ECE445

Fall 2023

Design Document

Automated Cat Laser Tower

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Contents

1 Introduction

1.1 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.

1.2 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.

1.3 Visual Aid

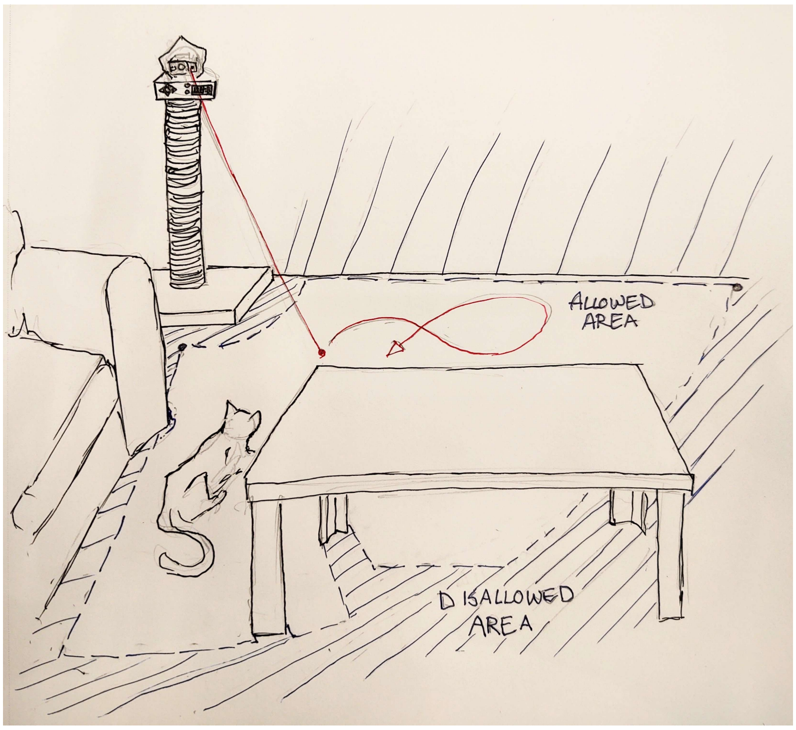

Figure 1: Automated Cat Laser Tower

1.4 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.

2 Design

2.1 Block Diagram

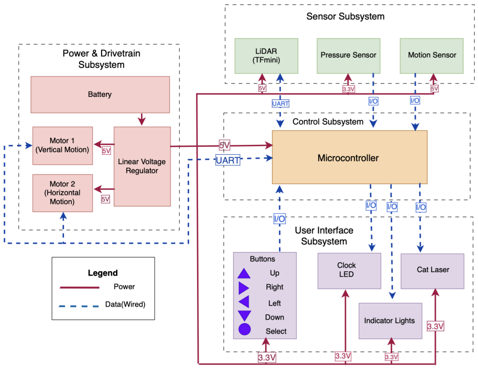

Figure 2: Project Block Diagram

2.2 Physical Design

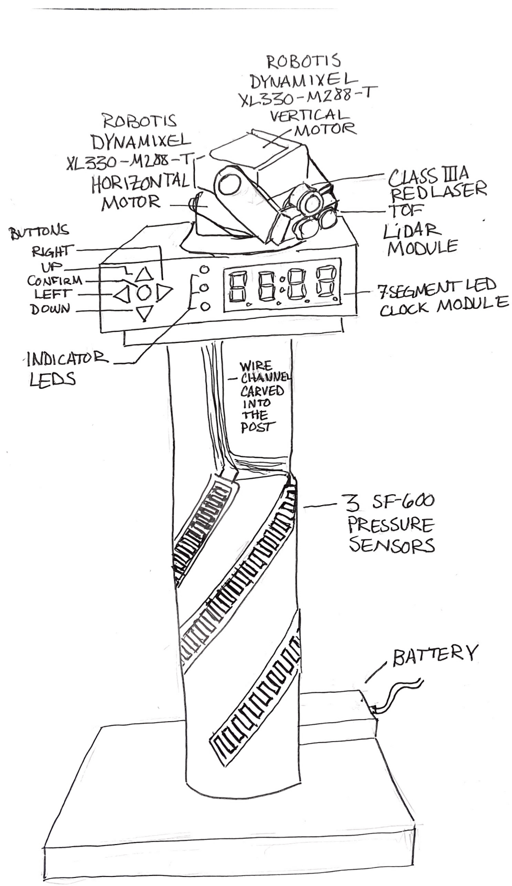

Figure 3: Physical Design

The scratching post is going to be 1m tall, and the user interface is going to be perched on top of it, and on top of that, is going to be 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', in the middle, 3 indicator lights, and on the right, a 7-segment LED Clock display.

Around the scratching post, the pressure sensors are wound loosely around to cover the most area. The wires of the pressure sensors will be wired up to the PCB along a channel carved into the post to protect the wires. Sisal rope will be wound around the post to protect the sensors and have the post act as a scratching post. The battery will be attached to the base, preferably hidden. It will be wired up to the PCB in another wire channel.

2.3 Power and Drive Train Subsystem

This subsystem delivers power to the Sensor, Control, and User Interface subsystems and the motors. It uses data from the Control Subsystem to direct or divert power from the other Subsystems.

The battery needs to be able to last for about a week without needing to be recharged. In section 2.8 we determined the battery will need to have a capacity of about 40 Wh. We're looking at a 12 V lithium ion batteries with minimum 3000mA deliverable current. To optimize the maximum battery life, our device will have an idling mode which will minimize power consumption from all non-essential components.

This subsystem also directs the speed and direction of the lasers via Dynamixel XL330-M288-T motors[1] using instructions from the control subsystem. The motors send position data back to the control subsystem. The position feedback data from these motors has a unit of about 0.088[°], which allows enough precision to determine the orientation of the laser.

Requirement	Verification
12V battery capable of providing voltages within 3.3V-6V with power regulators.	Use an oscilloscope to measure if the voltage across the battery and regulators reach desired values.
The IR motion sensor, motors, LiDAR, pressure sensors and the laser pointer should be all provided 3.3V +/- 5% or 5.0V +/- 5% from 12V battery using a voltage regulator.	Use a multi meter to determine whether voltage levels are reaching desired levels.
The motors send position feedback within an accuracy of $\pm$2.5 cm on the vertical plane, and $\pm$2.5 on the horizontal plane.	Use debug program to input coordinates and measuring the distance and height of the right triangle formed with the floor using the cat laser. Compare against values determined using the angle reported by the motor. Repeat for consistency check.
Micro-controller should be able to turn off components while in idle mode.	Will require simulating an "OFF" signal using a power source and then independently verifying that each component affected has no current running through them. If this works, the components would be floating and therefore not grounded while in idling.

Table 1: R&V Power and Drive Train Subsystems

2.4 Sensor Subsystem

This subsystem includes the TFMini-S LiDAR module [2], which is used to map out a designated area for furniture; pressure sensors [3], which are wound around the scratching post so as the cat can turn the cat laser on and off; and a motion sensor[4], 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.

2.4.1 LiDAR Sensor Subsystem

The LiDAR works in conjunction with the motors to send distance data for the hypotenuse of a triangle. The LiDAR 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.

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 will set up a testing range with objects of various widths and heights at different known points. The script compares the LiDAR response to the expected response. If the LiDAR response is within a margin of error of the expected response, one of the indicator lights will light up. If it is not, the other will. This test will be repeated multiple times to test for consistency.

Table 2: R&V LiDAR Module

2.4.2 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 sensors should trigger when additional pressure is added to the scratching post. As sisal ropes are going to be wound about it and exerting pressure, we will need to find the a voltage divider that allows for the device not to activate at rest, and to activate when pressure is added.

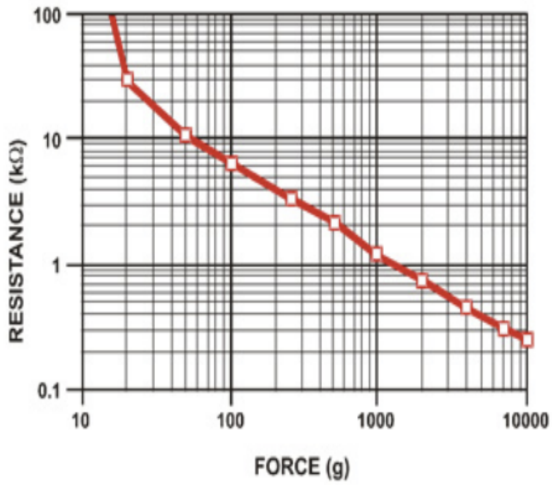

Figure 4: Typical Force Curve fore the FSR 408 Pressure Sensor [3]

Requirement	Verification
The pressure sensor does not trigger while no additional force is being added.	Prototype via a breadboard to determine the required resistor values to ensure that threshold voltage is only triggered under appropriate pressure.

Table 3: R&V Pressure Sensors

2.4.3 IR 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 4: R&V IR Sensor Module

2.5 User Interface Subsystem

The User Interface Subsystem is the vector by which the end user interacts with the system. It includes the cat laser [5] as an output, a seven segment hex clock system [6], and indicator LEDs to broadcast the state of the device while in operation, and five buttons (up, down, left, right, and confirm). The User Interface receives power from the Power and Drive Train Subsystem and sends and receives data from the Control Subsystem.

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. Pushing the left and right buttons at the same time 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, when not setting the time and not during calibration mode, the user should be able to run an active cycle at any time by pressing the confirm button. Indicator lights help the end user know what they need to enter next, and also blink when the battery runs low. Finally, a pet safe cat laser lights up during active cycles to play with the cat.

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 5: R&V User Interface Subsystem

2.6 Control Subsystem

The control subsystem consists of an ATmega328P chip microcontroller [7], which receives power from the Power and Drivetrain Subsystem and sends and receives data to and from every subsystem.

The control subsystem needs to be able to communicate with I2C and UART serial protocols and receive multiple sources of I/O data from the User Input Subsystem, and Sensor Subsystem. Input data includes data from the button inputs from the User Interface, which there are 5. Not shown below but will be included is a power switch that send a signal to shud down the entire device. Other inputs include the data streams from the electronic speed control 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.

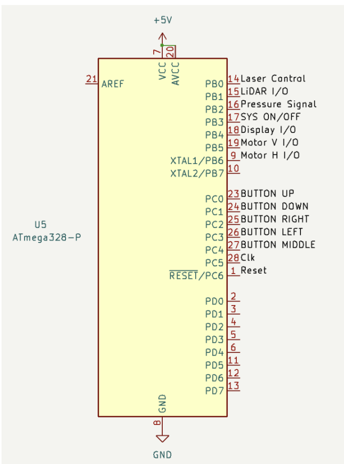

Figure 5: ATmega328 implementation in KiCad

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.	Connect both the pressure sensors and the motion sensor to the multi meter. Measure the current across the components while pressing on the pressure sensors to check if the current changes when the 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 Use an oscilloscope to measure the frequency

Table 6: R&V Control Subsystem

2.7 Software

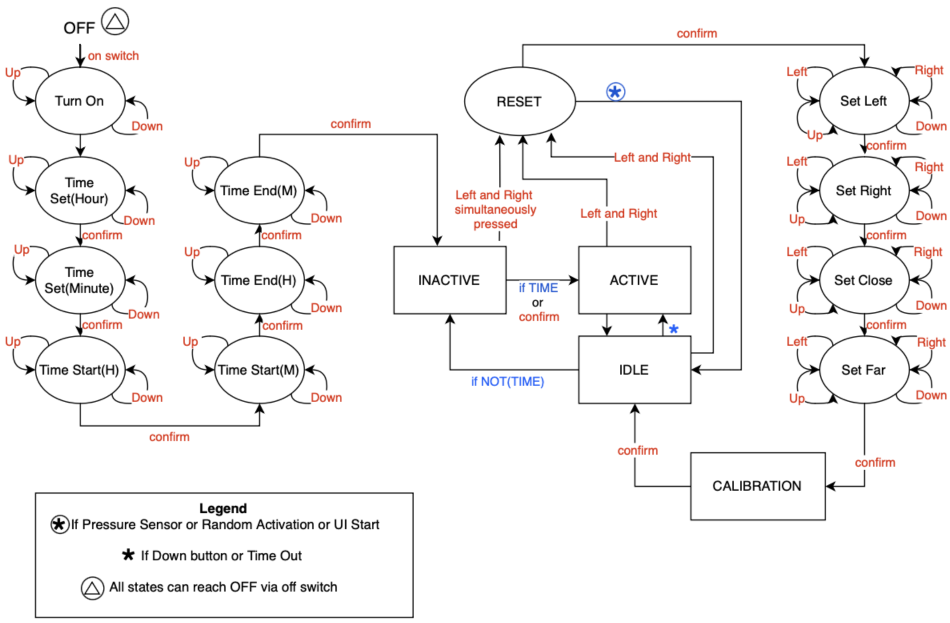

Figure 6: State Diagram

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. These values are stored such that when the user turns the device off, they will be available for selection when it is turned on again. As the device does not have an internal clock that will keep time while off, the end user will always have to input the current time on start up.

At any time after the times are entered, the end user can activate Calibration Mode by pressing the left and right buttons at the same time. After this, the end user enters the boundaries of the space they want the laser to be able to reach during Active Mode. After the boundaries are entered, the calibration creates a map of the area. The map uses Cartesian coordinates 5 cm apart, though 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. The motors move to the Most Close, Most Left position.
3. Find the nearest point on the Cartesian map within the motor angles.
4. If the point is not within the indicated space based on the input angles, set the point to a 0. Else:
   (a) Take the LiDAR reading, compare it against the calculated value 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.
5. If the motor position is not at the Most Right position, move the motors 5 cm to the right along the Cartesian map and repeat steps 4-5.
6. If the motor position is not at the Most Far Position, fix the horizontal motor position and move the vertical motor position 5 cm away from the scratching post on the Cartesian coordinates. Else, end calibration.
7. Repeat steps 3-4.
8. If the motor is not at the Left Most position move the motors 2 inches to the right along the Cartesian map and repeat steps 4-5.
9. If the motor is at the Left Most Position, repeat step 6.
10. Repeat steps 3-8.

Calculations used in this code can be found in 2.8 Tolerance Analysis.

Once the times are entered and stored, the 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. During this time, the cat laser starts up at a random point within the allowed space. It then chooses at random between a number of different subprograms that determine pathing for the laser.

Our project minimum viable product requires three subprograms. The first is a random subprogram, that checks which points adjacent to the current point are allowed, and then choosing one at random, on repeat. The second is a linear subprogram goes in straight lines along a random path until it has traveled 3-6 ft, or it reaches an edge.

Further sub-programs are stretch goals, and we have several. The first is the same as the random program, but following a curved line through the points. This will require the path to plan several steps ahead. The same with the linear subprogram. Then we wish to include a figure-8 sub-program, and a 'hiding' subprogram, a 'stay still' program that has minimal slow movement, and a 'jitters' subprogram that travels back and forth in small bursts. Further subroutines can be put on different speeds, or dynamic speeds.

These subprograms are going to be sorted into 2 types. The standard subprograms are what are used when the Active Mode starts, and the motion subprograms activate when the motion sensor activates. The motion subprograms only string together 2-3 sub-routines before returning to the standard subprograms. Of our minimum subprograms, the random movement subprogram is a standard subprogram, and the linear subprogram is a motion subprogram.

Active Mode lasts for 10-15 minutes, then moves into Idle Mode

2.8 Tolerance Analysis

2.8.1 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°. We are limiting our points to measure to ever 10 cm. Putting this in a matrix, we have a 10m x 5m, or a total of 5000 points to put into a boolean map. The standard bool is 1 byte, so we would need 5k SRAM and EEPROM to ensure data storage or manipulation of the boolean map alone. If we compress the data into one bit per bool, we can put the array into 625 bytes, or 650 bytes in practice. Our proposed microcontroller has 2k SRAM and 1k EEPROM, so this fits the data requirements.

2.8.2 Distance Calculation Error

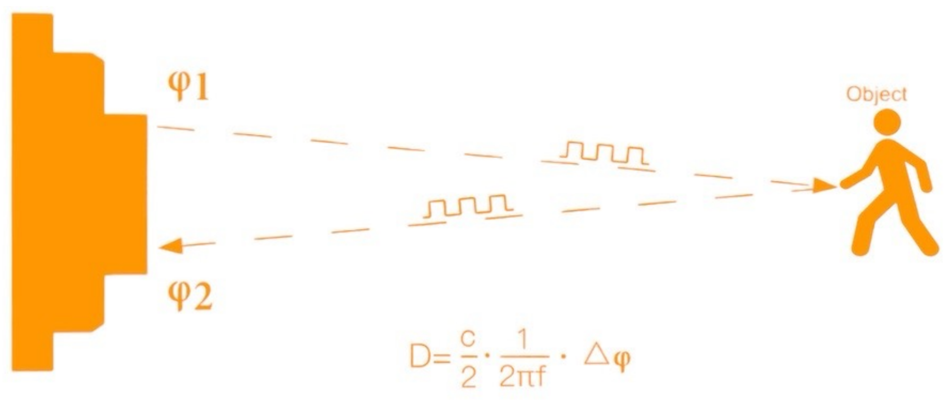

Figure 7: Schematics of Time of Flight Principle

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.

The LiDAR module we have chosen for this project, TFmini-S, has an operating range from 0.1 meters to 12 meters. The accuracy of the LiDAR varies depending on the distance and it's accurate to ±6 cm within 6 meters and ±1 cm within 12 meters.

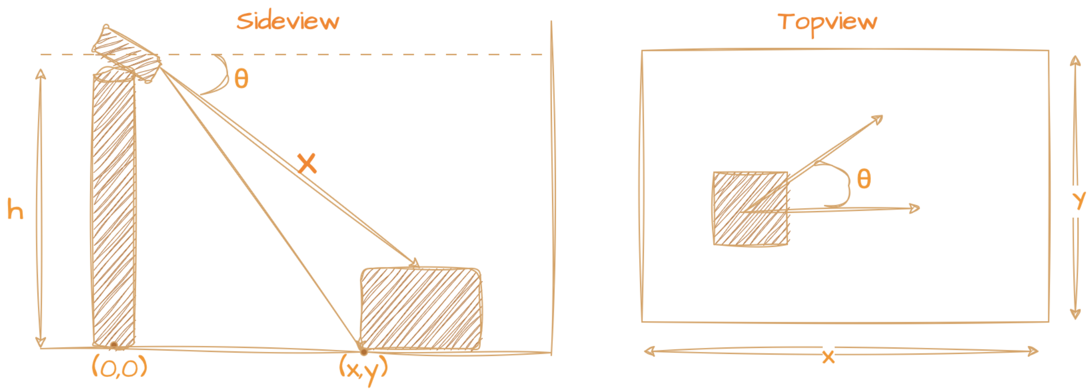

Figure 8: *Laser Angle Side and Top View*

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 [2], $\epsilon = 0.06$ m.

2.8.3 Power Consumption

Components	**Voltage Draw**	**Current Draw**	**Power Draw**
ATmega328P [7]	5V	200 mA max	1 W
Motors (x2) [1]	5V	17 mA	170 mW
Laser Pointer [5]	3V	1 mA	3 mW
LiDAR [2]	5V	140 mA	700 mW
IR sensor [4]	5V	50 uA	250 uW
Analog Display [6]	5V	30 mA	150 mW
Max7219[8]	5V	330 mA max	1.65 W

Table 7: Power Requirement per Project Component Analysis

We would like the Cat Tower to be able to operate without human intervention for more than a week on average playtime for a cat. A battery will be used to supply power to all our components. One of our concerns is the battery life. Having to change the battery every so often will be an inconvenience to the user, we want our cat laser tower to be able to supply enough power to all of our subsystems for at least a week.

We are assuming a cat to play with the cat laser tower 3 times a day and 15 minutes each time. So, we expect our device to be active for 45 minutes a day. During the times where the device is inactive, the two motors will be in idle state where they will consume less power.

In idle mode all nonessential components, meaning motors, buttons, laser pointers, and transistors, will be electrically ungrounded through the use of an NMOS powered by a signal from the microcontroller. This means while in idle mode, there will be minimal power consumption, with the only significant power loads being micro-controllers and the pressure sensor, which has a signal to switch the device from idle mode. Even in active mode, assuming that the largest draws of power are components, the maximum possible power draw (probably not achievable with our device, since that assumes maximum power consumption on our micro-controllers) would be approaching 4 W, which with a 36 Wh battery as planned would allow 9 hours of active use. Assuming that the motors and analog display would use 50% of the power in the system while non-idle, the average non-idle power draw would be 640 mW, providing roughly 56 hours of cat play time. Assuming in idle mode the Analog display is both on and consumes 75% of the power, the device would have 180 hours of idle use, or roughly 7.5 days of idling time. Thus we can achieve a week of operation with our device.

This calculations are done for the period after the calibration process. The calibration process will consume more power because of the use of the LiDAR. The LiDAR will be in an inactive state after the calibration is completed.

3 Cost and Schedule

3.1 Cost Analysis

Name	Hourly Rate	Weekly Hours Worked per Team Member	Weeks Worked	w/ Overhead
Victor	$50	20	9	$22500
Elisabeth	$50	20	9	$22500
Nour	$50	20	9	$22500
Total				$67500

Table 8: Cost of Labor

Description	Manufacturer	Quantity	Price	Final
Hemp Rope		1	$16.99	$16.99
Pressure Sensors [3]	Interlink Electronics	3	$15.61	$44.49
HC-SR501 IR sensor [4]	HiLetgo	1		$8.49
XL-330 Motor [1]	Dynamixel	2		$57.57
ATmega328P [7]	Atmel	1	$7.85	$7.85
NMOS [9]	Supply Center	4		$8.59
LM741 Op Amp	TI	5	$0.75	$3.75
CD4001	TI	3	$0.44	$1.32
CD4023	TI	3	$0.46	$1.38
12 V Battery	Unknown	1	Unknown	~$40
Laser Module	Unknown	Unknown	Unknown	~$15.00
Analog Digital Display	Unknown	1	Unknown	~$6.99
Additional Transistors	Unknown	Unknown	Unknown	~$15.00
Additional Microprocessors	Unknown	Unknown	Unknown	~$15.00
Total Parts Price				$242.42

Table 9: Cost of Project Components

Section	**Total**
Labor	$67500
Parts	$242.42
Total Cost	$67742.42

Table 10: Total Cost

Thus far, our group has already spent over $200 on components, but we still need to purchase additional transistors, the battery, probable additional microprocessors, an analog digital display, and miscellaneous PCB components.

3.2 Schedule

Week	Task	Responsibility
9/25/23	**Design Document Due**	All
	Finish Design Document	Elisabeth
	Finish Design Document	Victor
	Create Mock Design Review	Nour
10/2/23	**Design Review 10/3 at 4-4:30pm**	All
	PCB Review 10/3 4:30-6pm	All
	Finalize and order component list	Elisabeth
	Finalize PCB Design	Victor
	Study data sheets for Micro-controller and sensors	Nour
10/9/23	**Teamwork Evaluation I**	All
	Finalize Machine Shop Design, unit test components, Prelim code	Elisabeth
	Prototype on Breadboard, Unit testing	Victor
	Preliminary code, focusing on Calibration Mode	Nour
10/16/23	Write preliminary debug code for LiDAR and Motor Units	Elisabeth
	Soldering on PCB/Final Assembly	Victor
	Write preliminary code for Active Mode	Nour
10/23/23	**Individual Progress Reports Due**	All
	Finalize debug code, Test Units	Elisabeth
	Assembly and Program Microcontroller, Test Units	Victor
	Finalize debug code, Test Units	Nour
10/30/23	Testing and Debug, Finalize Software Code	Elisabeth
	Testing and Debug	Victor
	Finalize Software Code, Testing and Debug	Nour
11/6/23	Mock demo prep, Finalize Software Code	Elisabeth
	Mock demo prep, Begin final paper	Victor
	Mock Demo Prep, Finalize Software Code	Nour
11/13/23	**Mock Demo**	All
	Finalize, integrate and debug, Final Demo Prep	Elisabeth
	Finalize, integrate and debug, Final Demo Prep	Victor
	Finalize, integrate and debug, final paper	Nour

11/20/23	**Thanksgiving Break**	
	As needed, Final Demo prep	Elisabeth
	As needed, Final Demo Prep	Victor
	As needed, Final Demo Prep	Nour
11/27/23	**Final Demo**	
	Final Presentation Prep, Paper	Elisabeth
	Final Presentation Prep, Paper	Victor
	Final Presentation Prep, Paper	Nour
12/4/23	**Final Presentation and Final Pape**r	All
	Final Paper	Elisabeth
	Final Paper	Victor
	Final Paper	Nour

4 Ethics and Safety

In accordance with the standards of the IEEE [10], 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. [11]

The battery we are using is a Lithium-ion battery, which can be a fire hazard if stored improperly. We intend to ensure we only use the proper charger and not overcharge the battery, as well as include any information to this effect in the instructions. This can prevent the fault of overcharging. The device will not be stored near fire, and is intended to be used indoors[12].

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. [10]

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