slippage studies.

The effect of a localized stress on sensors data was presented and the possibility of detecting vibrations in the foot-pad's teeth shaped edges were demonstrated under experimental settings. Through the conducted experiments, a consistent repeatable relationship between the numerical readings from the sensors (when a certain area of the foot-pad was being touched) were observed. Detection of localized vibrations in the embedded PVDF sensors in this foot-pad can be used in future studies to measure the contact-patch area and investigate the relationship between the change in such area and incipient slip.

Although future studies and experiments should be conducted before this foot-pad is capable of detecting slip, the studied capability of PVDF sensors under experimental settings suggest that these sensors can provide a reliable step towards achieving that goal.

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