DESCRIBING CHANGES IN SUCKLE BEHAVIOR VIA TACTILE FEEDING NIPPLE BETWEEN HEALTHY & SICK DAIRY BREED CALVES

A Design Project Report

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Abstract

Master of Engineering Program

School of Electrical and Computer Engineering

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Project Title:
Describing Changes in Suckle Behavior Via Tactile Feeding Nipple Between Healthy & Sick Dairy Breed Calves

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Abstract:
Treating young calves promptly is challenging for caregivers because the diagnosis process is labor intensive and potentially a biohazard when multiple calves are involved. Previous studies have found that sickly calves exhibit weak suckling behavior – however, exact quantifiable differences in the bite force have yet to be defined. The goal is to create a robust instrumented feeding nipple that characterizes suckling behavior in the two groups. In the current iteration, we created a system that accurately measures bite forces of up to 50N and conducted preliminary field tests using portable milk feeders. We hope to integrate it into the commercial automated milk feeders to provide a quantified indicator of illness for early treatment and to improve clinical outcomes.

1 Executive Summary

Weaker biting forces correlate to diseased calves, especially those under six months suffering from diarrhea. The planned final product is a sensor that fits within current calf feeding systems to record the bite force of calves during the suckling process – in hopes of providing another illness indicator that is safer and more convenient for caregivers. The product must be rugged enough to withstand variations in temperature, exposure to liquids, and over fourteen thousand bites over its lifetime – all while maintaining a soft exterior that is comfortable for the calves to chew on.

The current iteration of the sensor is modeled after the feeding nipples attached to portable calf milk feeding bottles. Two force resistive sensors (FSRs) are encapsulated within two silicon layers and wired to a Wheatstone bridge. The output voltage is converted to a force via a calibration function in the form of an exponential growth function. All voltage-to-force translations are done on an Arduino Nano 33 IOT in real-time. The total cost of the sensor is $20.36, excluding the cost of the microcontroller.

We have validated that the design's calibration function adequately fits the industry standard. Comparisons between the developed sensor and the ground truth force have shown that the sensor accurately and precisely measures the true force up to 50N, with an error of ±3.09N.

Preliminary field testing found that healthy bites (N=160) had an average force of 14.97N with a standard deviation of 4.30N, while weak bites (N=221) had an average force of 4.55N with a standard deviation of 2.35N.

2 Background

To assess a calf's condition during health checks, caregivers typically look for subtle visual cues (e.g. depression, alertness) [3]. Reliance on these cues remains an issue because cows are a prey species and tend to hide their sickness as a protection mechanism against predators. Once signs of sickness present themselves, such as diarrhea and dehydration, the calf may have already sustained damage to its internal organs – driving the need for systems that help caregivers predict or detect illness in calves earlier than currently possible [3].

A few quantitative measures exist to help with the earlier identification of sick calves, such as elevated rectal temperatures. However, these methods provide no continuous monitoring options, are time-consuming, or require direct contact with feces– which may become a biohazard because of zoonotic pathogens [5].

Previous studies have shown that sickly calves generally have weaker suckling behavior than their healthy counterparts, but quantifiable differences in the bite forces between these two groups have yet to be defined [3]. The goal of this project is to create a sensor that defines the bite force differences between healthy and sickly calves, with the hopes of developing a general tactile sensor fit for rugged conditions.

3 Design Requirements

The sensor developed for this project must be embedded within feeding nipples used on portable milk feeding bottles. These feeding nipples are typically replaced once every 2 weeks, subjected to a wide range of temperatures, and exposed to liquids.

Given these standards, we aim to embed a sensor that measures bite force within a feeding nipple, ensuring that the final product is capable of:

- Accurately and precisely measuring bite forces of up to 50N
- Withstanding over fourteen-thousand chews without signal degradation
- Working when external liquids are introduced
- Maintaining consistent signal readings during temperature fluctuations
- Being inexpensive to facilitate frequent replacements

4 Implementation

4.1 Force Sensors

Force sensing resistors (FSRs) were chosen for this iteration among capacitance and magnetic sensors because of their durability, circuit simplicity, noise resistance, force repeatability, and lost cost of production. These sensors must also be flexible enough for the calves to chew on and must be able to differentiate between forces of at least up to 11N, as estimated by our calculation from the typical bite pressure and surface area of a calf's molars:

$$236\,kPa \times 0.0075\,m \times 0.006\,m = 10.62N$$

Given these requirements, we chose the Interlink Electronics FSR UX 406 series. Both long and short versions of this FSR were tested. Although the long version had more structural integrity, the final design opted for the short version because of our size constraints [2].

4.2 Mechanical Assembly

4.2.1 Silicon Mixture

Various mixtures of silicon were tested to create a product most similar in texture and stiffness to the current silicon rubber nipples on portable milk feeding containers. The final product utilizes Smooth-On PMC™-770, a mixture that has a shore hardness of 70A or similar to the sole of a shoe.

Thirty grams of Part A and fifteen grams of Part B of PMC™-770 are thoroughly mixed before being poured into 3 custom 3D printed molds. The result from the custom molds are as follows:

- A cylindrical inner layer that protects the sensors from milk within the feeder.
- A cylindrical outer layer that protects the sensor from degradation from the environment and calf chewing.
- A circular ring adhered to the outer and inner layer to keep the nipple attached to the bottle.

All molds are left to cure for at least sixteen hours at room temperature before being demolded.

4.2.2 FSR Wire Extensions

To date, the FSR UX 406 from Interlink Electronics only offers solder tab connections. Two wires are soldered onto those tabs – with careful consideration towards the heat of the soldering iron and stress applied to the joint, as these tabs are very fragile. We have found that wrapping the joint in electrical tape and setting the temperature of iron to just enough for the solder to melt significantly reduces the chance of tab breakages.

4.2.3 Components Layering

Two types of glue are used to ensure the FSRs stay in their designated areas during the setting and drying process. RapidFuse® All-Purpose Adhesive has a quick set time of thirty seconds and is initially applied to ensure the FSRs are centered throughout the entire glue curing process. E6000, an industrial strength adhesive, is then applied to increase the bond strength between the FSRs and the silicon rubber.

Four FSRs, two on each hemisphere, are adhered to the cylindrical inner layer by applying small amounts of RapidFuse® All-Purpose Adhesive to the back of the FSRs. The FSRs are held in place until the glue sets before E6000 is then applied to the back of the FSRs. A custom 3D print has been created to hold the FSRs in a circular shape during the curing process. After the E6000 is cured, the FSRs and the inner cylindrical layer is encapsulated within the outer cylindrical layer and the two layers are adhered to the silicon circular ring using the E6000. The wires from the FSRs are routed through the ring or above the ring depending on whether a milk or no milk version of the nipple is being created.

For the milk version of the nipple, a custom 3D printed box with a lid has been created to house the circuitry. The box is attached to the box via velcro. If opting for a no milk version of the nipple, a panel the size of the breadboard is cut out of the milk container and attached back to the container using a plastic hinge to create a panel for easy access to the circuitry. The breadboard can be attached to the panel via velcro or other adhesives.

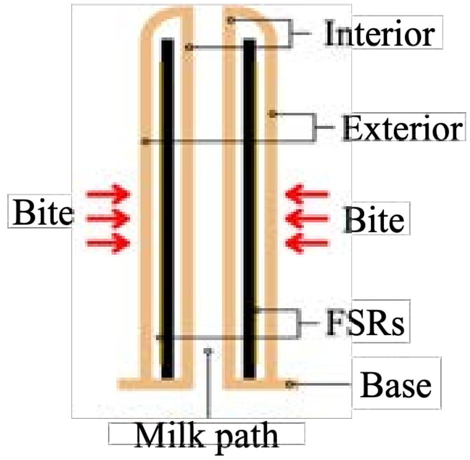

Figure 1. Cross section of a feeding nipple with only two FSRs.

Figure 2. Non-milk version of the manufacturing sample, with circuitry attached to a panel created by cutting out the portable milk feeder.

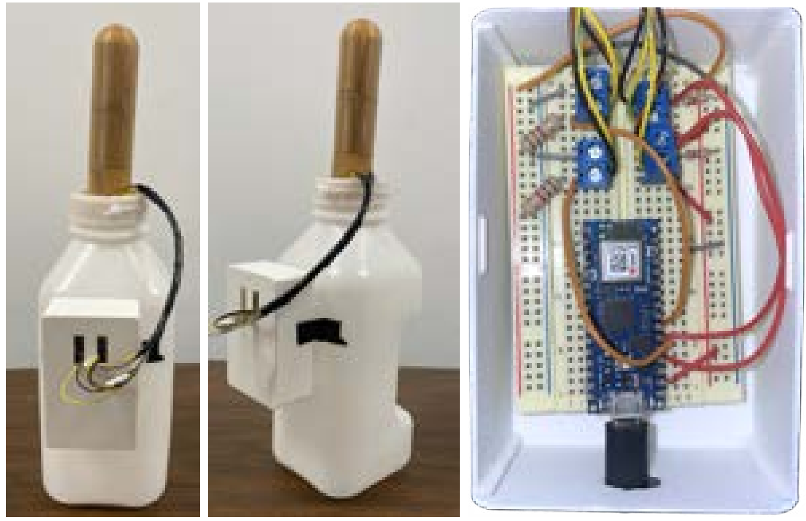

Figure 3. Milk version of the manufacturing sample, with circuitry (left) attached to the side of the portable feeder (right, middle).

4.3 Circuitry

The original circuitry design featured four FSRs, each a part of a two resistor voltage divider circuit. Initially testing found that this circuitry provided a narrow voltage output range of 0 to 2000 mV to forces between 0 to 50N – making it difficult to map a voltage to a force with certainty.

The final circuitry design instead features a pair of FSRs connected in one wheatstone bridge – for a total of two wheatstone bridges in this iteration of the project. Pairs of the wheatstone bridge are defined as FSRs that are directly across from each other on the nipple. To determine the values of R2 and R3, the following equation was used:

$$Vout = Vdd\left(\frac{R3}{R_{FSR1}+R3} - \frac{R_{FSR2}}{R2 + R_{FSR2}}\right),$$

such that the output voltage is 0 when no force is applied. The working principle is that when a calf bites on the FSRs, the resistances of those FSRs simultaneously decreases, causing the positive and negative terminals of the output voltage to increase and decrease respectively. This resulted in a new output voltage range of -3300mV to 1000mV, doubling the voltage range that we can map onto a bite force.

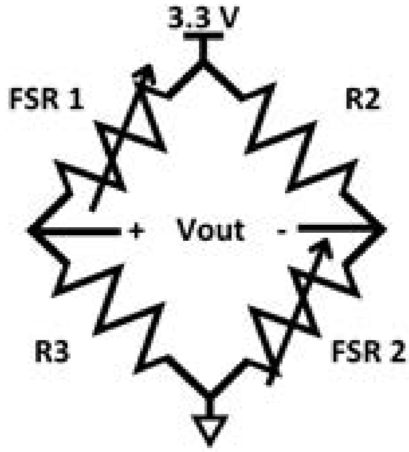

Figure 4. Schematic for one wheatstone bridge configuration.

4.4 Calibration

A drill press vise with a stationary base and the ATI Net F/T sensor were used to map the output voltages from the wheatstone bridge to a bite force. The Net F/T sensor is an external device we used to define the industry standards for force measuring instruments – which will now be referred to as the ground-truth force. The manufactured product and the Net F/T sensor were placed between the stationary and moving jaw.

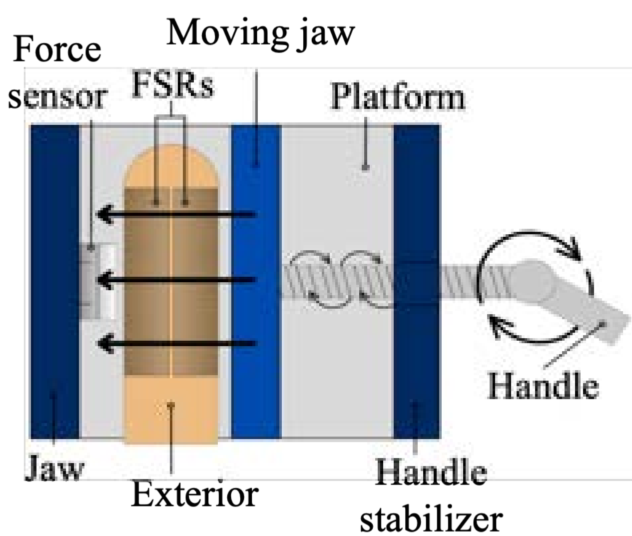

Figure 5. Sketch of the calibration setup using a bench drill press vise and ATI Net F/T sensor.

Figure 6. Manufactured sample placed inside drill press with force sensor, which is attached using yellow tape.

Thirty thousand samples from both the Net F/T sensor and the output voltage were recorded before being averaged by ground-truth force. The trend between increases in the output voltage and the ground-truth force most closely followed an exponential growth form with a standard deviation of ±3.09N, which was used as the mathematical model to relate the ground-truth force and the output voltage.

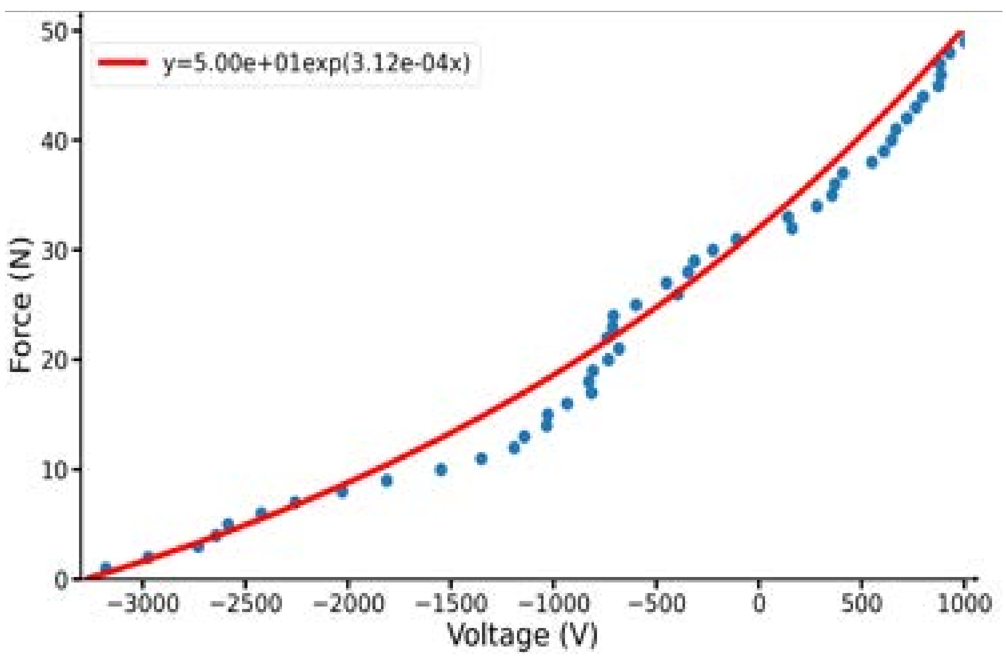

Figure 7. Voltage-force relation when force is applied. Line of best fit is shown in red for one specific sample.

5 Validation

Comparisons between the force estimates from the proposed product and the ground-truth force were conducted, using the drill press vise to mimic a chewing motion. Our trials found that our sensor's estimates were within one standard deviation of the ground-truth force sensors from 0 to 50 N.

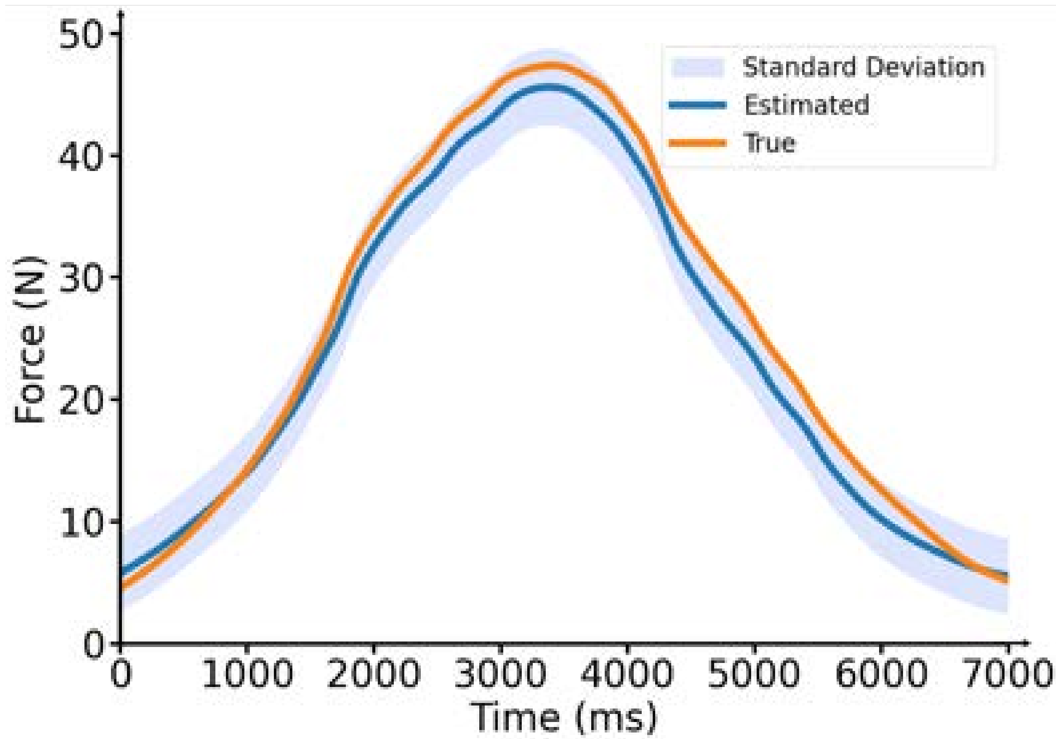

Figure 8. Estimated force (dark blue) with standard deviation (light blue) and ground truth force from external sensor (orange).

Trials were also conducted with live calves to determine whether the proposed product was capable of sensing differences between weak and healthy bite forces during suckling behaviors. During these experiments, weak bites were defined as non-suckling chewing behavior, such as play. Our trials found that healthy bites (N=160) had an average force of 14.97N with a standard deviation of 4.30N, while weak bites (N=221) had an average force of 4.55N with a standard deviation of 2.35N. The FSRs during these trials showed no signs of signal degradation and no major deformations were found on the silicon nipples after chewing.

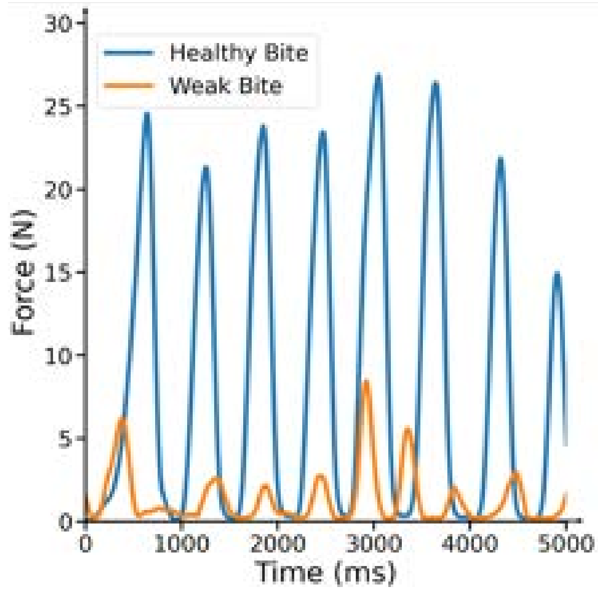

Figure 9. Estimated force from calves with healthy and weak bites.

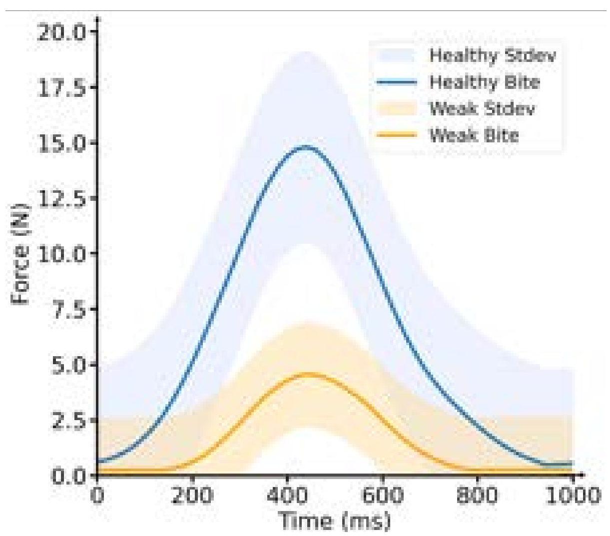

Figure 10. Average healthy (N = 160) and weak (N = 221) bites force from field trials.

6 Conclusion

Our testing and preliminary tests revealed some flaws with the current iteration of the proposed product. The current iteration with four FSRs total has a diameter and length that is too wide to comfortably fit within the mouth of calves – which caused the calves to engage in play behavior instead of suckling behavior. A smaller and narrower sensor with only two FSRs total should be developed to consistently encourage calf suckling behavior.

In addition, the generalized mathematical function $y = ae^{bx}$ typically does not translate well from sample to sample due to inconsistencies in the manufacturing process, and thus requires the parameters a and b to be calibrated for each specific sensor.

This iteration of the sensor requires a microcontroller with a wired connection to communicate with the serial monitor and allow a Python program to write the data into a csv file. Future iterations of this sensor should be self contained to make the sensor truly portable and for caregiver ease.

Finally, the total cost of the sensor is $20.36, excluding the cost of the Arduino 33 IOT. Considering that typical cow feeding nipples range from $1 to $4 and that these nipples are replaced frequently, a less expensive sensor should be developed. The largest factor in our sensor cost were the four FSRs, which totaled $19.96. Even if a sensor were developed with only two FSRs to more comfortably fit within the calf's mouth, the total cost would still exceed our requirements. One possible solution is to create flex sensors ourselves, which are considerably cheaper than those on the market [1][4]. Further testing is required to characterize these homemade flex sensors and how they compare to commercially available FSRs.

7 Appendix

A video tutorial of the process described below can be found here.

7.1 Nipple Construction

7.1.1 Silicon Molding

The custom molds are 3D printed with a 5% infill and PLA. A version of the molds for two FSRs have been provided. Line your surface with aluminum foil. Measure 15g and 7.5g of Part A and Part B of Smooth-On PMC™-770 using a scale and pour the mixture into a disposable cup. Mix together thoroughly for 3 minutes using a wooden tongue depressor. Spray a thin coating of Universal™ Mold Release, or any mold release, onto all surfaces of the outer layer, inner layer, and ring molds. Make sure the coat is evenly distributed using a paint brush. Pour your silicon mixture into the base molds and place the shapers in their respective base molds. The shapers should snap into place using the prongs from the base molds. Allow to cure for at least 16 hours before demolding.

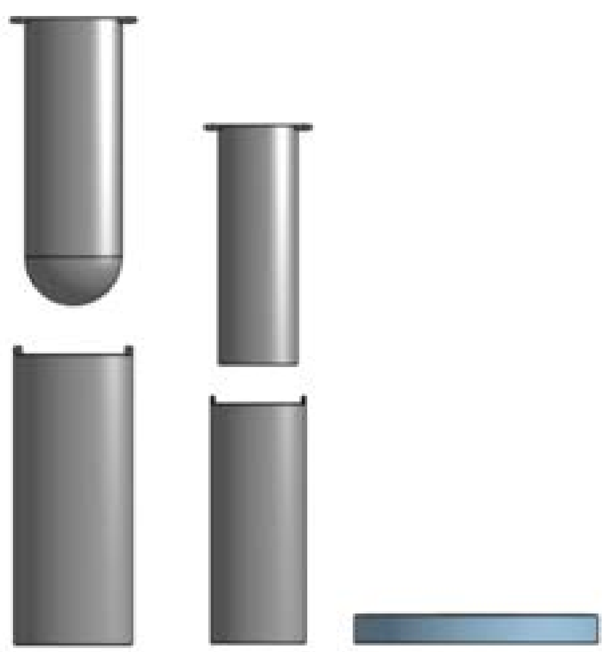

Figure 11. CAD models for the custom molds of the nipple for only two FSRs. Bottom: the base mold for the outer layer (left), the inner layer (middle), and the

ring. Top: the shaper of the outer mold (left) and the shaper for the inner mold (middle).

Figure 12. Top view of the inner layer (left), outer layer (middle), and ring (right) molds with silicone poured into them.

Figure 13. Side view of all molds, closeup of the outer layer mold (middle), and closeup of the ring mold (right).

Sometimes, the silicon expands, making it difficult to remove from the mold by sliding the shaper out. In this case, use the backside of a hammer to break a line down the center of molds.

Figure 14. Silicon parts demolded.

7.1.2 FSR Wire Extensions

Solder two 24 AWG wires onto each lead of each FSRs. Be sure to heat the soldering iron to the minimum temperature required to melt the solder, as excessive heat may damage the leads of the FSR and cause them to melt off. To minimize breakage at these points, wrap the leads with tape.

Figure 15. FSR soldered with 24 AWG wires (left) and wrapped with tape (right).

7.1.3 Component Layering

Once all the FSRs are soldered, apply a small amount of RapidFuse® All-Purpose Adhesive to the back of the FSRs and adhere them to the silicon inner layer. Place inside the custom 3D printed holder and wait for 30 minutes, or until the glue cures. Once that glue cures, add E6000 adhesive to the back of the FSRs. Allow to cure for 24 hours.

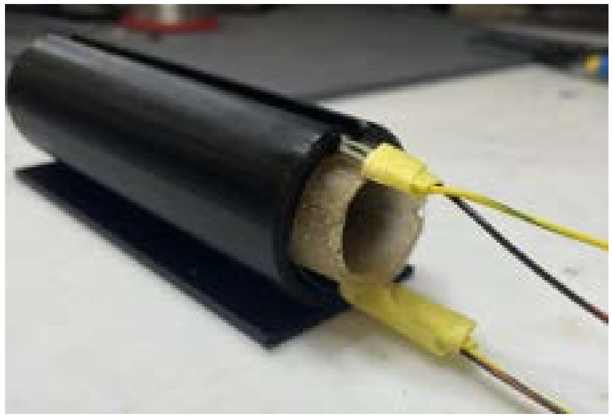

Figure 16. FSRs glue and placed into a custom 3D printed holder.

After the E6000 cures, encapsulate the inner layer with the outer layer and glue both to the ring using the E6000. Place upright and allow to dry for 24 hours. This nipple should screw onto the portable milk feeder.

Figure 17. Constructed nipple (left) and screwed into feeder (right).

7.2 Calibration

Place the sensor within the two jaws of a drill press vise with a stationary base. Attach the ATI Net F/T sensor to the stationary jaw of the drill press vise such that it directly aligns with the center of one of the FSRs (Figure 6). When calibrating, be sure that voltage outputs from all forces ranging from 0 to 50N, in increments of 5N or less, are being recorded. Code to start the FT sensor, the Arduino, and to combine the readings between the two devices to generate a mathematical model.

References

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