ECE445

Fall 2023

Final Report

Automated Cat Laser Tower

Team #11
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1 Abstract

This report details the design and implementation of an automated cat laser tower which would provide entertainment for cats when their owners are unavailable. The device created for this project is able to be calibrated to point lasers in only a set area and to be triggered by random times within a set time frame or by direct activation via a pressure sensor. The components and implementations used to create such a device are described.

Contents

2 Introduction

2.1 Problem

Cat owners are sometimes busy or out of the house, and cats need stimulation. An automatic laser toy that interacts with them and reacts to them would be a useful way to keep them active and mentally stimulated in a safe and healthy way.

The automatic cat laser toys on the market don't provide satisfactory reactions to the cat; they just have pre-programmed and random paths to follow. As a result, the area the laser dot occupies is limited by their motors, which leads to either a small area for the cat and laser to be active in if the toy is placed on the ground, or they run the risk of leading cats onto furniture or into the wall if placed higher (say, on a table or shelf). A laser toy that can cover a larger area and map out the area to avoid furniture, as well as react to the motion of a cat would be much more effective at keeping a cat interested and active during times when the cat owner is not available.

2.2 Solution

Our solution is a cat laser toy that uses LiDAR to map out an area, designated by the cat owner, with furniture detection and to determine the space in which it can move. Mounting the toy on a cat scratching post allows for a larger range of choice for the cat owner to choose, and allows for a clever way for the cat to activate the laser themselves, via pressure sensors, rather than merely wait on random activation. A motion sensor angled at the detection area will allow for the micro-controller to select different laser paths and speeds when the cat 'pounces' on the laser, and even 'catch' it.

To do this, we have mounted the LiDAR and cat safety laser in parallel on a 2 degree-of-freedom robotic arm. Dynamixel motors are used for their precision and position feedback, which are necessary to make the project work. PIR motion sensors allow the microcontroller to receive feedback from motion and change between pathing algorithms. We used a ATmega328P microcontroller to control the project.

2.3 Visual Aid

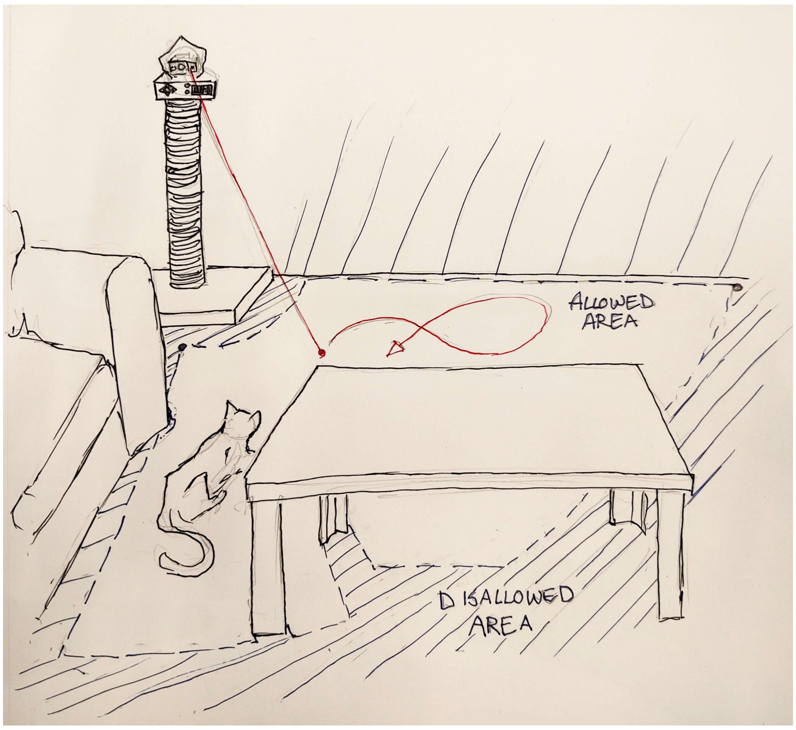

Figure 1: Automated Cat Laser Tower

2.4 High-Level Requirements

- The system's default state should be in low power mode until the pressure sensor triggers or random intervals during the time frame indicated during user set up; or via buttons on the user interface.
- The system should be able to create an area map on startup and once the area map is created, the laser module's range will be within the created area.
- The system should be able to detect fast motion and once detected, the control module should respond quickly by changing its pathing algorithm.

3 Design

3.1 Block Diagram

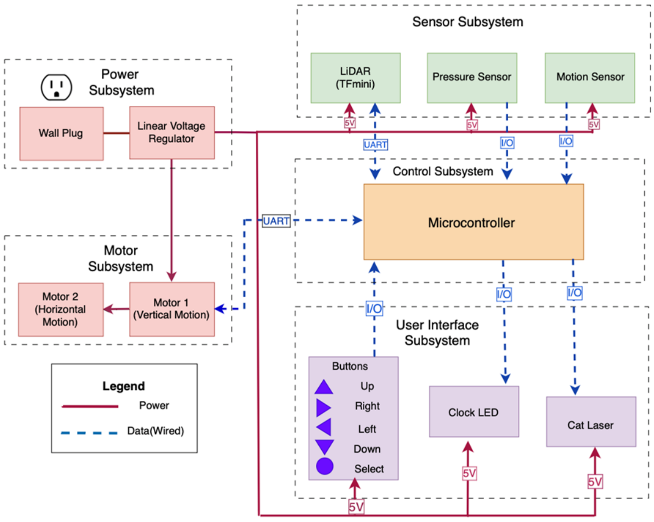

Figure 2: Project Block Diagram

3.2 Physical Design

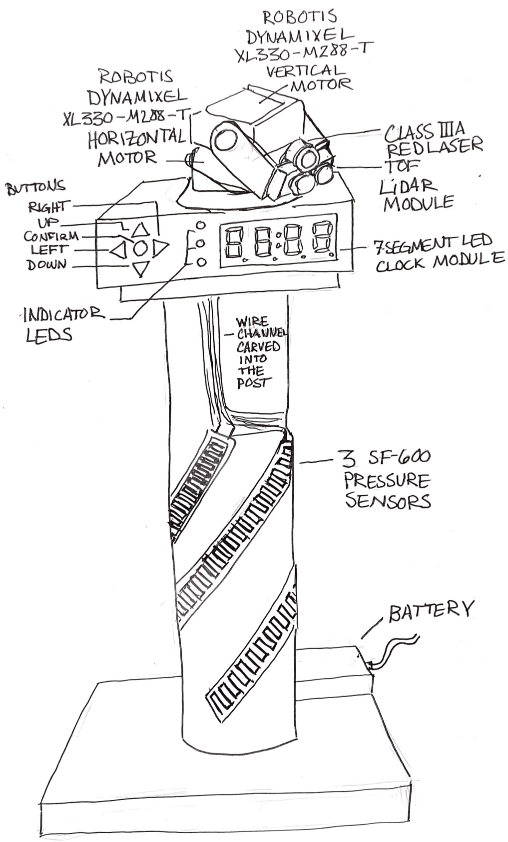

Figure 3: Physical Design

Figure 3 shows our initial physical design, and figure 4 shows the final product. The scratching post is 85 cm tall, and the user interface changed from being perched on top of of the pole, to being on the base near the edge. On the top of the post is the 2 degrees of freedom mechanical arm that holds the LiDAR and Class IIIa red laser pointer in parallel.

The user interface is a panel that holds, on its left, the 5 buttons, 'Up', 'Down', 'Left', 'Right', and 'Confirm', and on the right, a 7-segment LED Clock display.

Around the scratching post, the pressure sensors are spaced evenly. Wires will be lead down through the center of the scratching post.

The prototype we created can be seen below in Figure 4.

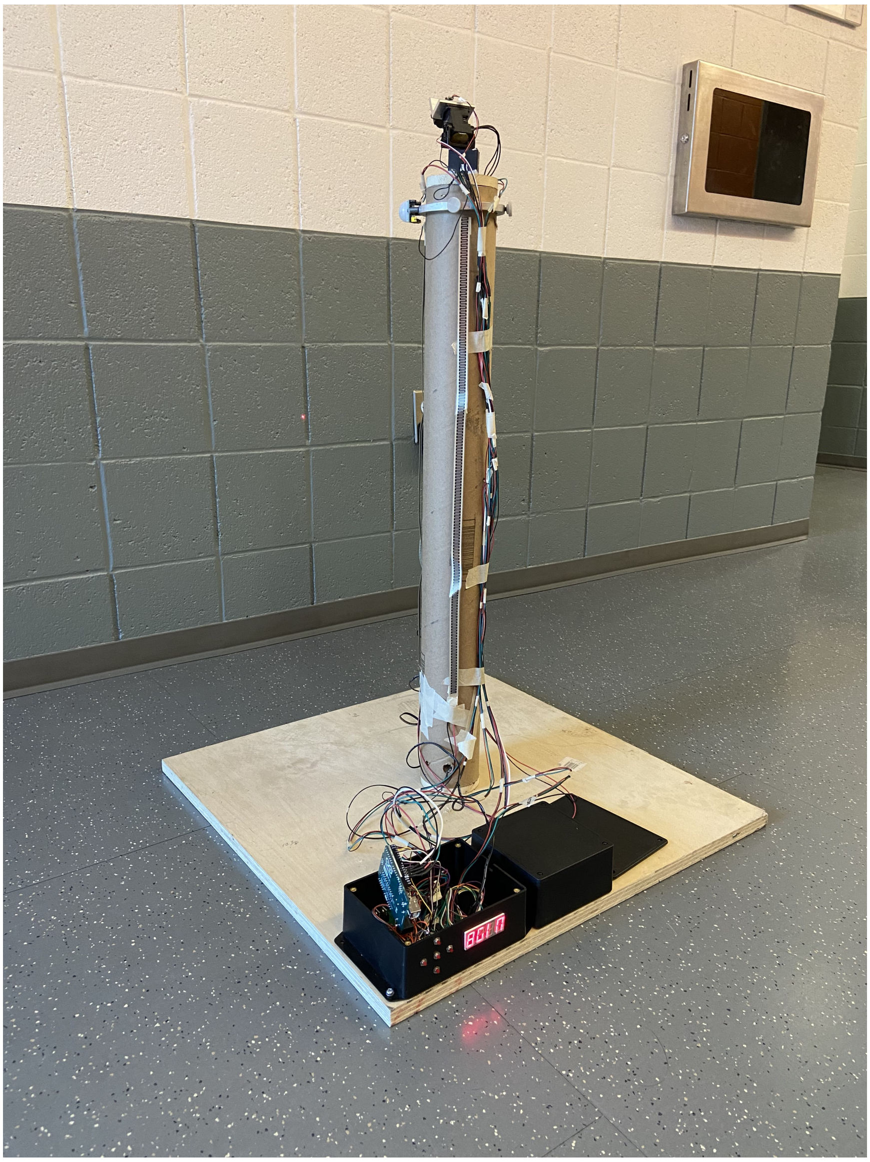

Figure 4: Prototype

3.3 Power Subsystem

This subsystem delivers power to the rest of the device, including the sensor, control, user interface, and the motor subsystems. It powers the rest of the device using a 12 Volt power source to drive a pair of LM1117MP-5.0 linear voltage regulators (LVR) that in turn provide 5 Volt DC power to the rest of the device. Each LVR provides up to 800 mA each, with a combined potential 1600 mA for the device. Our device uses roughly 850 mA during active mode consumption.

3.3.1 Design Considerations

At the start of the design process, it was decided to use two different voltages, 3.3 and 5 V for this project. We proceeded to choose components and designs accordingly. However it was later decided that two 5 V rails were preferable due to potentially having each motor requiring a separate 5 V source in order to prevent intervention from the other motor during operation. All of the components we already acquired that could operate with 3.3 V worked better with 5 V, especially with the MOSFETs chosen that had a turn on voltage in excess of 3 V, allowing less stringet design requirements on our pressure sensor submodule in particular. For the external source, we first selected a 12 V 3000 mAH lithium-ion battery pack. However during the project build, we discovered that the ports/connectors for the 12 V battery pack were not readily available in either of the electronic service shop or at local shops. As a replacement, we acquired a 12 V 5000 mAH lead-calcium battery. It functioned perfectly for a time before extensive use damaged the battery chemistry and thus we elected to use a 13.1 V wall plug as the final external power source for our device. Verification of the power subsystem are described in Table 1.

Requirement	Verification
12 V battery capable of providing voltages within 5 V with power regulators.	We used a multimeter to verify that the voltages across the power source and regulators reach desired values.
The IR motion sensor, motors, LiDAR, pressure sensors and the laser pointer should be all provided 5.0 V +/- 5% from the ¿12 V power source using a voltage regulator.	We used a multimeter to verify that voltage levels are within desired levels.

Table 1: R&V Power Subsystem

3.4 Motor Subsystem

For our device, we chose to use 2 XL330-M288-T Dynamixel Motors. These motors would perform horizontal and vertical rotation to move the laser and LiDAr modules of our devices to provide laser movement and enable liDAR scanning to create the object avoidance map during calibration. The Dynamixel motors we chose have 3 input ports and 3 output ports. The input ports consists of a 5 V input, a ground, and a UART connection for transferring data both from and to the microcontroller. The 3 output ports of a Dynamixel motor can serve as the input ports for another Dynamixel motor, allowing multiple motors to be run on a single UART connection. To use the UART for the Dynamixel motors from our microcontroller, we required a 74LS241 octal buffer to turn TX and RX on our microcontroller into a single signal that the Dynamixel motors can interpret. The implementation of 74LS241 tristate buffer to drive the motors is outlined in Figure 5.

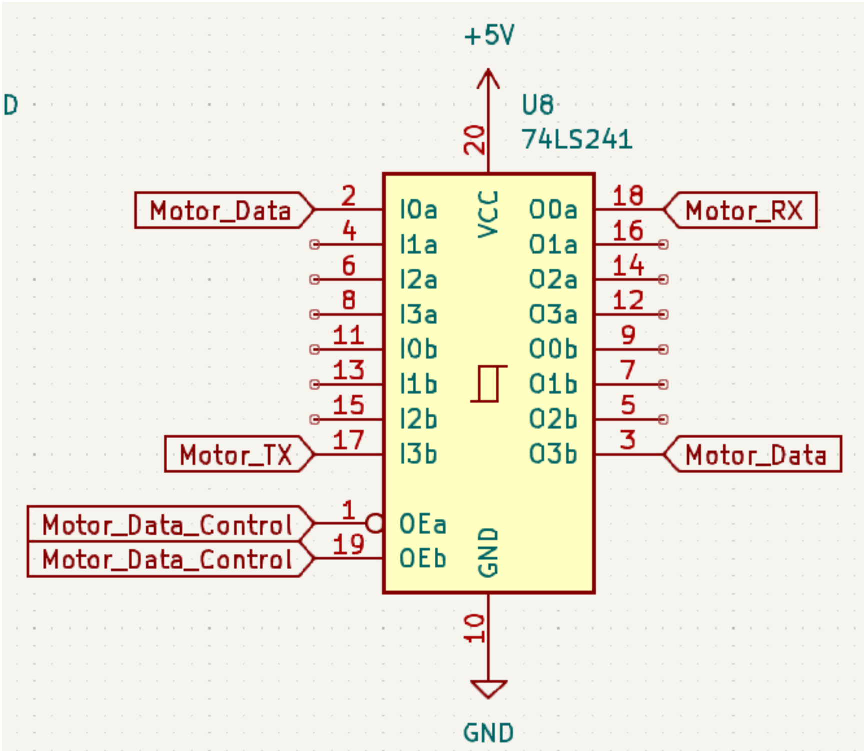

Figure 5: Tri-state buffer with Motor I/O

3.4.1 Design Considerations

The motors needed to be able to be moved accurately to designated positions, and also needed to give position feedback. Neither the standard servo motor or stepper motor fullfilled this requirements, so we went with a robotics motor, the dynamixel. It had position feedback and the ability to be directed with units of 0.088 degrees, which was well beyond the accuracy we required. This allowed for the position mapping with the LiDAR to be consistent every time we moved the motors. Additionally, we chose a dynamixel motor that could handle a bit more torque, so that we could be sure it wouldn't be inconvenienced by the LiDAR and Laser mounting.

The motors needed to move within 2 degrees of freedom, so we had a base that rotates to move the laser pointer horizontally left to right (along a vertical axis), and daisy chained to that a motor that rotates to move the laser pointer radially from the post (along a horizontal axis).

Additionally, the motors had a TTL half duplex asynchronous serial communication connection, which required us to use a tri-state buffer to control it with the microcontroller which had to be worked into the PCB as can be seen in Figure 5. Verification of the Dynamixel motors are outlined in Table 2.

Requirement	Verification
The motors send position feedback within an accuracy of ± 2.5 cm on the vertical plane, and ± 2.5 on the horizontal plane.	We created a debug program to verify the position of the laser when moving the motor and compared them against values determined using the angle reported by the motor. Repeated for consistency checks.
Micro-controller should be able to turn off motors while in idle mode.	This functionality of our design was never implemented due to scheduling considerations for a minimal viable product.

Table 2: R&V Motor Subsystem

3.5 Sensor Subsystem

This subsystem includes the TFMini-S LiDAR module [1], which is used to map out a designated area for furniture; pressure sensors [2], which are wound around the scratching post so as the cat can turn the cat laser on and off; and a motion sensor[3], which allows the programming to react to the cat pouncing on the laser dot. These sensors send and receive data to and from the Control Subsystem during their active cycles, and receive power from the electronic speed controller in the Power and Drive Train module. This subsystem's purpose is to receive data from the room and from the cat.

3.5.1 LiDAR Sensor Subsystem

The LiDAR works in conjunction with the motors to send distance data for the hypotenuse of a triangle. LiDAR detects objects and measures distances by obtaining the time of flight by measuring round-trip phase difference and then calculating relative range between itself and the detection object. Verification of the LiDAR is outlined in Table 3.

Requirement	Verification
LiDAR consistently detects the surfaces of objects and objects with wide bases within a range of 5m that are at least a 30cm wide and will be able to detect a change in height of more than 6cm.	Using a debug program, we set up a testing range with objects of various widths and heights at different known points. The script compared the LiDAR response to the expected response. when the LiDAR response is within a margin of error of the expected response, the digital display indicated so. When not, the digital display indicated that. This test was repeated multiple times to test for consistency.

Table 3: R&V LiDAR Module

3.5.2 Pressure Sensor Subsystem

The pressure sensors act as an on/off switch that can be triggered by the cat using the scratching post. When the pressure sensors are triggered, the device should enter an active cycle.

The pressure sensor system involves four main components, the pressure resistors themselves, the use of operational amplifiers to buffer the signal, a MOSFET to act as a trigger as to whether a signal is passed, and a 3 input NAND gate to pass the 3 separate pressure resistors' outputs as a single output that can be relayed to the microcontroller as seen in Figure 6. The force vs resistance curve for the resistance strips can be seen in Figure 7.

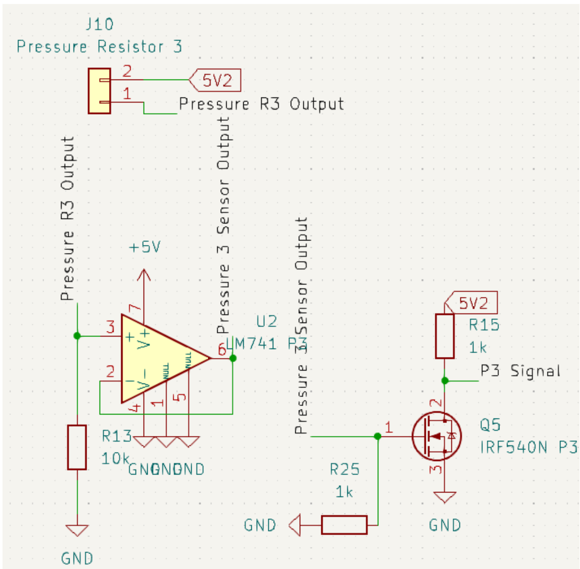

Figure 6: Individual pressure sensor circuit

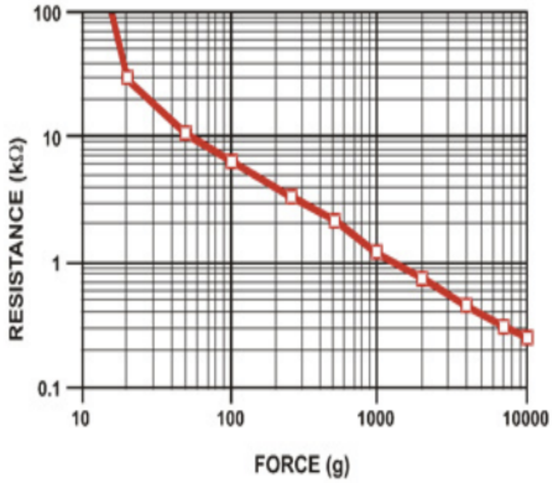

Figure 7: Typical Force Curve fore the FSR 408 Pressure Sensor [2]

Requirement	Verification
The pressure sensor does not trigger while no additional force is being added.	Prototyping on the breadboard determined the resistance values to create the desired sensitivity and confirmed the range of resistance values the sensors operate at.

Table 4: R&V Pressure Sensors

3.5.3 PIR Motion Sensor

The IR sensor is active during the active cycle of the programming, and tells the control system when the cat pounces on the laser. This device will also react to motion of people, and continued motion, so once it sends the initial signal, the signal will be ignored for 15 seconds before being input is accepted again again.

Requirement	Verification
The sensor needs to be able to detect motion within 5m of the scratching post at cat height.	Initial tests for range of the IR sensor will be performed by moving in front of the IR sensor at various ranges. Using a debug program, if motion is detected, an indicator light will light up. Once the range is determined, cat and kitten sized objects will be rolled in front of the IR sensor to ensure that it is at an appropriate height and angle to pick up cat motion.

Table 5: R&V IR Sensor Module

3.5.4 Design Considerations

The LiDAR we have chosen for this project, TFmini-S has an accuracy rating of ±6 cm which will have to be accounted for in the programming, and at 6m requires a side of 21cm in length to get an accurate reading. This means that the laser may not detect table and chair legs, but will detect tabletops, or seating furniture with wide bases. We deemed this a reasonable restriction as to accuracy. The distance it could reach needed to be at minimum 5 meters. This model reached beyond that. The distance from our LiDAR needed to be compared to an expected distance we found an equation by analyzing collected data, as seen in Figure 8.

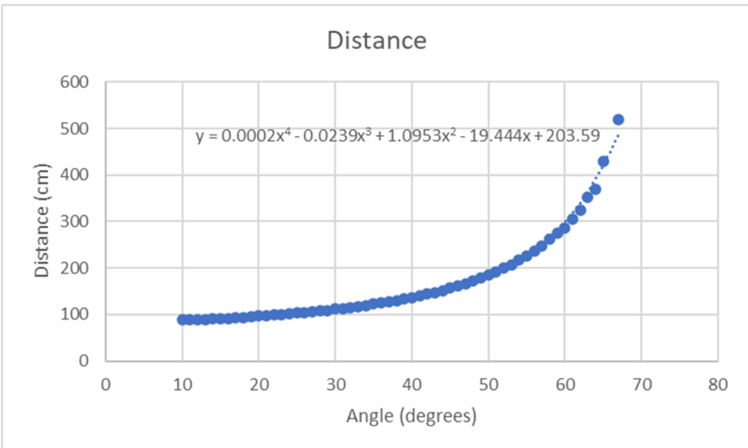

Figure 8: LiDAR Distance Data

For our pressure sensor system, the choice of long resistive strips were ultimately chosen due to the nature of where they would be placed: along the tower where the cat could scratch. The resistive strips themselves during testing had loads from 200 kOhms when no pressure is applied to a minimum of 2 kOhms under max pressure. Because of the the turn on voltage of the MOSFETs were greater than 3 V, if the pressure sensors were powered by a 3.3 V input, the load resistors for the pressure sensors would have to be 100 kOhms in order to provide an adequate output voltage able to drive the MOSFET. This described setup however is too sensitive and inflexible for our project and impossible to further develop under 3 V. Thus this system was swapped to entirely run on 5 V. Under 5 V, the load resistor for the pressure sensor could be 10 kOhm, and with

$$5 * R_{pressure}/(R_{pressure} + R_{load}) = V_{out}$$

, the pressure sensor could trigger with roughly 130 grams of pressure (roughly equivalent to 5 kOhm across the sensor) to produce a positive signal. 3 Pressure signals are to be part of the device as to be able to trigger them from any angle from the tower. Their outputs would be combined into a single signal with a 3 input NAND gate, a CD4023 transistor, as to minimize the number of pins required.

The current design includes two motion sensors with a total range of 270 °. However, the maximum horizontal angle for the motors and the laser is set to 180 degrees. Blinds at the sides of the two sensors could be used to limit the range to 180 °.

3.6 User Interface Subsystem

The User Interface Subsystem is the vector by which the end user interacts with the system. It includes the cat laser [4] as an output, a seven segment hex digital display system [5], and five buttons (up, down, left, right, and confirm). The User Interface receives power from the Power Subsystem and sends and receives data from the Control Subsystem. The implementation of these subsystems can be seen in Appendix C.

This interface would both allow the user to set the time for the device and to enter a start time and an end time between which the device would be activate during the day. This is done using the up, down, and confirm buttons. The calibration phase of our device allows the end user to use all the buttons to set the limits of the area in which the laser is allowed to operate. Finally, a pet safe cat laser lights up during active cycles to play with the cat.

3.6.1 Design Considerations

We decided to put a delay between button presses for easy navigation. Originally, we had two indicator lights to guide the user and show which state device is currently in. We chose to remove these lights from our design as we are able to print letters on the display to indicate the states.

Originally for the laser, we decided to purchase a typical hand held button activated cat laser from the local pet store and take it apart to identify how it works and possibly incorporate components for our project. Upon not being able to replicate the cat laser's functionality after taking it apart, we decided to acquire a different class 3A laser that has an input voltage of 3 V. The acquired laser only has a GND and a voltage terminal, so to control it we utilized a MOSFET driven by a signal from the control module to turn it on and off. This can be seen in Figure 9.

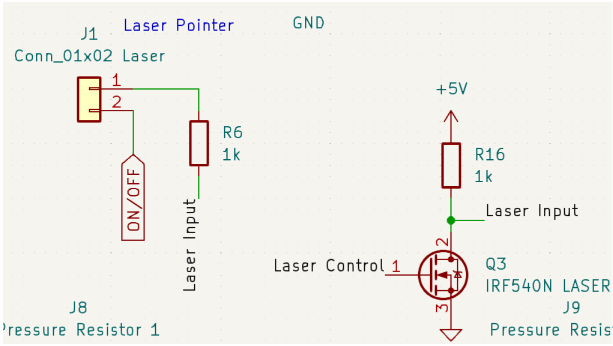

Figure 9: Laser implementation in KiCad

Requirement	Verification
The power used by the cat laser pointer must be lower than 5mW.	Identify internal diode resistance and measuring the current across the cat laser, determines power consumption.
The user interface needs to feel responsive. A lag of under 100ms would be ideal.	Probe the the button response current with a a program such as Scopy.

Table 6: R&V User Interface Subsystem

3.7 Control Subsystem

The control subsystem consists of an Arduino Uno development board as a microcontroller [6], which receives power from the Power Subsystem and sends and receives data to and from every subsystem.

The control subsystem is able to communicate with I2C and UART serial protocols and receive multiple sources of I/O data from the User Input Subsystem, the Sensor Subsystem, and other subsystems. Input data includes data from the button inputs from the User Interface, which there are 5. Other inputs include the data streams from the RX, TX, and motor select signal for the motors, the distance data from the LiDAR, signals from the IR motion detector, and the signal data from the Pressure sensors. Output data includes the aforementioned data for the LiDAR, clock signal, data for the Analog Hex Display, motor control signal, system on/off signal, and laser control signal.

3.7.1 Design Considerations

When we first started discussing the control module during the very beginning of the design process, we assumed that we would be able to run the device with an Arduino development board.

It's only after we were told that we were required to run the board with a microcontroller that we switched to the ATMega328P[7] as the closest equivalent. For the PCB design, we chose the through hole 28 pin model of the microcontroller as we were more familiar with soldering it compared to SMD equivalents. Furthermore when we were not able to burn/program the chip as expected (using MOSI/MISO/SCK/RST/5V/GND as ports for a 6 pin AVR-ISP connector), we were able to program the through hole version of the microcontroller with an Arduino Uno model that incorporated a removable through-hole version of the chip and placing it on the PCB via two soldered on 14 pin transistor IC sockets in place of soldering the microcontroller on the chip itself. Pin desginations on the PCB can be seen in Figure 10.

However we had to ultimately abandon the ATMega328P because of unforeseen issues with implementing Serial on the microcontroller running 8 MHz internal without an external crystal and additional required capacitors for UART and the Dynamixel itself not being designed for Arduino usage in mind. Instead we decided to replace the microcontroller with the development board. We did this by removing the microcontroller but keeping the two soldered on 14 pin IC sockets and wiring the Arduino directly to the sockets. The only significant changes to the programming arbitrarily choosing pins on the Arduino to run to various inputs.

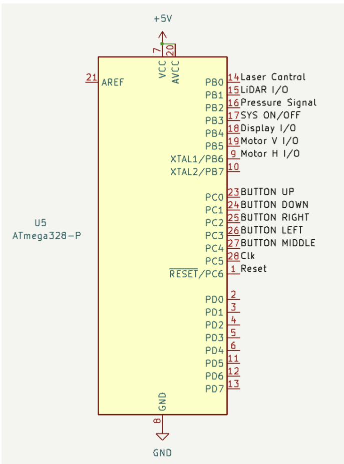

Figure 10: ATmega328 implementation in KiCad

Requirement	Verification
MCU should stay at low power mode while the device is in inactive state. The device is in inactive state before force is detected by the pressure sensors or outside the user set times.	Low Power mode not functionally implemented besides having an active state and an inactive state. Verified inactive state only changing to active state when pressure sensor detects force.
Operate at a reasonable clock speed for effective data processing.	Let the MCU output the system clock signal onto a generic microcontroller clock output pin. Verified frequency with an oscilloscope.

Table 7: R&V Control Subsystem

3.8 Software

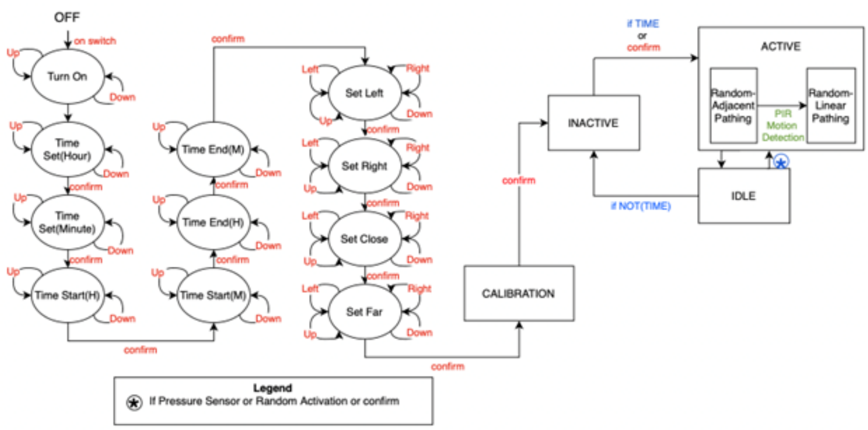

Figure 11: State Diagram

The programming on Start Up requests end user input for the current time, start time, and end time, each starting with the hour, then the minute. After this, the end user enters the rightmost, leftmost, closest and furthest boundaries of the space they want the laser to be able to reach during Active Mode. These boundaries are stored as phi and theta values. The flow of the entire process can be seen in Figure 11.

After the boundaries are entered, the calibration creates a map of the area. The map uses Polar coordinates 5 degrees apart and the area mapped is conical based on the angles of the vertical and horizontal motor positions selected by the end user.

The Calibration process follows this pseudo-code:

1. Create a matrix of zeros that acts as a map of the floor, with 5 cm between each point.

2. Move the motors to rightmost closest position.
    (a) Take the LiDAR reading, compare it against the calculated value(3.9) of the distance to the floor based off the angle of the motor and the distance to the floor.
    (b) If the LiDAR reading is within an acceptable margin of error from the calculated distance, set the point to a 1 in the matrix map. Otherwise, leave it as a 0.
3. Move up the column 5 degrees at a time, and repeat step 2 for each point until the motors reach furthest point.
4. Move the horizontal motor 5 degrees to move to the next column. Repeat steps 2-3. End calibration when motors reach leftmost furthest position.

Once the times are entered, device enters Inactive Mode. Inactive mode is a mode that allows the device to idle between the End Time and the Start Time. It's only function is to compare the current time against the start time and end time, and if the time is after the start time and before the end time (i.e. start ¡ current ¡ end), then it switches to Active Mode.The Active Mode is the mode in which the device plays with the cat.

The device has two pathing algorithms. First one is the random-adjacent pathing. During this time, the cat laser starts up at a random point within the allowed space. Then, one of the available adjacent points to that initial point is picked and the laser moves to that position. This algorithm picks adjacent available points and sets it to next point in path until cycle limit is reached.

The second pathing algorithm is called random-linear pathing. It activates when motion is detected by the pressure sensors. Similar to the adjacent pathing a random initial point is picked from the available points. In this algorithm we pick an available direction instead of a point. Once an available direction is picked, the device continues on that path for 4 points and picks another direction. Laser keeps moving in different directions until cycle limit is reached. The cycle limit of the random-linear pathing is smaller and the device goes back to adjacent pathing unless there is motion.

3.9 Tolerance Analysis

3.9.1 Data Storage

The system needs to map an area with a radius of, at maximum 5m, and we are limiting it's horizontal rotation to 180° and vertical motion to 70°. We are limiting our points to be 5 degrees apart. Putting this in a matrix, we have a 16 x 36 matrix, or a total of 576 points to put into a boolean map. The standard bool is 1 byte, and we are compressing the data into one bit per bool.

We are storing all map points in EEPROM with every memory address containing 8 points. ATMega328P has 1k EEPROM and so it has 256 memory addresses available. The map takes up 72 memory addresses in EEPROM. Other variables stored or planned to be stored in EEPROM are boolean calibrated, start time and end time. So, this fits the data requirements.

3.9.2 Distance Calculation Error

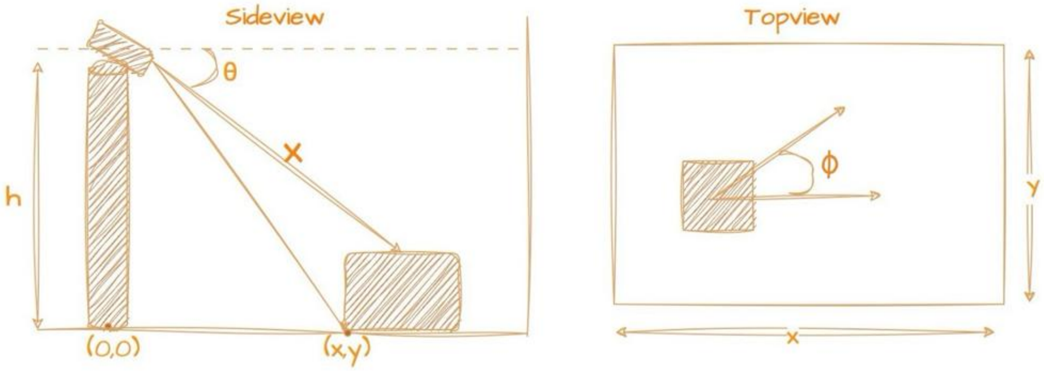

Figure 12: *Laser Angle Side and Top View*

We will use the following formula to obtain the Cartesian coordinates:

$$\hat{x} = h * cos(\theta)$$

where $\hat{x}$ is the distance measured by the LiDAR, h is the height of the scratching post, and θ is the angle at which the LiDAR is positioned relative to the ground. The height of the scratching post, h, is fixed and theta can be obtained from the motor controlling vertical motion.

$$f(x) = \begin{cases} 1 & \text{if } |\hat{x} - x| < \epsilon \\ 0 & \text{if } |\hat{x} - x| \geq \epsilon \end{cases} \tag{1}$$

As the LiDAR has an error component of ±6 cm [1], $\epsilon = 0.06$ m.

4 Cost Analysis

Assuming that we worked on average 20 hours a week for 11 weeks on this project, each team member has accrued a total of 440 hours each by project completion. With an hourly wage of 50 dollars and an overhead cost of 150 percent, the cost of each team member over the course of the project is 27500 dollars, for a total of 82500 dollars for all three team members.

As for project parts, our team has accrued a total of a little over 300 dollars in total project component costs. The largest portion of this comes from battery, motors, and LiDAR costs. A more detailed breakdown can be referenced in Appendix A.

5 Conclusion

We are able to design a functioning automatic cat laser toy that limits itself to a set area with multiple activation methods including random activation, pressure sensor activation, and button activation. The design is able to map out, with accuracy, an area input by the user. Some portions of the project need to be reworked, for example we need a reworked PCB to allow for UART connections with our microcontroller, and the LiDAR subsystem needs to be functionally worked into the rest of the programming. These can all be overcome with minor redesigns and additionaly programming.

5.1 Ethics and Safety

In accordance with the standards of the IEEE [8], we promise to uphold high standards of integrity, responsible behavior, and ethical conduct during the course and production of our project.

We seek to design safe systems for the use of the public, and to that end, the Cat Laser Tower must be safe and not cause significant harm to the health of cats or humans. All wires will be internal or tucked away safely, and all components will be safely stored within the device so as not to be easily accessed by cats.

The cat laser will be a class IIIa laser, which is low powered and not dangerous if one does not stare into the laser for more than a moment. The LiDAR will only be active during the calibration period, during which no cat or human should be looking into the laser. Both laser and LiDAR will have warning labels appropriate for the laser type. [9] Furthermore, the laser will constantly be in motion while on outside of calibration phase, where there should be no cat around to ensure the laser will not be pointed at the same location for longer than a moment to further maximize safety.

We seek to be transparent in the capabilities and usage of our device. Any shortcomings or flaws of our final device will be addressed, whether by informing end users or finding ethical workarounds.

While working on this project, we seek to be open and cooperate with each other and to not engage with harassment or discrimination of any form. To do this, our group members will seek to hold each other accountable and ensure everyone follow the IEEE code of ethics in both letter and spirit. [8]

6 Appendix

6.1 Appendix A

Description	Manufacturer	Quantity	Price	Final
Pressure Sensors [2]	Interlink Electronics	3	$15.61	$44.49
HC-SR501 IR sensor [3]	HiLetgo	1 set of 3	$8.49	$8.49
XL-330 Motor [10]	ROBOTIS	2	~$23.90	$57.57
XL-330 Motor	ROBOTIS	1	~$9.80	$9.80
TFmini-S LiDAR [1]	Sparkfun	1	~$39.99	$39.99
ATmega328P [7]	Atmel	1	$7.85	$7.85
NMOS [11]	Supply Center	8		$17.12
LM741 Op Amp	TI	5	$0.75	$3.75
CD4023	TI	1	$0.46	$0.46
12V Battery	Studica	1	~$44.99	~$44.99
12V Battery	Continental	1	~$40.30	~$40.30
Laser Module	IADIY	1	$8.00	~$8.00
Analog Digital Display	SunLEDUSA	1	$6.24	~$6.24
MAX7219	Maxim Integrated	1	$10.45	~$10.45
LM1117MP Voltage Regulators	TI	2	~$1.46	~$2.92
Total Parts Price				$302.42

Table 8: Cost of Project Components

Name	Hourly Rate	Weekly Hours Worked per Team Member	Weeks Worked	w/ Overhead
Victor	$50	20	11	$27500
Elisabeth	$50	20	11	$27500
Nour	$50	20	11	$27500
Total				$82500

Table 9: Cost of Labor

Section	**Total**
Labor	$82500
Parts	$302.42
Total Cost	$82402.42

Table 10: Total Cost

6.2 Appendix B

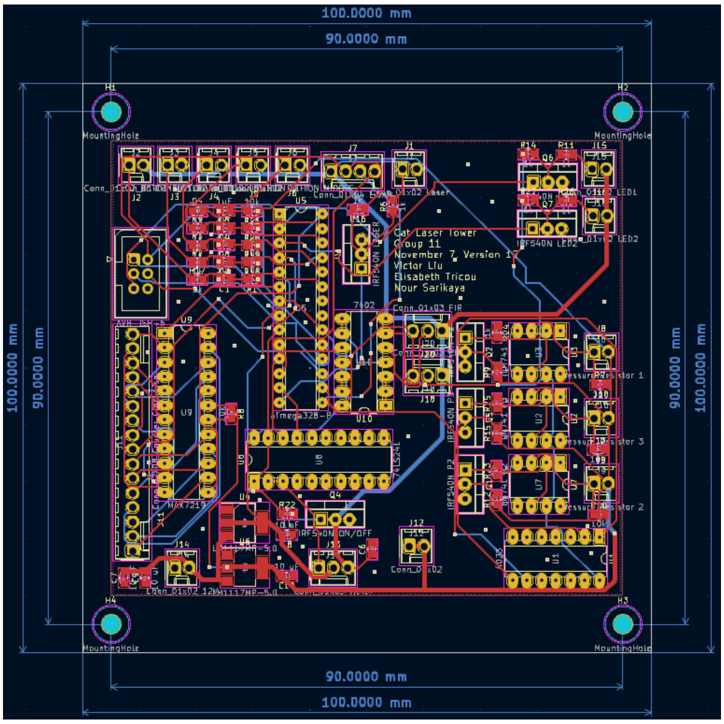

Figure 13: Final PCB design

6.3 Appendix C

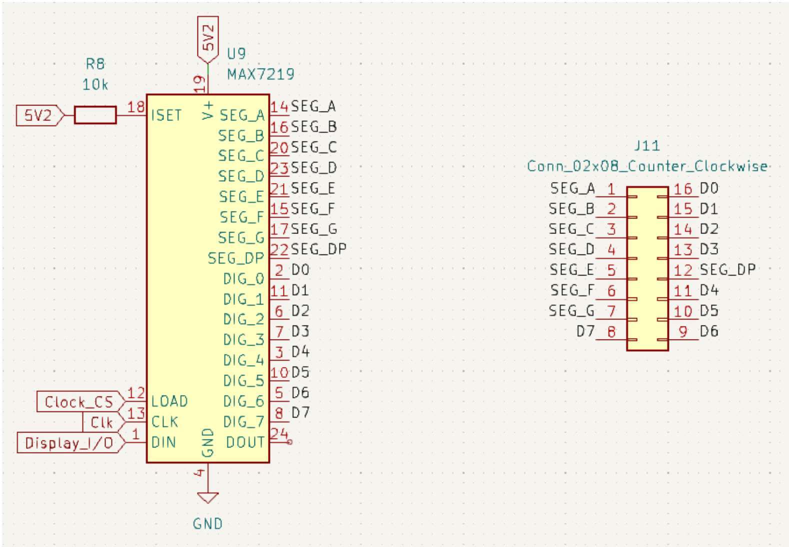

Figure 14: Display schematics

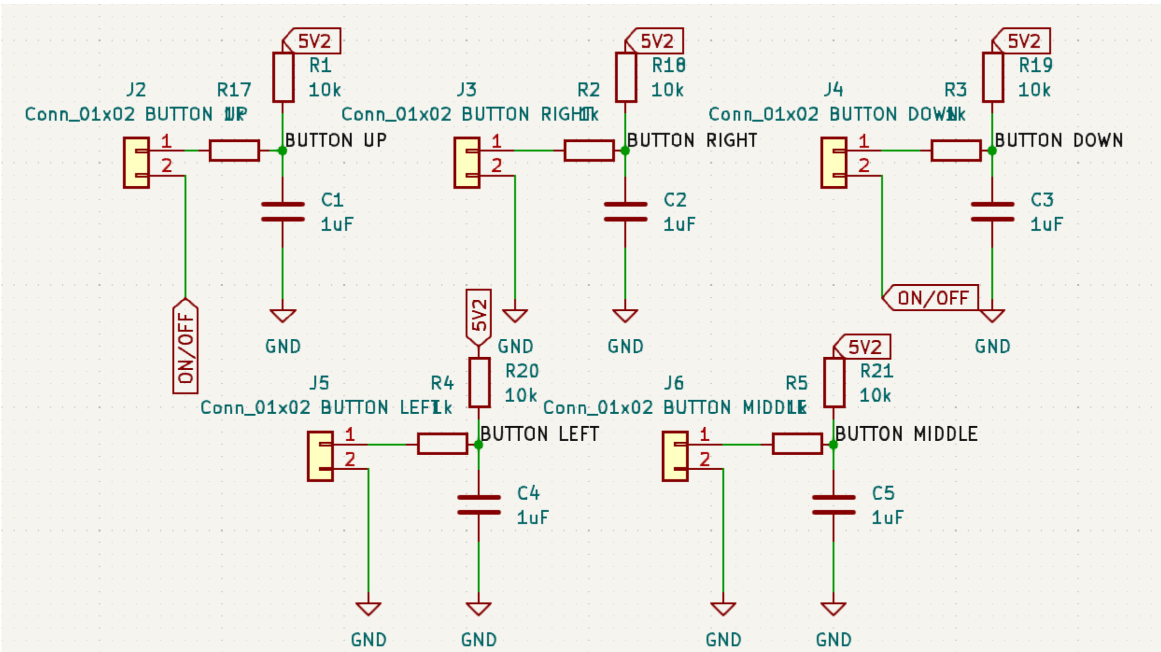

Figure 15: Buttons schematic

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