ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Electric Dog Teeth Cleaning Toy

Team #57

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Abstract

The Electric Dog Teeth Cleaning Toy brushes plaque off of dogs' teeth and dispenses a treat as a training mechanism. The toothbrush toy uses a vibration motor and pressure sensors to imitate an electric toothbrush. The system also includes a treat dispenser that incorporates a buzzer to induce a habit in the dog to bite the toy and brush their teeth twice a day. This paper will explain the design process and how each component of the system works.

Contents

1 Introduction

1.1 Problem

Many dog owners don't put in the effort to manually brush their dog's teeth more than a couple of times a week. They either use a dog teeth cleaning treat or liquid which won't get rid of all the plaque. Nowadays, at least 80% of dogs over the age of three have oral problems [1]. To combat this pet health issue, dog owners need a tool that is able to conveniently clean dogs' teeth and regulates the frequency of cleaning.

1.2 Solution

The solution we have is to develop an electric dog toy that is capable of cleaning the dog's teeth and monitoring the cleaning. When the timer reaches two minutes, the treat dispenser will produce a buzzer sound and dispense a treat. This will be used as a training mechanism, so the dog will eventually realize that biting the toy will dispense a treat. Treats are also used as the incentive in the dog toy to interest the dog to continue biting the bristles. The dog toy we developed specifically aims for small dogs (<30 lbs) that have a bite force less than 100 psi. The dog toy must be made of materials that is able to withstand 100 psi and will be covered in bristles. Under the exterior cover, there are several thin pressure sensors to detect dog bites. Internally, the toy is equipped with a vibration motor that will create moderate motions in the dog's mouth for cleaning. When turned on and being bitten, the toy will vibrate and adjust the force according to the data from the pressure sensor. The dog toy will be attached to a separate box containing the treat dispenser and circuit components. When the treat is dispensed, the toy then enters a sleep state and stops responding to biting until a preset time interval has passed. After recess time, the toy will be available for cleaning again. Overall, the dog will be able to play with the toy and get their teeth cleaned two times a day.

1.3 Subsystem Overview

The system contains five subsystems: the control subsystem was designed to process input data and transmit control signals to other subsystems; the censor subsystem reads the pressure applied on the toy to detect biting activity; the buzzer/treat dispensing subsystem uses sounds and treats to train the dog to constantly brush their teeth; the state indication subsystem shows the current operation state through a LED display, to help the user track their dogs' brushing behavior; the power subsystem is used to power the entire system with a 12-V battery. The project's high-level requirements are listed below.

- The dog toy will be able to brush away food with similar properties of plaque off.
- The dog toy will use treats and a buzzer sound to help make brushing their teeth a habit for dogs.
- The electronic system will be solid enough to withstand the vibration, and the shell should be strong enough to withstand a small dog's bite (about 100 psi).

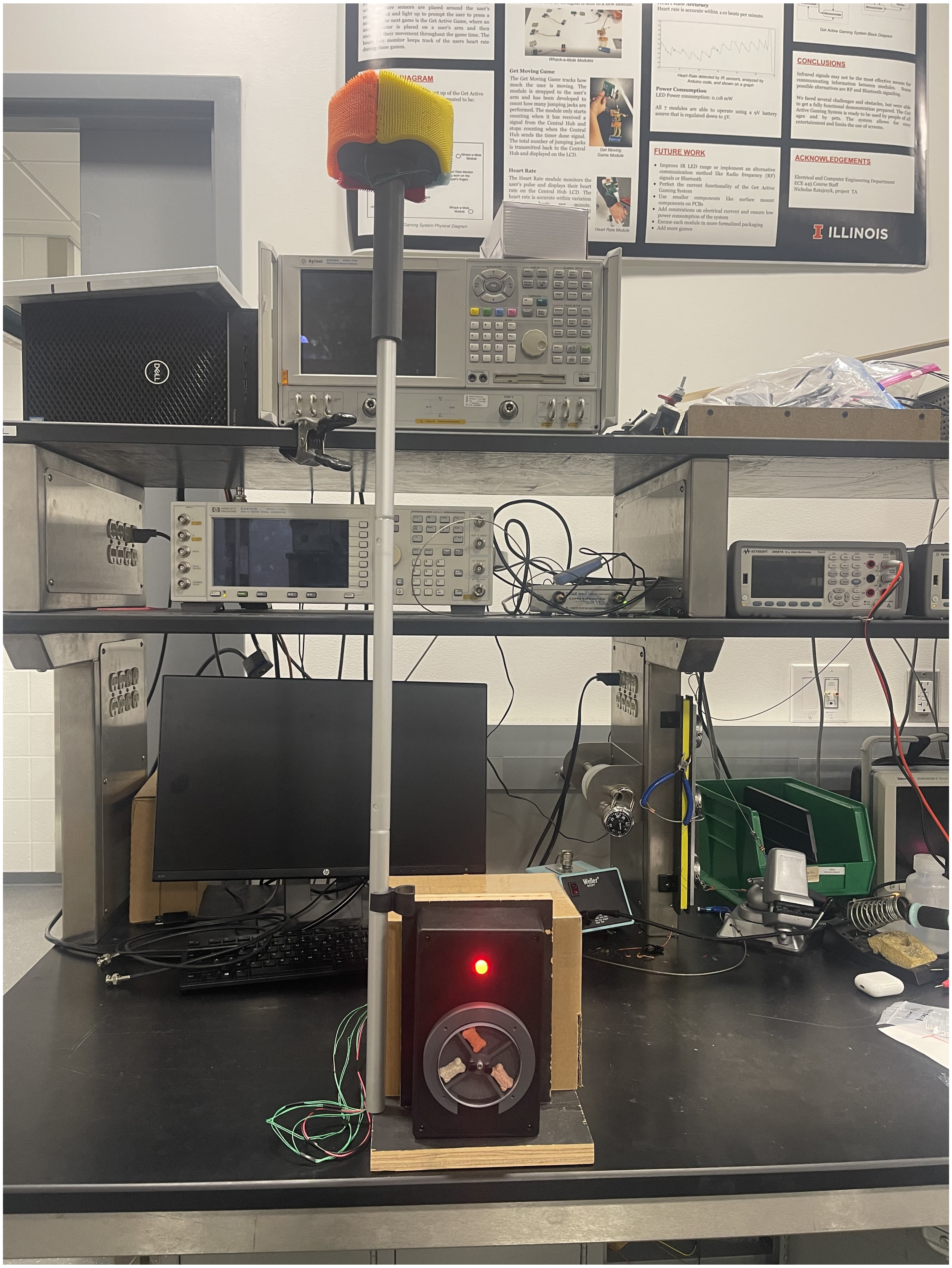

Figure 1: Final Design

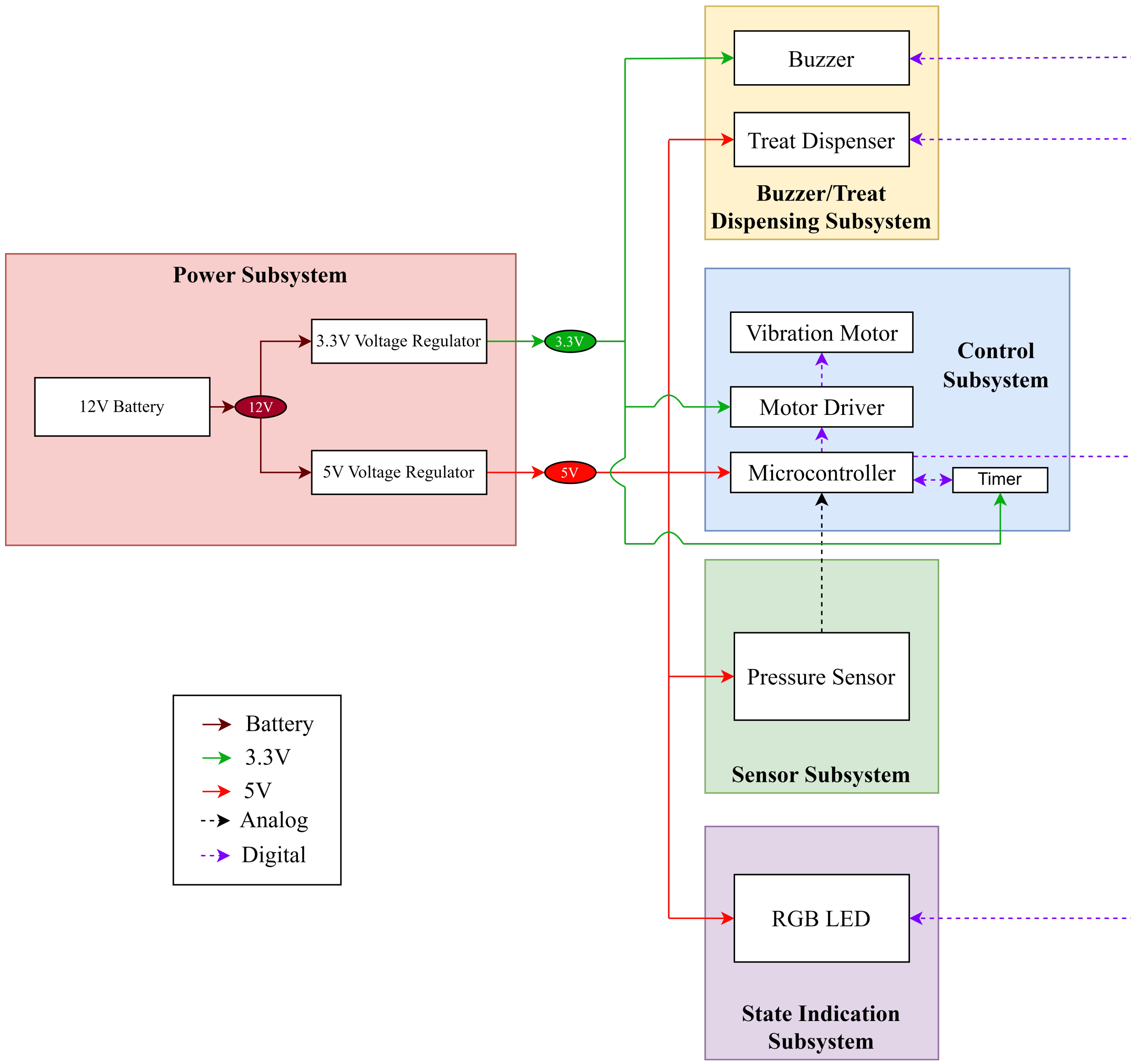

Figure 2: High level block diagram

2 Design

2.1 Design Procedure

2.1.1 Control Subsystem

The control subsystem consists of two portions: hardware and software.

The design of the hardware revolved around choosing the appropriate microcontroller and timer chip. For the microcontroller, the most essential requirement is number of digital IO and PWM output pins. Our project requires at least nine digital IOs and five PWM outputs. ATmega328P provides sufficient number of pins as it has 14 digital IOs, and six of them are capable of PWM. This particular microcontroller is also cheap and low-power while possessing adequate speed and memory for our purpose. Therefore, ATmega328P was adopted in our design.

When it comes to the timer chip, a low-power chip that has a mature library was desirable. The DS3231 is widely used in other projects for similar reasons. Thus, the DS3231 was chosen as the external timer. Besides an external timer chip, an internal timer can also be used as an interruption source to control our microcontroller. Another popular choice in real-world projects is the the watchdog timer inside our ATmega328P-PU MCU. It can provide an interruption interval of up to 8 seconds in theory. Considering the possible power usage to frequently reset the watchdog timer, the external DS3231 is believed to be a better choice in practice.

Another essential hardware component is the vibration motor and its control circuit. To create sufficient vibration, a motor with high RPM is needed. A 3 V DC motor that is rated for 15000 RPM is the highest available option, and it was adopted. As for control circuit, a MOSFET controlled by PWM signal is a cheap and reliable way to control the power of the motor. There are two variants − high-side-switching PMOS and low-side-switching NMOS. The former was chosen as it provides a direct path to ground, allowing for easier electrical debugging.

For the software portion of the control subsystem, the first dilemma was about the usage of Arduino functions and libraries. Due to the size of Arduino libraries, it is harder to achieve efficiency in memory management than coding in plain AVR-C. Since AVR-C is a register-based language, coding in this way also provides unlimited freedom for hardware control, which coding in Arduino cannot provide. On the other hand, using Arduino libraries significantly improve the readability of the control program, saves time during debugging. Overall, since the built-in memory on ATmega328P (32KB) is much larger than compiled control program ($\sim$11KB), and the program's limited loading/storing activities inside the memory, Arduino libraries are kept in the control system.

The second dilemma of software design is about the MCU's sleeping behavior. In the original design, the MCU is planned to enter sleep mode in two situations: first, when the brushing goal is not completed and the toy is not being bitten; second, when the brushing goal is completed and the next brushing session (i.e., 12-hour period) hasn't arrived. In the final implementation, however, only the latter sleep situation is kept. The reason behind this is that the only wake-up signal source is the analog input, which is not only inaccurate but also forces the MCU to stay in a ”lighter” sleep mode. This ”lighter” sleep mode drains more power compared to normal MCU operation modes. Since the key motivation of putting MCU into sleep mode is to save energy, it is no longer necessary to keep the sleep implementation in the first situation.

2.1.2 Sensor Subsystem

The sensor subsystem is responsible for generating data that is easy to work with. The data of interest is the pressure applied by the dog. A means of converting applied pressure to an electrical variable is necessary. A thin film pressure sensor serves this purpose as its resistance varies according to applied pressure. In order to utilize this feature, an op-amp circuit that takes the form of an inverting amplifier was conceived as shown in Figure 3.

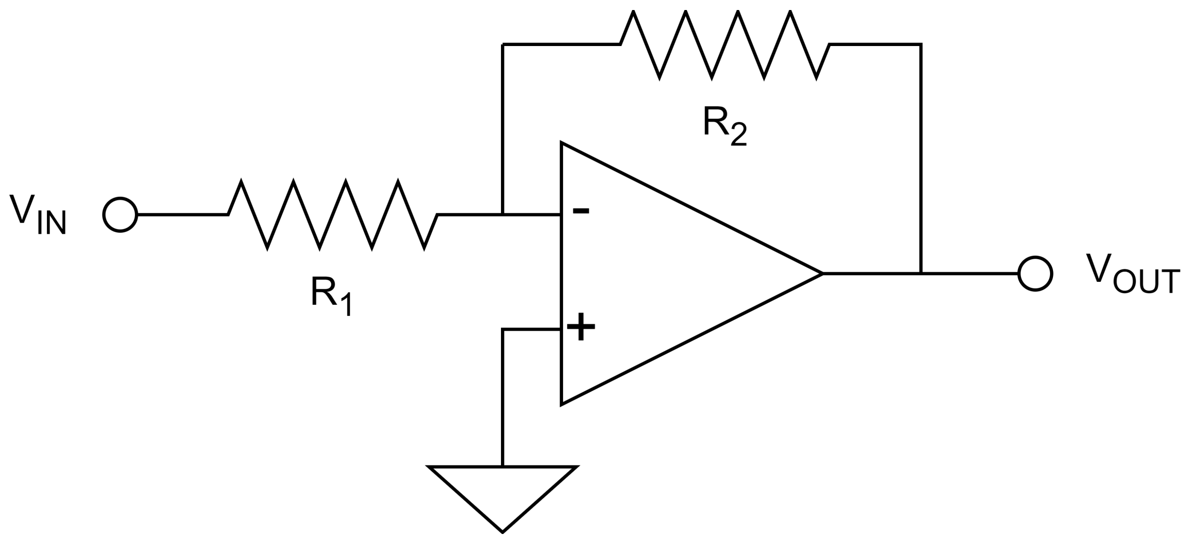

Figure 3: Inverting Amplifier Configuration

Compared to other topologies, the inverting amplifier provides the highest resolution and range as well as having a reasonable power consumption. Therefore, it was regarded as viable. The circuit would be able to generate a voltage based on the ratio of resistances, and the voltage can be read by the ADC of the microcontroller. The voltage-resistance relationship can be derived by applying ideal op-amp rules [2]:

$$I_+ = I_- = 0 \text{ A} \tag{2.1}$$

$$V_+ = V_- \tag{2.2}$$

Regarding the op-amp, OPA196 was chosen. This particular op-amp is low-power and has a rail-to-rail output swing, making it ideal for the project. With OPA196, the current consumption is always less than 2 mA, and the output swings approximately from 30 mV to 4.95 V. The performance of the op-amp was checked in advance through a LTspice simulation.

2.1.3 Buzzer/Treat Dispensing Subsystem

The buzzer/treat dispensing subsystem is comprised of a buzzer and a treat dispenser.

The buzzer was chosen to be a 3.3 V piezoelectric buzzer. This kind of buzzer only draws tens of milliamps of current and is generally loud enough. Similar to the vibration motor, the buzzer was chosen to be driven by a high-side-switching PMOS.

For the treat dispenser, using a stepper motor is a natural choice. A stepper motor can be controlled so that it rotates at precise angles. To reduce the number of output pins needed, a bipolar stepper motor is adopted. The driver is a H-bridge out of concern for cost. To run the stepper motor more smoothly, additional resistors are attached to each coil, and a single-phase stepping sequence was used. These reduce the current consumption and hence the torque generated, enhancing the precision of the stepper motor.

2.1.4 State Indication Subsystem

The project is designed to be operated by a human being. In this case, it is crucial to convey the state of the machine in a clear fashion. The user needs to know if the machine is active and whether the cleaning session is complete. For this purpose, a RGB LED and a corresponding color code were chosen. The different colors and lighting patterns make it simple for users to see the different states of the system.

Concerning the electrical aspect of the RGB LED, a high-side-switching PMOS is used as the controller. Resistors in series are added to limit the maximum current consumption to 20 mA to prolong the battery life.

2.1.5 Power Subsystem

It is imperative for the power subsystem to provide adequate currents at the correct voltage levels. Since multiple digital ICs are used in the design, it is also essential to have a low-voltage ripple for correct operation and damage prevention. For the above requirements, the main voltage source chosen is a battery. A battery closely resembles an ideal voltage source that is ripple-free. In comparison, DC-DC converters create considerable ripples, and it can be difficult to debug. Rectifying from 120 V mains voltage also has a similar ripple issue, and it can be dangerous for the user and the dog. Thus, a battery was adopted. The battery is connected using a barrel connector.

The project requires 3.3 V and 5 V for operation. To generate different voltages from the battery, two LDOs are used. LDOs can have moderate power efficiency: approximately 60% power efficiency and 90% current efficiency. This can be helpful to the battery life. Another essential advantage is load regulation. Since the system features motors, high current consumption is expected. LDOs are able to maintain output voltage even when heavily loaded. For these reasons, two LDOs are chosen. LT-1085CT3.3 and LT1085CT5 are 3 A LDOs that satisfy specifications and are eventually adopted. Technically, any voltage source that has ≥ 6 V and enough current can be used.

2.2 Design Details

2.2.1 Control Subsystem

The circuit-level implementation is shown in Figure 4, Figure 5 and Figure 6.

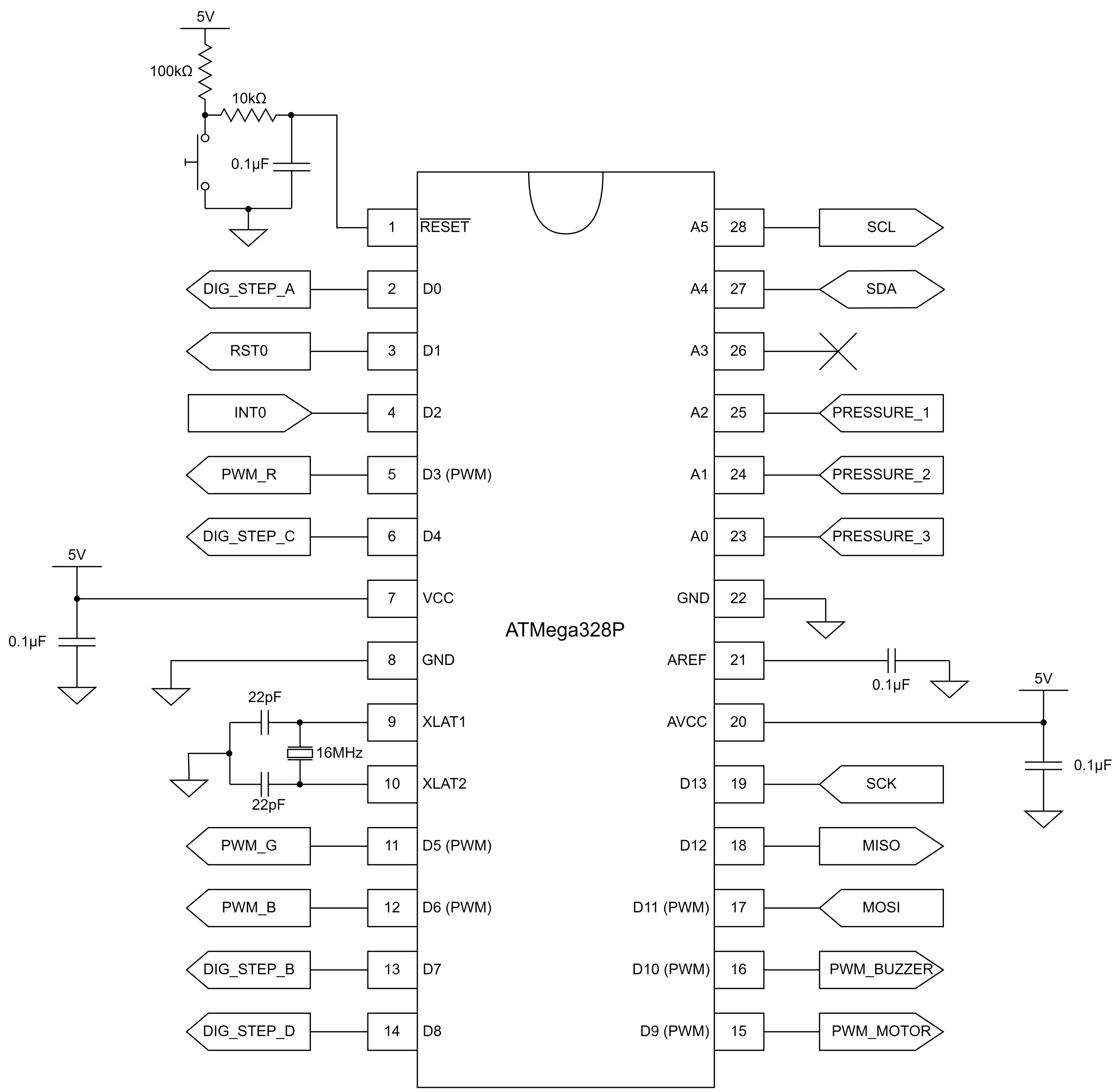

Figure 4: Microcontroller Circuit

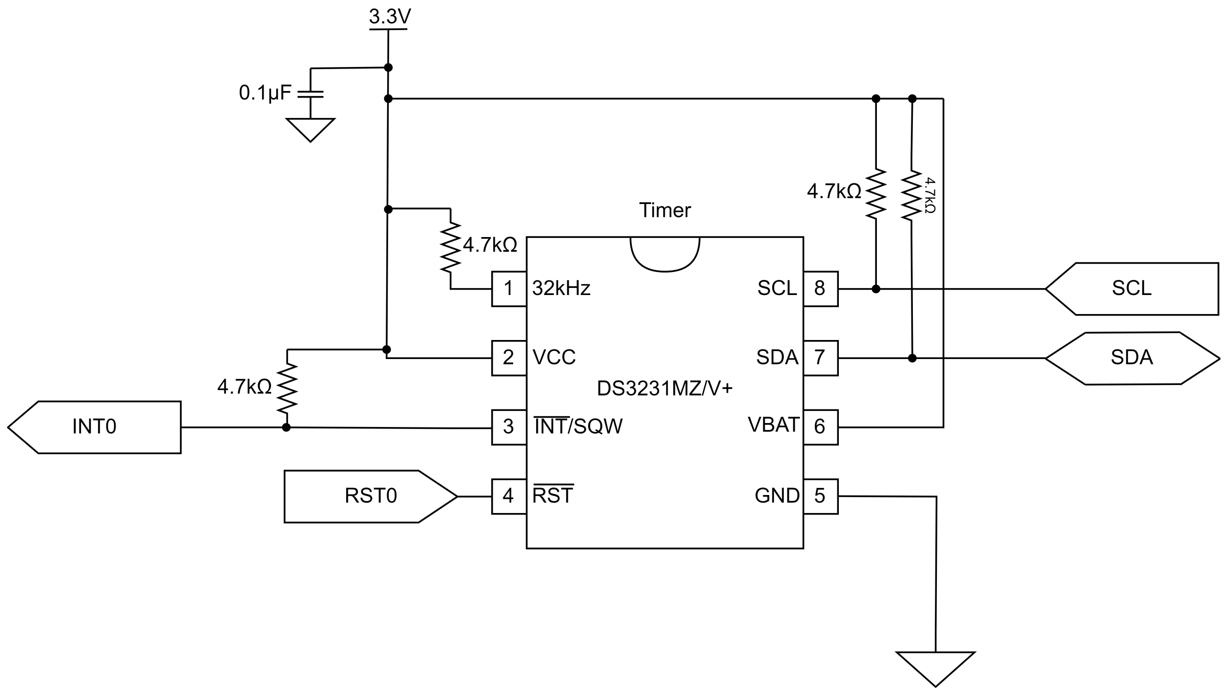

Figure 5: Timer Circuit

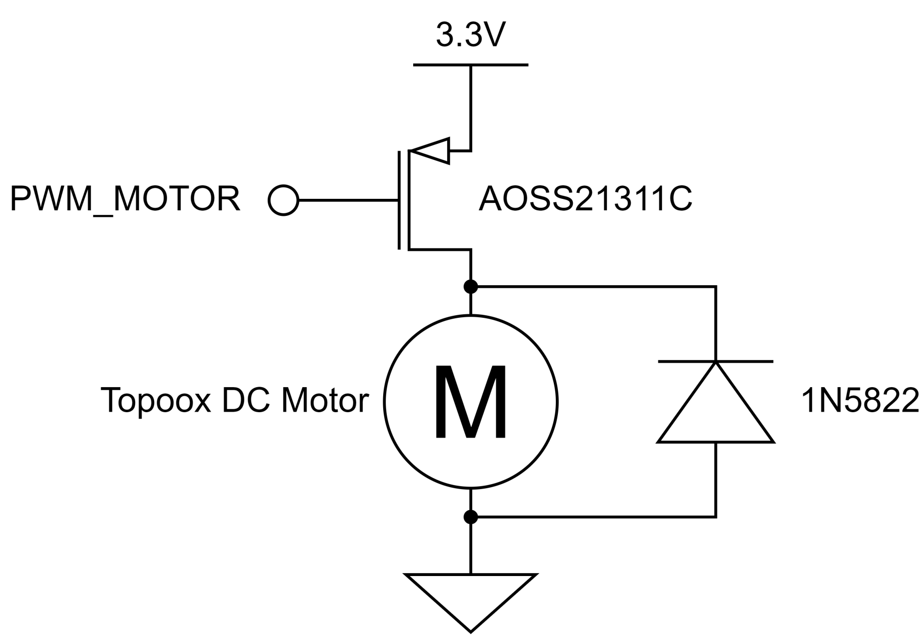

Figure 6: Vibration Motor Circuit

The software of the control subsystem contains two parts: setup and loop. A brief flow chart of the control program is shown in Figure 7.

In setup, the control program starts up the microcontroller by first initializing each input/output pin on the chip. The memory is then updated to contain the initial brushing goal value (e.g., 120 seconds). The control parameters of the motors are also assigned during this stage. Finally, after all the previous works are complete, the program will set up the timer to start the first brushing session (e.g., 12 hours).

As the program enters the loop stage, the LED will be set to red, indicating that a new brushing session has started and the brushing goal hasn't been met. The MCU will then be controlled to continuously fetch the input from the sensor subsystem to detect if a dog is biting the toy. When a strong enough bite is detected from any of the three pressure sensors in the sensor subsystem, the program will be released from the previous state and start the vibration motor after setting the LED to blue. If the dog is still biting the toy and the brushing goal in this brushing session hasn't been met, the MCU will stay in this stage, and the pressure readings will be fetched on a second basis to help adjust the frequency of the motor's vibration. The relationship between the frequency of vibration and pressure readings is shown in Figure 8. At the same time, the brushing goal value in memory is updated constantly according to the frequency of vibration. For each second during the vibration, the brushing goal (i.e., remaining brushing time) is deducted by an amount of (vibration duty cycle / 50%) seconds. Overall, greater bite force results in greater vibration frequency and less brushing time. If the dog stops biting the toy, the control program will stop the vibration motor and go back to the start of the loop to wait for the dog to bite again. On the other hand, if the brushing goal time is met (i.e., less than 0) before the dog stops biting, the MCU will also stop the vibration motor. Then, the buzzer/treat dispensing subsystem will be activated to generate "attractive" sounds and dispense a dog treat to the dog. The MCU will then enter sleep mode to save power and wait for an interrupt signal to wake up and start a new brushing session.

Notice that the interrupt handler is designed to be handled only when the system is either idle or in sleep, while the interrupt itself can be fired at any time from the timer. This is because it is unwise to let the vibration or treat dispensing processes be interrupted by the timer since they are related to the dogs' behavior of learning.

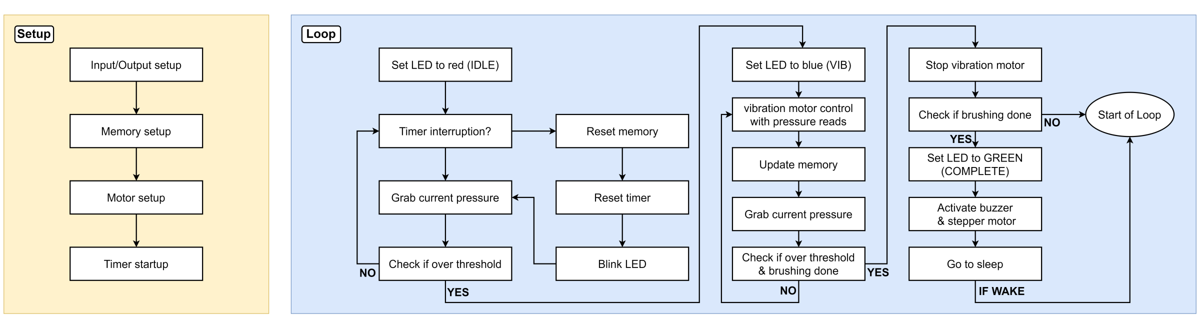

Figure 7: Flow Chart of Control Program

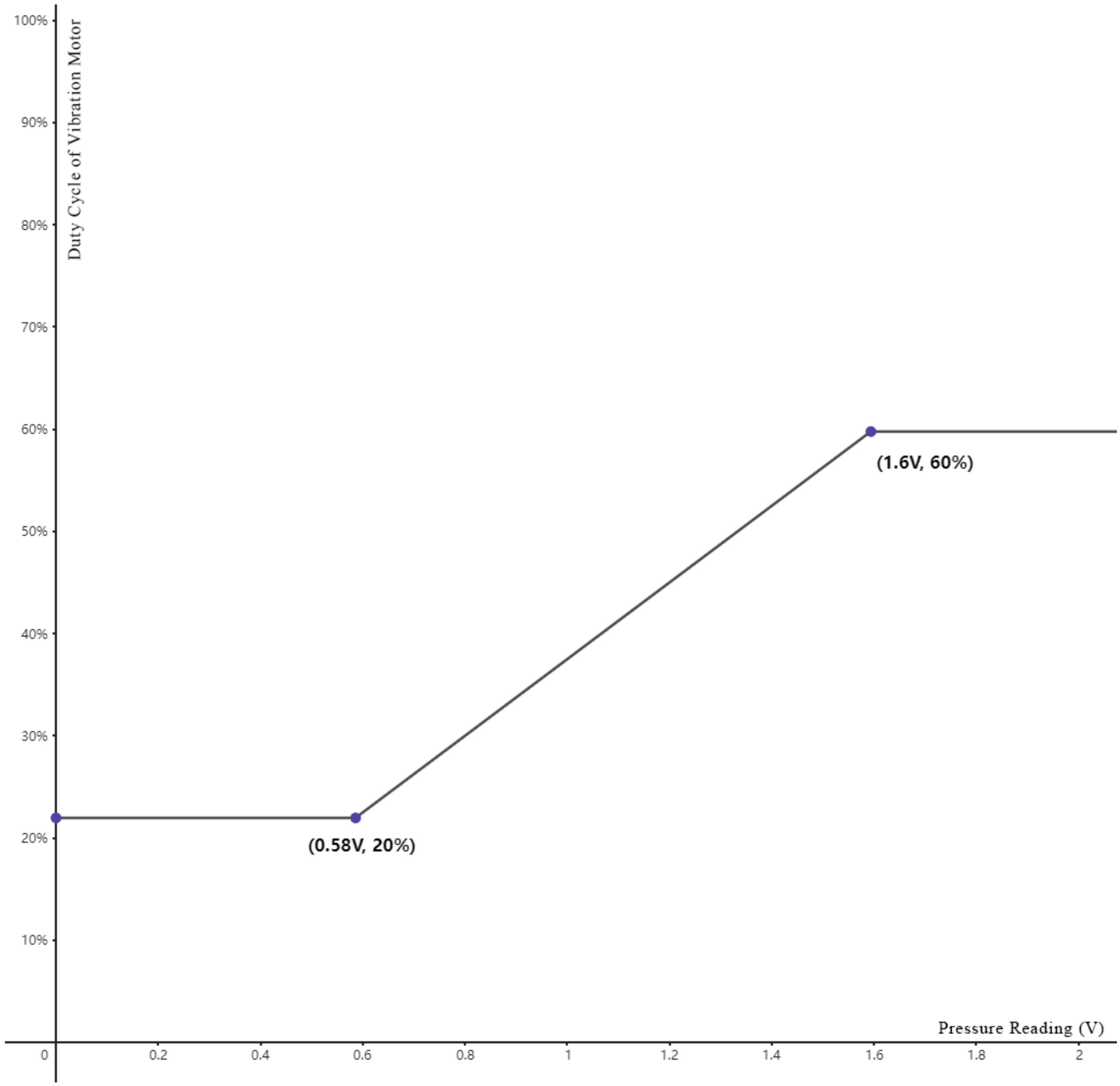

Figure 8: Pressure vs. Frequency of Vibration

2.2.2 Sensor Subsystem

The circuit-level implementation of the pressure sensor is shown in Figure 9.

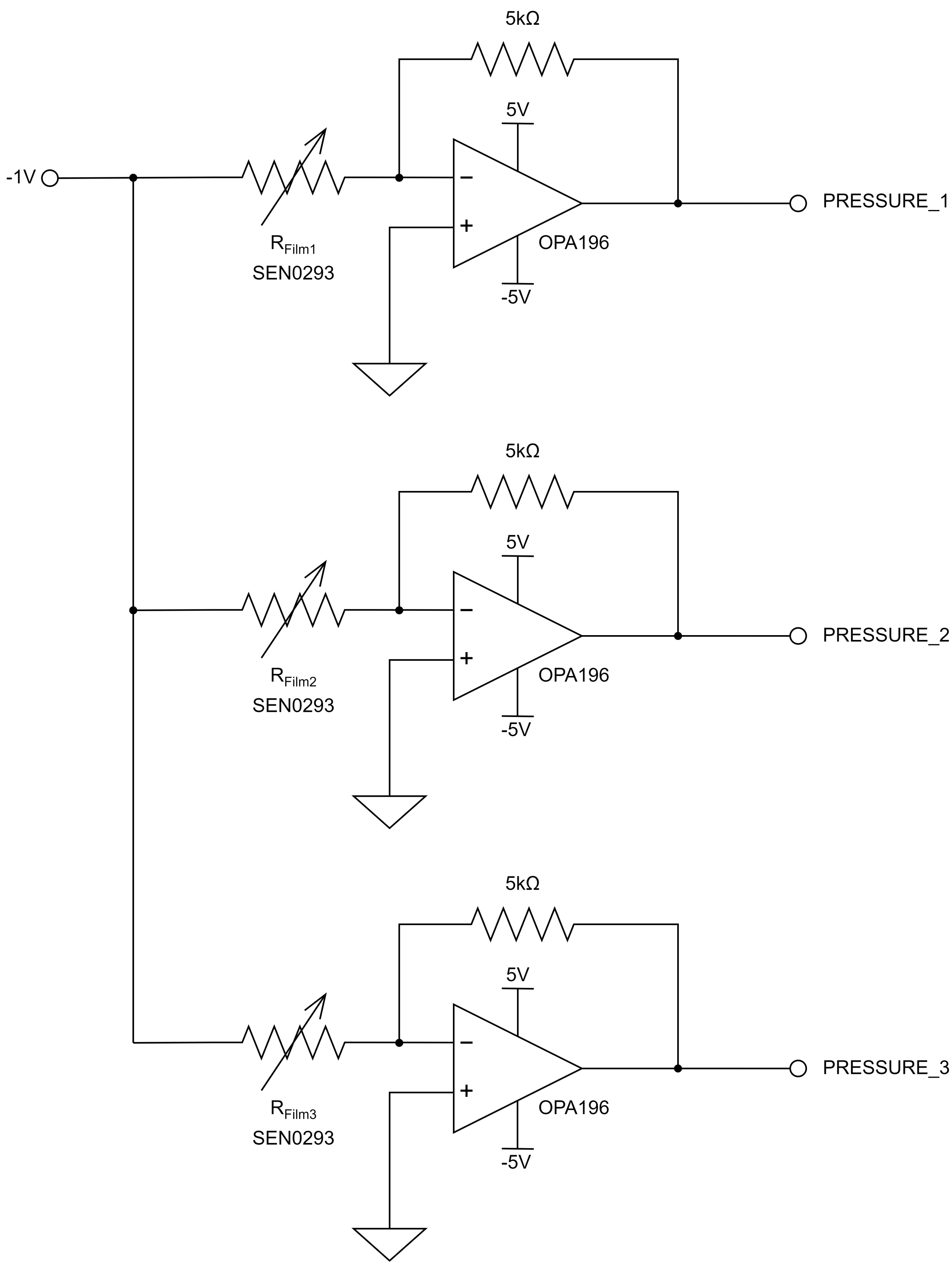

Figure 9: Pressure Sensor Circuit

The circuits for -5 V bias generation and -1 V reference generation are shown in Figure 10 and Figure 11.

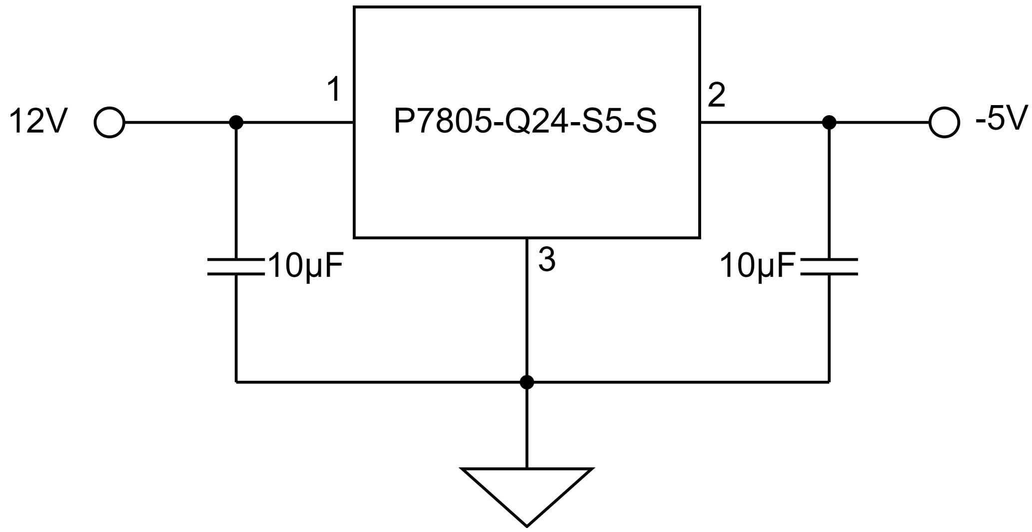

Figure 10: -5 V Bias Generation Circuit

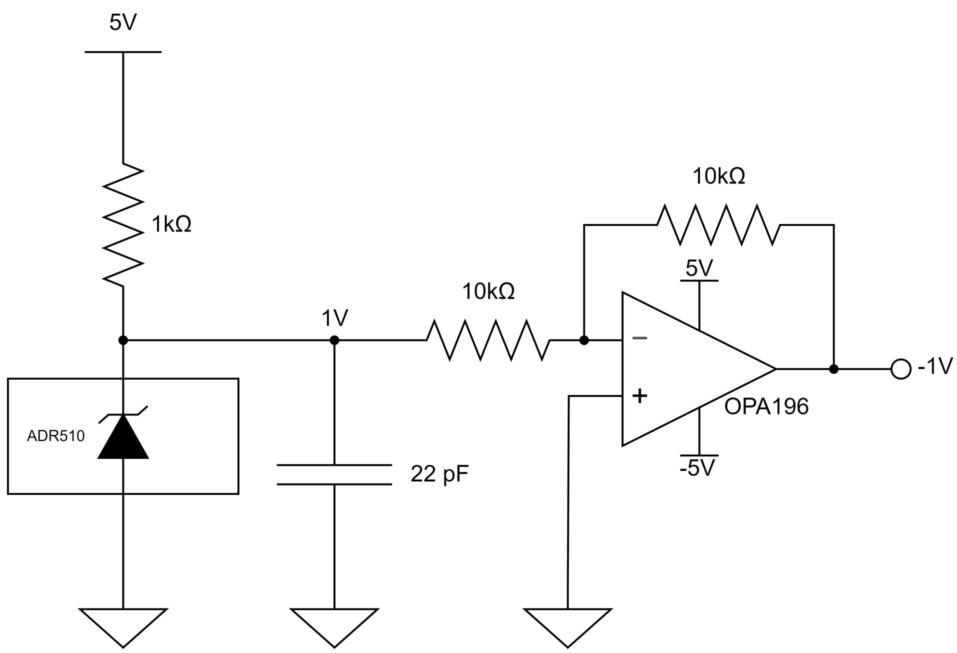

Figure 11: -1 V Reference Generation Circuit

The output of the pressure sensor can be determined by ideal op-amp rules:

$$\frac{-1-0}{R_{Film}} = \frac{0-V_{OUT}}{5000} \tag{2.3}$$

$$V_{OUT} = \frac{5000}{R_{Film}} \tag{2.4}$$

Based on the resistance R_{Film}, the output voltage ranges from 0 V to 5 V. The output voltage is quantized by the microcontroller ADC into 1024 levels. This results in a resolution of approximately 0.005 V. The resistance of SEN0293 versus applied force is shown in Figure 12 [3].

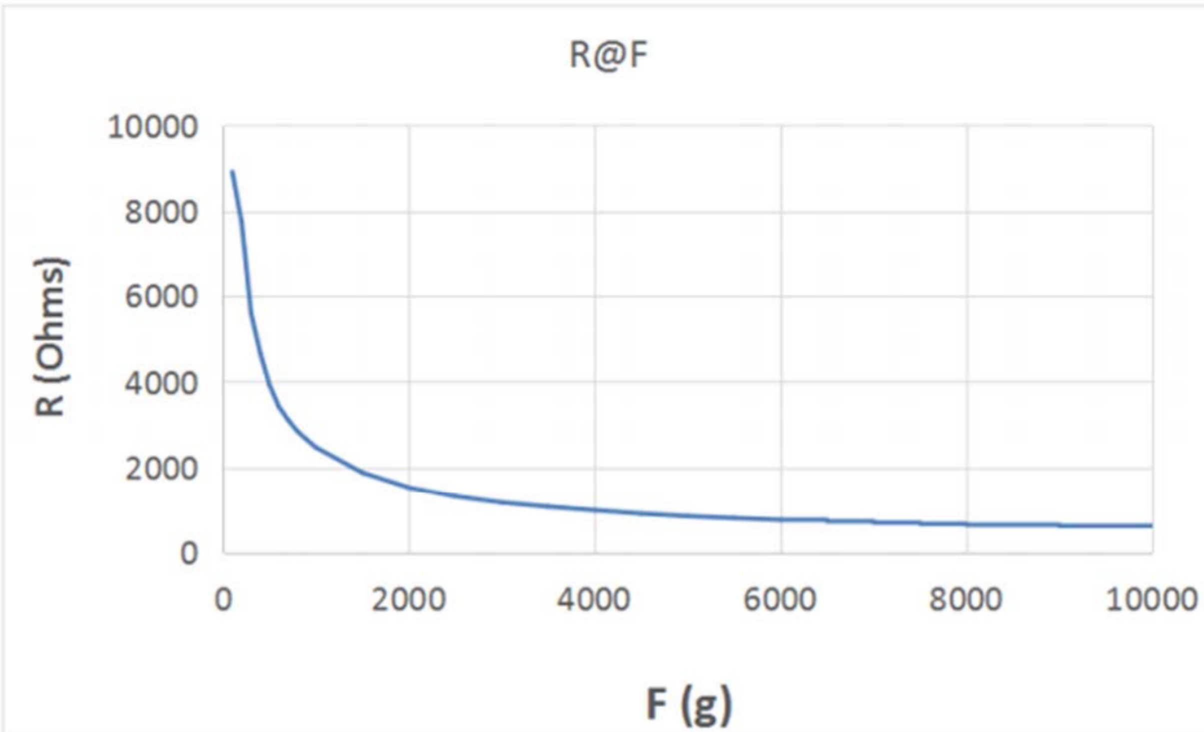

Figure 12: Thin Film R vs. F

The output of the pressure sensor will be discussed further in verification section.

2.2.3 Buzzer/Treat Dispensing Subsystem

The circuit-level implementation for the buzzer is shown in Figure 13.

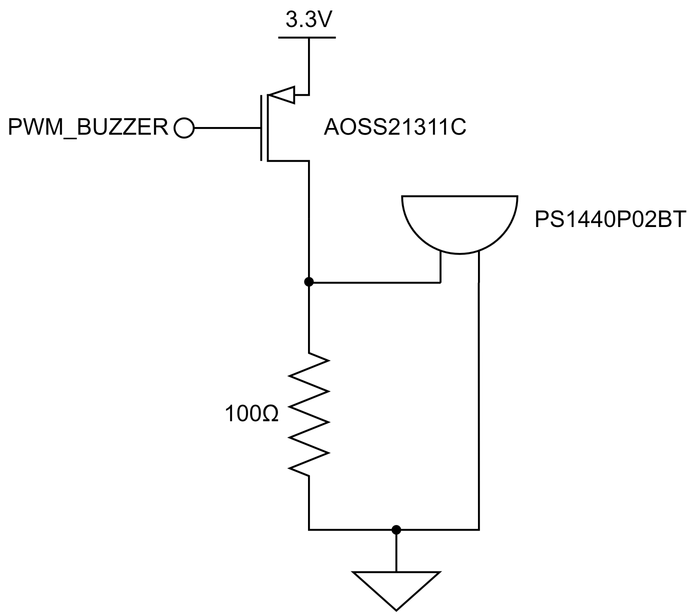

Figure 13: Buzzer Circuit

The stepping sequence and the circuit-level implementation for the treat dispenser stepper motor are shown in Figure 14 and Figure 15.

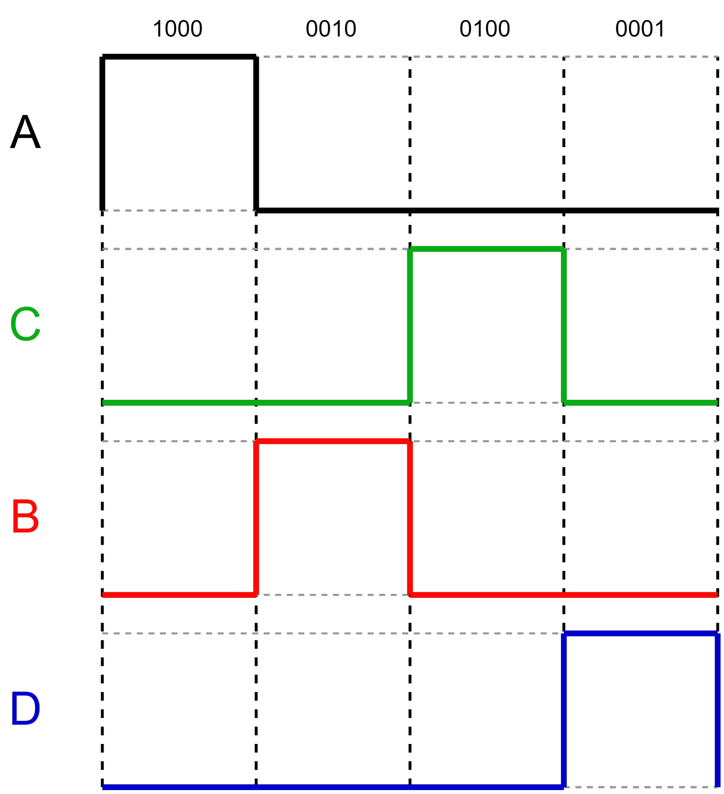

Figure 14: Stepping Sequence

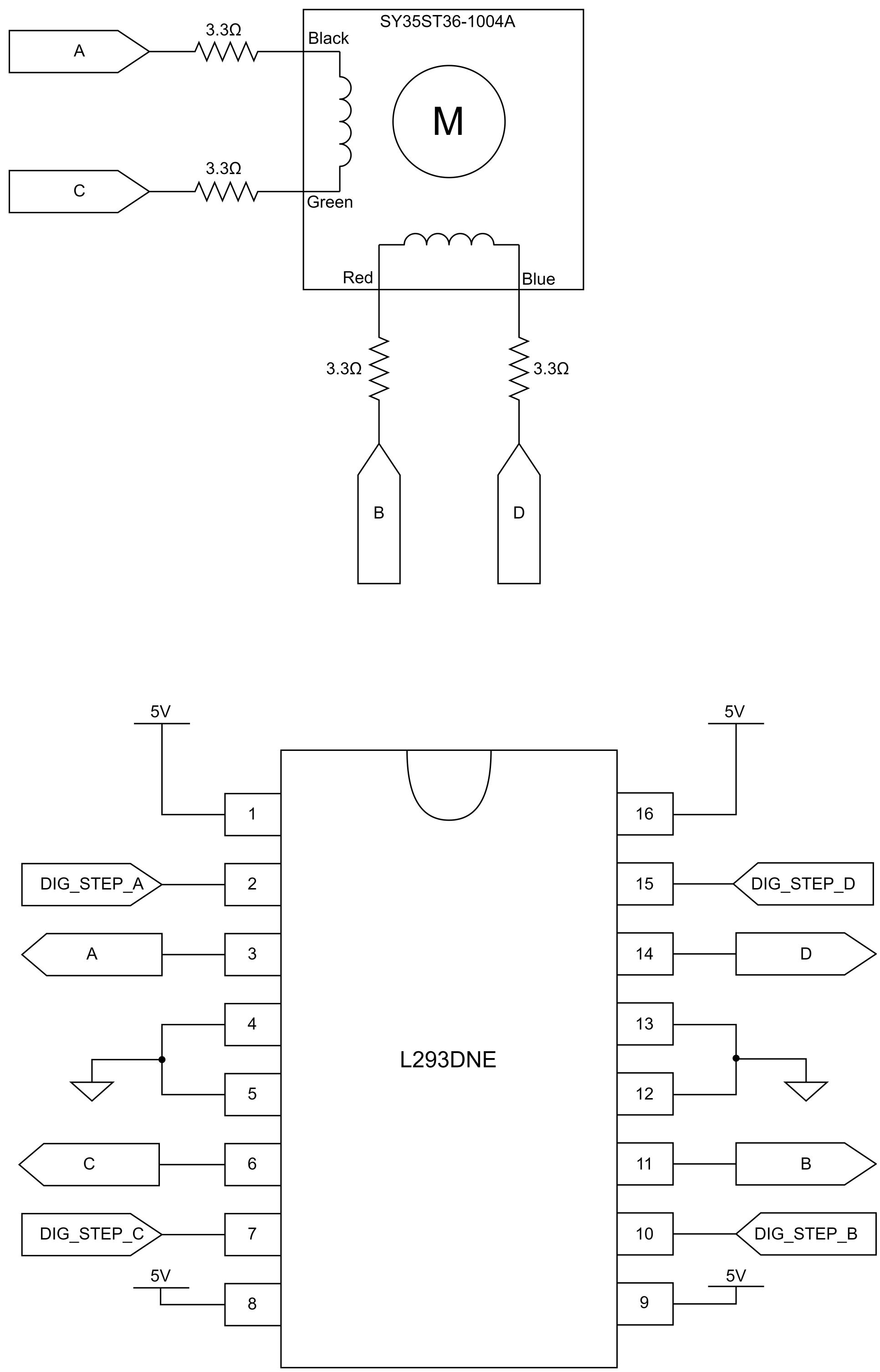

Figure 15: Stepper Motor Circuit

2.2.4 State Indication Subsystem

The circuit-level implementation of the state indication subsystem is shown in Figure 16.

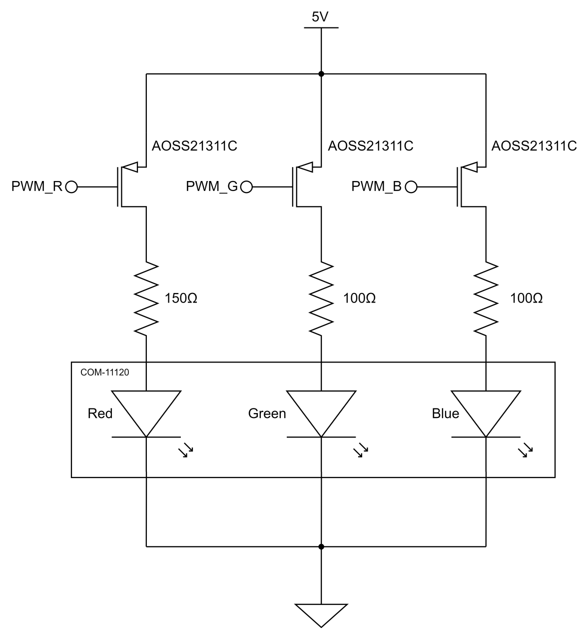

Figure 16: RGB LED Circuit

2.2.5 Power Subsystem

The circuit-level implementation of the power subsystem is shown in Figure 17.

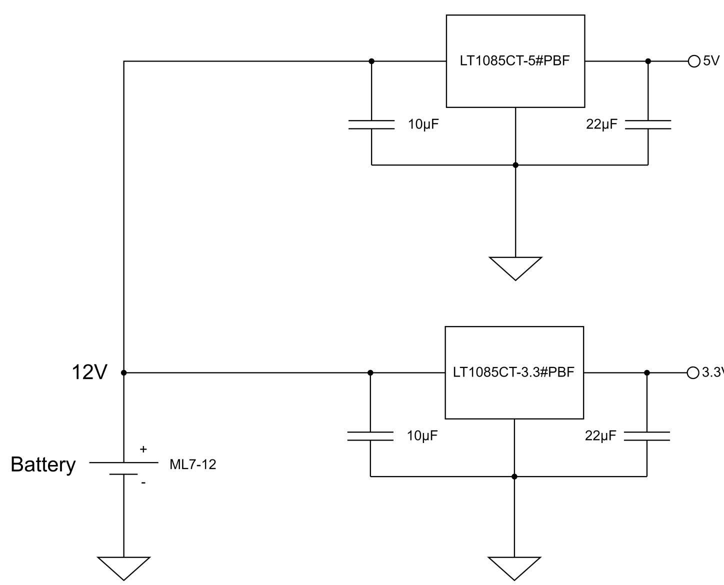

Figure 17: Power Supply Circuit

2.3 Verification

The whole system was tested accordingly, using both the lab power supply and the 12 V battery. Overall, the final product was able to carry out specified functionality. The vibration was strong enough to brush the mock plaque off and the handle withstood more than 100 lb of weight. Also, the buzzer is audible and treats are dispensed accordingly.

Since the project was designed to be a battery-operated device, power consumption is a critical indication of practicality. Power-related metrics are presented in Table 1, Table 2, Table 3, and Table 4.

Table 1: Power Supply Performance

Regulator	V_{OUT}	I_{MAX}	V_{Ripple}	$I_{Quiescent}$
LT1085CT3.3#PBF	3.314 V	3A	N/A	8 mA
LT1085CT5#PBF	5.000 V	3A	$<$ 50 mV	8 mA

Table 2: Major Current Draws Excluding Vibration Motor

Device	**Current**
Stepper Motor	$<$ 0.5 A
Digital IC	50 mA $-$ 80 mA
Buzzer	17 mA
Red LED	20 mA
Green LED	17 mA
Blue LED	17 mA

Table 3: Battery Performance

Condition	**Battery Voltage**
No Load	12.998 V
Loaded	12.700 V

Table 4: Vibration Motor Current Draw

Duty Cycle	**%Power**	**Vibration Motor Current**
85%	15%	0.893 A
23.5%	76.5%	2.016 A

The current in the idle state dictates the battery life as the system is on all day. Under the idle state, the system should draw approximately 50 mA. Therefore, the battery should be able to last greater than three days which is reasonable.

Another key component was the pressure sensor. The pressure sensor serves as the interface between the system and the dog. Therefore, it is crucial that its circuitry can operate in the expected way. The pressure sensor output voltage versus thin film resistance is shown in Figure 18.

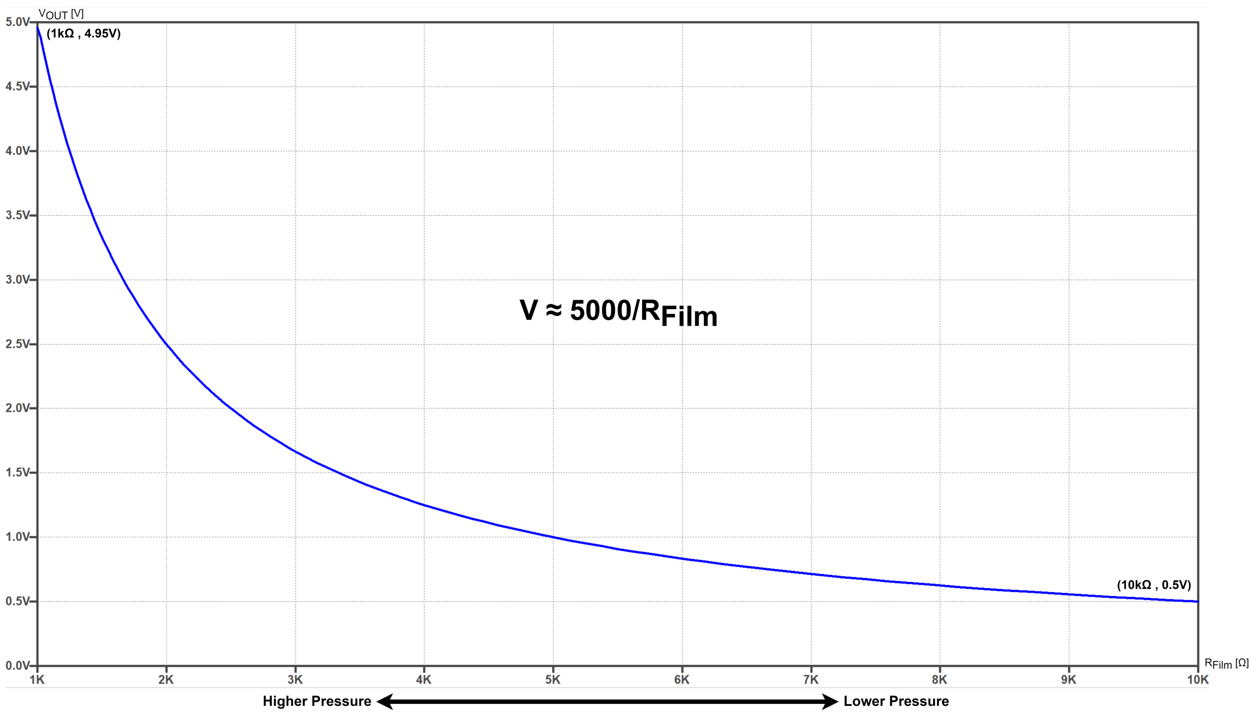

Figure 18: Pressure Sensor Ouput Voltage vs. R_{Film}

The actual performance of the inverting amplifier was rather similar to the expected performance. This allowed us to implement the control algorithm successfully.

3 Costs

3.1 Table

Our project incorporates many different components outside of what is given to us by the machine shop. Please see Appendix B for a list of all the parts and its cost. The cost of all the parts is $169.07.

3.2 Estimated Hours of Labor

Our group consists of two Computer Engineering students and one Electrical Engineering student. According to the latest information published by the ECE department of the Grainger College of Engineering, Computer Engineering students make an average of $105,352 per year and Electrical Engineering students make an average of $80,296 per year [4]. Assuming that each member worked 40 hours per week, 52 weeks a year, this would average out to be $50.65 per hour for the former and $38.60 for the latter.

Each member is estimated to contribute 10 hours per week for nine weeks, so the total cost of labor of the project will be:

$$(\$38.60 + \$50.65 * 2) * 10 * 9 * 2.5 = \$31,477.50 \tag{3.1}$$

3.3 Machine Shop Materials

For our project, we requested the machine shop to build the treat dispenser and toothbrush. This required a cylinder of PVC plastic which would be cut into the shell of the toothbrush and a plastic enclosure for electronics which would also serve as the treat dispenser. In total, the materials costed about $130.

3.4 Total Estimated Cost

The total estimated cost of the project will consist of the cost of parts ($169.07),the cost of labor ($31,477.50), and the cost of the machine shop ($130), which sum up to a total cost of $31,776.57.

4 Conclusions

4.1 Accomplishments

The toothbrush toy is able to generate vibration strong enough to brush plaque away, ensuring good oral hygiene twice a day. As an incentive to continue this behavior, our project dispenses a treat and a loud sound, so the dog will eventually learn that biting the toothbrush will result in a treat. Overall, the project successfully meets all the high level requirements.

4.2 Uncertainties

While designing the project, there were many uncertainties that led to design changes. This type of product does not exist in the market today, so it was difficult to determine if certain parts would work as intended. We were particularly concerned about the power of the vibration motor because we could not test the motor until the entire project was built. Mass plays a big role in how much vibration the toothbrush can get, so we decided to separate the system and put as little mass around the vibration motor as possible. This worked in our favor and the toothbrush toy produces an adequate amount of vibration.

4.3 Ethical Considerations

According to the IEEE Code of Ethics, the safety and health of the public are to be held paramount [5]. We need to pay close attention to the safety aspects of the project due to the interactive nature of our proposed device. Our project uses a high volt battery that can serve as a potential fire and health hazard. We were able to mitigate the chances by creating a protective cover, but ideally we can switch to a smaller power source. Another safety aspect we need to pay close attention to is the materials of the toothbrush. Due to certain limitations, we used PVC plastic and silicone sponges as bristles. These materials are not guaranteed to be dog friendly. Finally, we also had to make sure all exposed wires could be covered or out of the dog's reach. We were able to accomplish this by placing all wires inside a box or protected by a metal pipe.

4.4 Future Work

There are many improvements we can make to the project. One improvement we would like to include is an user interface where the user can set the duration of the brushing session or be able to reset the device. Another aspect we would like to improve is the shape and size of the toothbrush. After building our project, we believe we can achieve the same effect with a more ideal shape and smaller size. In addition, we could also integrate our project with already existing dog food dispensers. This would make it more convenient for dog owners to take better care of their dogs.

References

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Appendix A Requirement and Verification Tables

Requirement	Verification
When the dog fails to brush enough time in a brushing session, the system will reset automatically.	• Start the system in IDLE state, conduct pressing with enough force to trigger vibration for 0 seconds, 30 seconds, 1 minute, or 1.5 minutes during a brushing session. Wait till the next brushing session to check if the remaining time is reset correctly. • Adjusting alarm period from 12-hour to 5-minute for easier verification.
When the timer chip's alarm raises during vibration, the system will reset only after the vibration is stopped.	• Start the system in IDLE state, conduct pressing with enough force to trigger vibration for a specific length of time. • Adjust the alarm period so that it will interrupt before the vibration stops. Observe the LED output to check if the state transition is correct.
When the required brushing time is reached, the pressure sensor will not trigger a transition in state.	• Start the system in COMPLETE state, check if pressing the toy will result in vibration or changes of color of the LED display.
The vibration motor should be able to rotate at least 1000 RPM when a weight of least 200g is attached.	• The vibration motor is connected to a that imitate what we use for the toy, and is controlled to vibrate for over 2-minute. • A mobile app (e.g.VibraTestPro) will be used to measure the working frequency of the motor.

Figure 19: Control Subsystem RV Table

Requirement	Verification
Depending on the external pressure applied to the thin film pressure sensor, the output of the pressure sensor circuit should be able to at least swing from 0.5V to 4.9V to give an adequate resolution.	● Set the digital multimeter to DC voltage mode. Connect the positive probe to the output of the op-amp and the negative probe to the negative terminal of the battery. ● Ensure that no pressure is applied to the thin film pressure sensor and the toy is left on a hard surface. ● Note down the minimum voltage value measured by the digital multimeter. ● Then, place 10kg of weight on the thin film pressure sensor. ● Note down the maximum voltage value measured by the digital multimeter.
The maximum current draw of each pressure sensor circuit should not exceed 2 mA.	● Set the digital multimeter to DC current mode. Connect the positive probe to the 5V voltage supply. Connect the negative probe to the common node of 5V inputs of the pressure sensor circuit and -1V reference circuit. ● Place 10kg of weight on the thin film pressure sensor. ● Note down the maximum current values measured by the multimeter. ● Repeat the above procedure for -5V inputs. ● Sum the current values for 5V and -5V up and note down the value.

Figure 20: Sensor Subsystem RV Table

Requirement	Verification
Depending on the number of compartments in the final design, the treat dispenser should be able to rotate for 40° or 72° and release a treat correctly.	● Place a dummy treat in each compartment. ● Ensure that the toy is in IDLE state. ● Place 10kg of weight on the thin film pressure sensor. ● Wait for 2min until the toy enters COMPLETE state. ● Observe the rotation of the stepper motor and the releasing of the dummy treats.
The buzzer should draw ≤ 20 mA to obtain a reasonable battery life.	● Set the digital multimeter to DC current mode. Connect the positive probe to the 3.3V voltage supply. Connect the negative probe to the source of the PMOS that is in series with the buzzer. ● Ensure that the toy is in IDLE state. ● Place 10kg of weight on the thin film pressure sensor. ● Wait for 2min until the toy enters COMPLETE state. ● Note down the maximum current values measured by the multimeter when the buzzer is buzzing.

Figure 21: Buzzer/Treat Dispensing Subsystem RV Table

Requirement	Verification
The brightness of individual red, green and blue LEDs in the RGB LED can be adjusted separately. The LED should be bright enough such that they are easy to identify.	● Ensure that the toy is in IDLE state. ● Observe the LED from a 45° viewing angle. Note down if the viewer can tell the LED is on. If so, note down the color of the LED. ● Place 10kg of weight on the thin film pressure sensor. ● Observe the LED from a 45° viewing angle. Note down if the viewer can tell the LED is on. If so, note down the color of the LED. ● Wait for 2min until the toy enters COMPLETE state. ● Observe the LED from a 45° viewing angle. Note down if the viewer can tell the LED is on. If so, note down the color of the LED.
The RGB LED should draw ≤ 60mA in total to obtain a reasonable battery life.	● Set the digital multimeter to DC current mode. Connect the positive probe to the 5V DC voltage. Connect the negative probe to the common node of PMOS sources. ● Ensure that the toy is in IDLE state. ● Note down the maximum current value measured by the multimeter. ● Place 10kg of weight on the thin film pressure sensor. ● Note down the maximum current value measured by the multimeter. ● Wait for 2 min until the toy enters COMPLETE state. ● Note down the maximum current value measured by the multimeter.

Figure 22: State Indication Subsystem RV Table

Requirement	Verification
The battery should output 12V +/- 0.24V.	• Set the digital multimeter to DC voltage mode. Connect the positive probe to the positive terminal of the battery. Connect the negative probe to the negative terminal of the battery. • Note down the voltage value measured by the digital multimeter.
The 6V voltage regulator should output 6V +/- 0.12V.	• Set the digital multimeter to DC voltage mode. Connect the positive probe to the output terminal of the 6V voltage regulator. Connect the negative probe to the negative terminal of the battery. • Note down the voltage value measured by the digital multimeter.
The 5V DC voltage should be maintained at 5V +/- 0.1V. Also, the voltage ripple needs to be less than 50mV peak-to-peak.	• Set the oscilloscope to high-Z mode. Set the oscilloscope to measure average voltage and peak-to-peak voltage. • Connect the positive probe of the oscilloscope to the output terminal of the voltage regulator. Connect the negative probe to the negative terminal of the battery. • Note down the measured values of average voltage and peak-to-peak voltage.
The 3.3V voltage regulator should output 3.3V +/- 0.066V.	• Set the digital multimeter to DC voltage mode. Connect the positive probe to the output terminal of the 3.3V voltage regulator. Connect the negative probe to the negative terminal of the battery. • Note down the voltage value measured by the digital multimeter.

Figure 23: Power Subsystem RV Table

Appendix B Cost of Parts Table

Description	Part Number	Quantity	Unit Price	Price for Quantity
12V battery	ML7-12 (Lowe's)	1	$19.99	$19.99
12V battery charger	2059-PCCG-SL A12V300-ND (Digikey)	1	$13.11	$13.11
15000 RPM mini electric motor (6 pack)	Topoox (Amazon)	1	$6.99	$6.99
OPA196 op-amp	296-48157-2-ND (Digikey)	3	$1.50	$4.50
ADR510 voltage reference	505-ADR510AR TZ-REEL7TR-N D (Digikey)	1	$2.25	$2.25
30V PMOSFET	785-AOSS21311 CTR-ND (Digikey)	5	$0.42	$2.10
RGB LED	COM-11120 (Digikey)	1	$1.15	$1.15
Thin film pressure Sensor	1738-SEN0293-ND (Digikey)	3	$6.08	$18.24
ATmega328P microcontroller	ATMEGA328P-PU-ND (Digikey)	1	$3.03	$3.03
AVR ISP adaptor	1528-1189-ND (Digikey)	1	$0.95	$0.95
MBR0520 Diode	MBR0520LT1G OSTR-ND (Digikey)	1	$0.38	$0.38
16MHZ crystal oscillator	X433-ND (Digikey)	1	$0.71	$0.71
Stepper Motor	SY35ST36-1004 A (Digikey)	1	$21.95	$21.95

Figure 24: Cost of Parts Table Part 1

Dog-safe plush for bristles	Silicone Sponges (Amazon)	1	\$10.99	\$10.99
DS 3231 Timer	DS3231MZ+-ND (Digikey)	1	\$10.31	\$10.31
Non-Isolated Switching Regulator	P7805-Q24-S5-S (Digikey)	1	\$5.48	\$5.48
3.3Ω resistor	13-MFR-25FTE52-3R3CT-ND (Digikey)	4	\$0.15	\$0.60
100Ω resistor	100QBK-ND (Digikey)	6	\$0.10	\$0.60
1kΩ resistor	1.0KQBK-ND (Digikey)	1	\$0.10	\$0.10
4.7kΩ resistor	4.7KQBK-ND (Digikey)	4	\$0.10	\$0.40
10kΩ resistor	10.0KXBK-ND (Digikey)	10	\$0.14	\$1.40
100kΩ resistor	100KQBK-ND (Digikey)	1	\$0.10	\$0.10
0.1 uF capacitor	399-9867-2-ND (Digikey)	4	\$0.49	\$1.96
10 uF capacitor	399-13968-ND (Digikey)	4	\$0.79	\$3.16
22 pF capacitor	399-8917-ND (Digikey)	5	\$0.42	\$2.10
Piezoelectronic Buzzer	445-5242-1-ND (Digikey)	1	\$0.80	\$0.80
L293DNE half H-bridge	296-9518-5-ND (Digikey)	1	\$4.29	\$4.29
LT1085CT-3.3 voltage regulator	584-LT1085CT-3.3 (Mouser)	1	\$10.55	\$10.55

Figure 25: Cost of Parts Table Part 2

LT1085CT-5 voltage regulator	LT1085CT-5#PBF-ND (Digikey)	1	$11.98	$11.98
1N5822 diode	497-11370-1-ND (Digikey)	1	$0.45	$0.45
Barrel connector	CP-102AH-ND (Digikey)	1	$0.82	$0.82
Barrel adapter	DAYKIT (Amazon)	1	$0.80	$0.80
2-pin KK254 connector	A31080-ND (Digikey)	5	$0.22	$1.10
4-pin KK254 header	WM4202-ND (Digikey)	1	$0.35	$0.35
2-pin KK254 header	900-0022232021-ND (Digikey)	3	$0.21	$0.63
1729128 2-port header	277-1247-ND (Digikey)	1	$1.94	$1.94
1729144 4-port header	277-1249-ND (Digikey)	1	$2.68	$2.68
Push Button	450-1650-ND (Digikey)	1	$0.13	$0.13
			Total	$169.07

Figure 26: Cost of Parts Table Part 3

Appendix C PCB Design

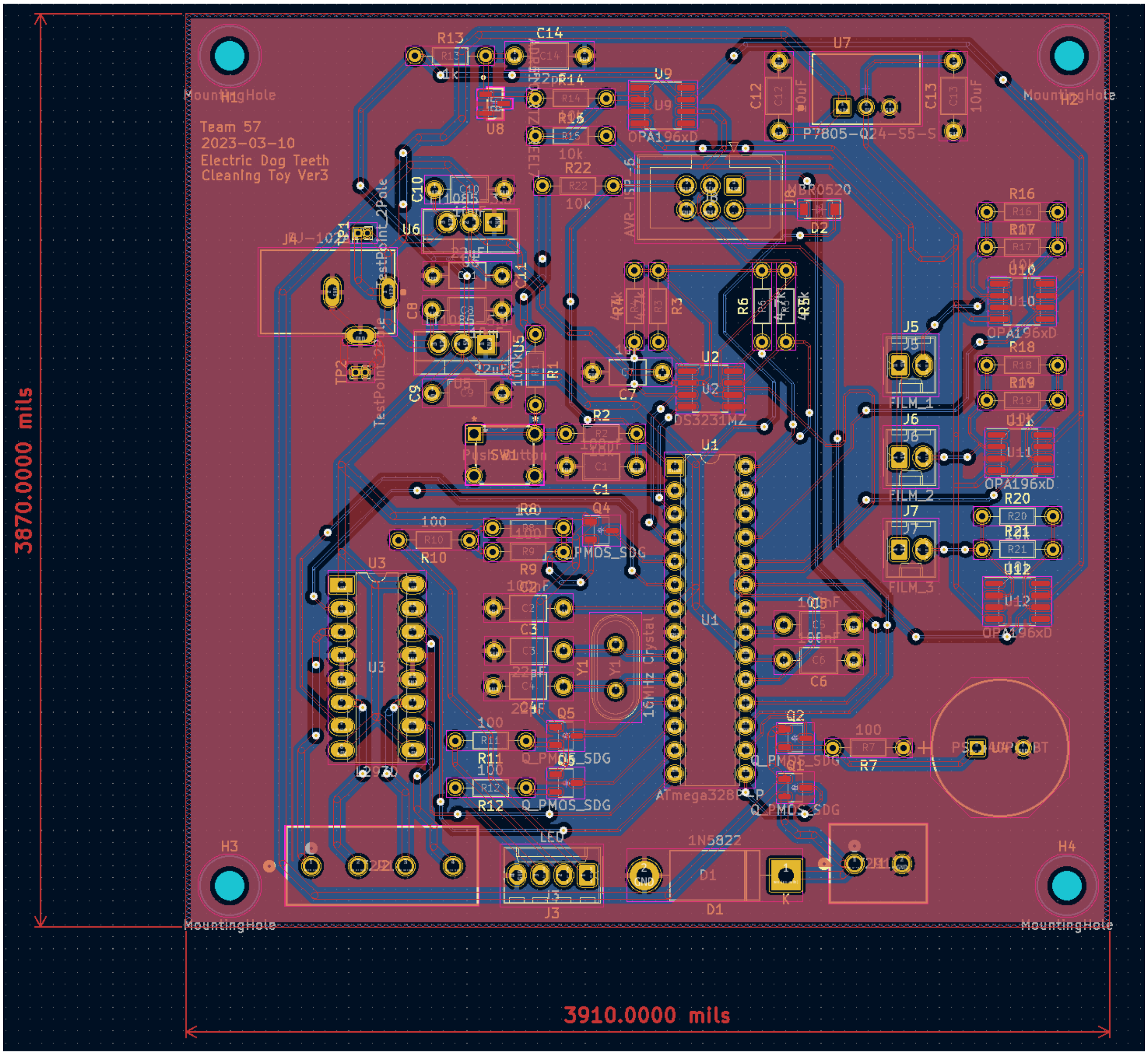

Figure 27: PCB Design

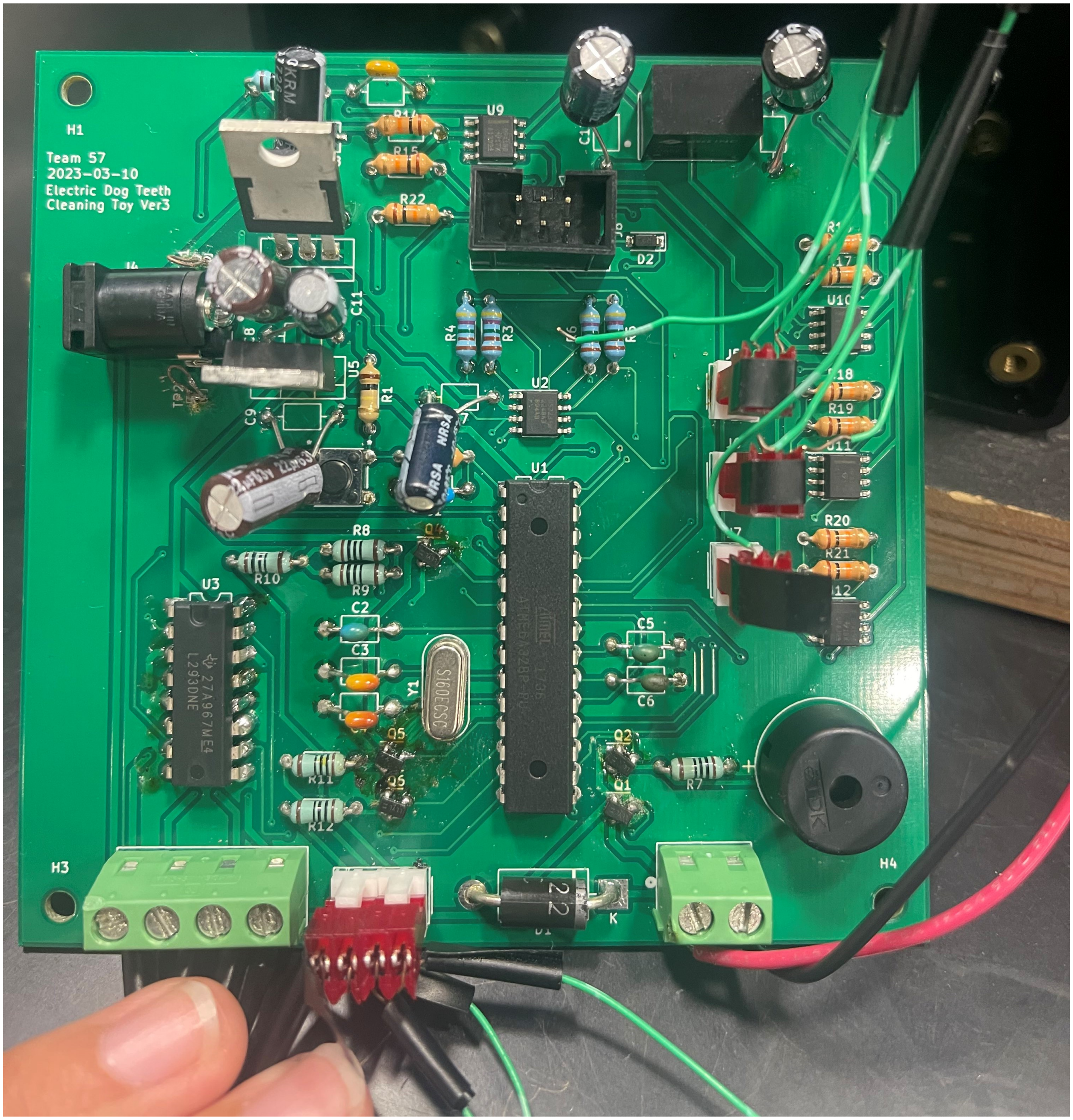

Figure 28: Finished PCB