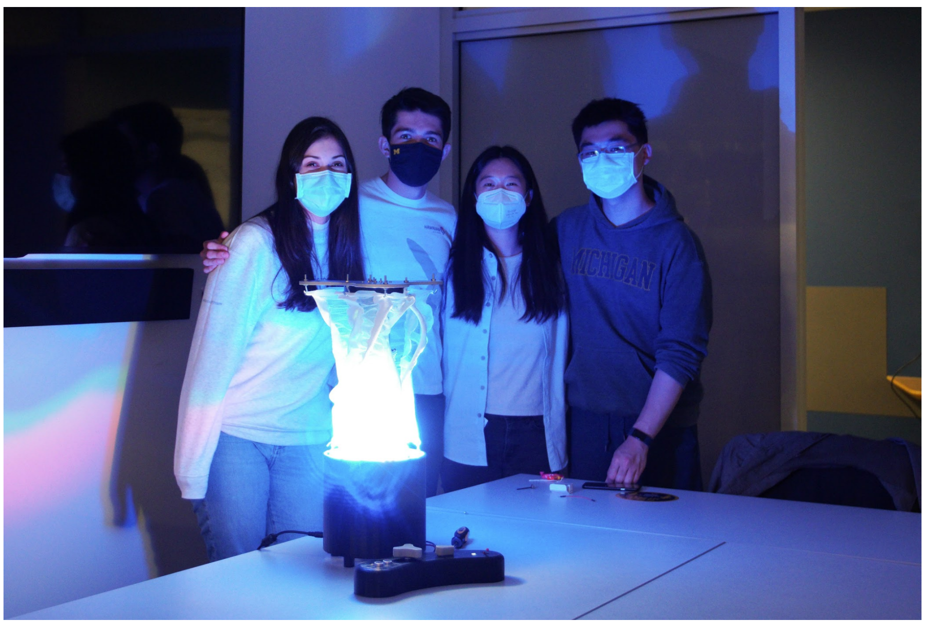
Sensor.IO

Final Report: Team 34



ME 450 Sec 007
Professor Saitou

Nadya Barghouty
Nicholas Chan
Claire Huang
Leandro Martinez

Executive Summary

The Ann Arbor Center for Independent Living (AACIL), an organization led by people with disabilities to empower the lives of people with disabilities, wants an electronic input/output device that gives a unique sensory experience for their members. The device must map user inputs to outputs, enabling users with varying levels of ability to interact with the device and giving them autonomy in the final output of the device. This need was identified by our three primary stakeholders: Sean Ahlquist (A. Alfred Taubman College of Architecture and Urban Planning Professor), Claire Moore (AACIL's Visual Arts teacher), and Jane Smith[1] (AACIL Visual Arts participant).

Our investigation began with benchmarking and research, focusing on devices used to better the life of people with cognitive and/or physical disabilities through visual, auditory, and/or tactile experiences. With an existing solution space explored, we met with our stakeholders to determine appropriate requirements and specifications, which are presented in Table 2 (page 9).

The team went through an ideation phase utilizing various methods including analogical thinking, SCAMPER, and a morphological chart to explore our solution space. We then screened our ideas using our requirements and specifications and by considering the feasibility of each idea and converged on 3final designs. These final designs were evaluated using a Pugh chart and the final design of an input/output device that manipulates a textile to alter the projections of a light shining through the textile. The results of our initial ideation are shown starting from page 16,our converged designs start on page 22,and our final design selection begins on page 26.

The team further developed the selected design using engineering analysis to make design decisions. Based on a theoretical model of the system, experiments to characterize the interaction between lights and textiles, and preliminary electrical analysis, we created a detailed CAD model of our design to prepare for manufacturing and ordering purchased components.

The team finished all the detailed CAD and performed a failure mode and effect analysis (FMEA) to mitigate risks before beginning manufacturing and Arduino software development. Our parts were manufactured using 3D printing, laser cutting, and water jetting, or were purchased. We then assembled the device and conducted extensive user testing and verification of our requirements and specifications.

The team verified 8 of our 10 requirements, including our user engagement and accessibility requirements. Some of our requirements were not met due to time and budget limitations, including durability and safety labeling. The device cost was within budget, at $319. Overall, the device achieved its purpose of providing an accessible, interactive, engaging input/output device for self-expression.

[1] Name of AACIL Visual Arts Participant redacted for privacy reasons.

The purpose of this report is to demonstrate our ideation process, concept screening, evaluation, and selection, engineering analysis, and solution development and verification, as well as critique our final design and provide recommendations for future work.

Table of Contents

Problem Description and Background

People with disabilities can have a hard time expressing themselves in conventional ways. Marti et al. claim that people with disabilities, especially children, can become isolated from the social environment if they are not allowed or able to express themselves [1]. Fortunately, interactive technologies can support the development of social skills and promote social inclusion. Many methods of self expression and play tend to be designed for fully able-bodied people. By designing objects around the majority, we often find that people with disabilities use everyday objects in ways that may seem creative to most. The AACIL collaborates with UofM's ARCH409 class to make tools to help people with disabilities express themselves in unconventional, creative ways. However, in years past, many of those projects have been too prescriptive. For example, Figure 1 shows a previous project where wooden spheres were dyed through a piece of fabric. The students felt as though they had no control over the outputs of the materials and were merely used as a means for execution.

Figure 1. A former ARCH409 project where AACIL students were tasked with dyeing wooden spheres through textured fabrics.

While these projects were creative, they lacked modularity or the ability for the AACIL student to make their individual mark on the final product. Simply, there was only one way to use them. As mechanical engineers, we possess a skill set that may have not been applied to this challenge before, and coupled with the ME450 design process, we believe we will be able to make a truly engaging device that gives students an interactive way to be creative.

The goal of our project is to create an input-output device for users with auditory sensitivity and mobility limitations, in collaboration with ARCH409. The device will feature multiple sensors and a textile, and will be tested by a student from the AACIL virtual arts class.

Users with Auditory Sensitivities and Mobility Limitations

While the AACIL and their virtual arts class serves all types of individuals, our project will focus on users with auditory sensitivities and mobility limitations. Jane Smith is our proxy user and gives critical insight by being a person with auditory sensitivities and mobility limitations. Jane Smith also helps us understand the needs of an art student in the visual arts class. This device is, first and foremost, an artistic input-output device that needs to be engaging. Due to the ongoing COVID-19 pandemic, we have limited access to more proxy users. In a standard ME450 semester, we would gather further information from other people with these sensitivities and limitations.

Benchmarking and Research

To further understand the problem and help inform our design, our team completed a literature review to benchmark existing products geared towards people with disabilities. Because our problem is more abstract, we began looking into general assistive technologies with a focus in visual, auditory, and/or tactile experiences. We found that interactive play devices have been shown to provide social benefits for people with disabilities. Some are even used for therapeutic and research purposes. One example is the Keepon robot, pictured in Figure 2. The Keepon robot was developed for researchers to interact with children with autism. The simpler body of the Keepon robot is less daunting to children who may perceive humans as too complicated to approach. The Keepon reacts to the child's touch and actions, and can even dance to music. The researcher can also control the robot and speak to the child through the device [2].

Figure 2. The Keepon robot. The eyes are cameras and the nose is a microphone, allowing for the researcher to observe the child's interactions with the robot and control the robot to react accordingly. [2]

Microsoft's Xbox adaptive controller is another assistive technology that focuses more on physical interactions. As games have become more sophisticated, so have their controllers. Game lovers with limited mobility find it difficult to play with the standard Xbox controller. The adaptive controller is a base that allows for various plug-in buttons, joysticks, and touchpads. By choosing different controllers based on their needs, the user is given full control of their gaming experience. Controls like a joystick or button can be purchased separately to connect to the controller base. The Xbox adaptive controller in juxtaposition to the standard controller is picture in Figure 3.

Figure 3. Two children play Xbox together. One plays with the traditional controller, while the other plates with the adaptive controller. [3]

Lastly, we researched a product called the Soundbeam, which allows for sound and music creation without requiring physical contact. The Soundbeam uses movement sensors, projecting a "beam" that, when crossed, produces a reaction in the sound system. It tracks the direction in which the beam is crossed, as well as how quickly the user moves, mapping these motions to music and sound [4]. The Soundbeam is pictured in Figure 4.

Figure 4. The Soundbeam. The red flashlight-shaped objects on the left and right of the figure are the "beams." When the user crosses this beam with an object (i.e. an arm or hand), the device maps their motion to music. [4]

The devices for people with disabilities that we have benchmarked are summarized in Table 1, including the price of each product.

Table 1. Purpose and price of each of the devices for people with disabilities.

Product	Purpose	Price
Keepon Pro	Research tool used to interact with and observe children with autism	$30,000 [2]
Xbox Adaptive Controller Base	Enables gamers with limited mobility to play Xbox on their terms	$100 [3]
Soundbeam 6 "Solo"	Allows a person to create music using only motion	$3,500 [5]

Requirements And Specifications

With helpful feedback following our Design Review 1 (DR1) presentation, our team decided to narrow our scope to an input-output device that uses sensors to create an unique experience for our users. The device also has to include a textile developed through the ARCH409 class.

From our interviews and research, the stakeholders and team generated a list of requirements. Our team then adapted these requirements into a set of measurable and verifiable specifications. The requirements and corresponding specifications are presented in Table 2.

Table 2. Design requirements and specification created for the input/output device, as specified in the problem definition phase.

#	Requirement	Specification
1	Device accepts multiple user inputs with electronic sensors	- $\geq$ 3 types of inputs (types: sound, light, movement, touch, temperature) - All inputs should be able to operate simultaneously - Sensor response time $\leq$ 5s
2	Device produces outputs that address visual, auditory, and/or tactile sensory modes	- $\geq$ 2 types of outputs (types: auditory, visual, tactile) - All output types should be able to operate simultaneously
3	Device maps between user inputs and device outputs	- All outputs are directly controllable by $\geq$ 1 input

#	Requirement	Specification

4	Accessible to persons with auditory sensitivities and mobility limitations	- Auditory:
		    - Output sound intensity ≤ 80dB
		    - Output sound is adjustable to ≤ 40dB
		    - Sound inputs are sensitive to sounds ≥ 40dB
		- Tactile:
		    - Device fits within maximal working area as specified in ISO 14738:2002(E) §6.3 [6]
		    - Tactile inputs should require < 5 Lbs of force to actuate
		- Movement:
		    - Motion inputs are sensitive to movements within the maximal working area as specified in ISO 14738:2002(E) §6.3 [6]

5	Device is engaging for the user	- User engages with the device for an average of 15 minutes
6	Transportable between UM and student's home	- Size when transported: - Width/Depth/Height: ≤24" - Weight is ≤20 lb
7	Device is safe to operate	- Complies with ASTM-F963-17 §5.3.1 [7] where warnings of potential hazards are displayed (User can identify all warnings in ≤ 1 minute) - Electronics are fully enclosed

8	Durable	- Can withstand ASTM-F963-17 [7] sections:
		    - 8.8 Torque Tests for Removal of Components
		    - 8.9 Tension Test for Removal of Components
		- Lifetime is >30 uses

9	Operates on household power	- Operates on 120V AC (60 Hz)
10	Includes a textile	- Includes ≥ 1 textile

After creating this list of requirements and specifications, our team reviewed them using resources to evaluate product quality outlined in the ME450 block. We considered requirements that may have not been explicitly mentioned by our stakeholders and created a holistic outline of the product we aim to make. We will continue to review our requirements and specifications, as we recognize it is an iterative process and our stakeholders may present new information as we progress with the project.

The rationale behind each requirement and their respective specifications are detailed below.

1. Device Accepts Multiple User Inputs with Electronic Sensors

The requirement for the device to receive multiple user inputs with electronic sensors is derived from several key stakeholder needs, the first of which is the need for the device to be interactive.

This requirement addresses interactivity by mandating some means of user input to the device. We are also requiring the device to accept multiple inputs to address the need for individuals with varying levels of ability to interact with the device. Finally, the requirement for electronic sensors is based on Professor Ahlquist and Claire's request for us to explore electronic systems, an area that has yet to be explored in prior ARCH409 projects.

The categories of inputs we chose to explore include sound, light, movement, touch, orientation, temperature. The specifications for this requirement are that the device should accept at least 3 inputs, with all inputs being able to operate simultaneously. The quantity and types of inputs were chosen by the team as sufficiently diverse to satisfy the stakeholder needs, and provide sufficient interactivity for a wide range of users. The specification that the response time be less than, or equal to, 5 seconds was chosen to ensure the system was sufficiently responsive to user inputs.

2. Device Produces Outputs that Address Visual, Auditory, and/or Tactile Sensory Modes

It is critical that outputs of our device can be perceived by individuals with varying levels of ability. To address this need, we are requiring that our device produce outputs that span the visual, auditory and/or tactile sensory modes. We chose these three sensory modes to limit our design space as we cannot accommodate for every possible disability.

The specifications for this requirement are that the device should produce at least two types of outputs from the categories of visual, auditory, and tactile outputs. This quantity was similarly chosen by the team as sufficiently diverse to provide an accessible and engaging end-user experience.

3. Device Maps Between User Inputs and Device Outputs

The requirement that the device maps user inputs to device outputs provides the interactivity of the device, allowing users to directly control outputs. Additionally, a key need identified by Claire was to make a device that was not overly prescriptive, as this was frustrating to students [8]. To satisfy this need, we have specified that each output must be controllable by 2 or more inputs. This quantity was chosen by the team to provide sufficient options to avoid being overly prescriptive.

4. Accessible To Persons With Auditory Sensitivity And Mobility Limitations

Accessibility is a key consideration for our device, given the nature of the AACIL and our stakeholders. The specifications for this requirement are based on input from Jane Smith [9].

One need she identified was her sensitivity to loud sounds. To address this, we are requiring that any sounds from the device can be adjusted to ≤ 40dB, with a maximum intensity of ≤ 80dB. These values were chosen because 40dB corresponds to the noise level of a quiet library and 80dB corresponds to an alarm clock [10]. The 40dB upper bound for adjustability presents little concerns for individuals with sensitivity to noise. The 80dB would be the maximum audio level our device could reach. Anything above 85dB for an extended period of time could cause hearing loss, therefore adjustable or not, we would not want our device ever operating at that level. Additionally, we are requiring the device to be sensitive to sounds louder than 40dB, which we consider sufficiently sensitive for users to interact with the device.

A second need identified by Jane Smith was for device elements to be accessible from a stationary seated position, particularly for individuals in wheelchairs [9]. This need is addressed by the specification for the device to fit within the maximal working area specified in ISO 14738:2002(E) §6.3, which details dimensional data for workstation design in a seated position [6]. Keeping device elements within this area will allow users to operate the device through touch. Additionally, we are specifying all tactile interfaces to require ≤ 5lbs to actuate. This value was adopted from the Americans with Disabilities Act (ADA) Best Practices Tool Kit, which recommends input forces of less than 5 pounds [11].

For inputs involving movement, we are specifying that the inputs are sensitive to movements within the maximum working area, as detailed in the tactile specifications. Choosing this specification allows users to interact with the device with movement throughout the entire working volume.

5. User Engagement

A key need identified by Professor Ahlquist was to design a device that is engaging to the users, as previous designs were too prescriptive and did not allow for much creativity [12]. To measure user engagement, we will measure the average amount of time a user spends operating the device, including exploring the controls and creating the final output. The amount of time the user is engaged must be at least 15 minutes.

6. Transportable between UM and Student's Homes

Claire explained the logistics of how we will transport our device and she explained that our projects would be picked up from the University of Michigan campus using her personal car [8]. The team translated this requirement to a size and weight specification. We chose a standard shipping box size from FedEx, weighing 20 lbs to approximate an easy to carry and transportable box.

7. Device is Safe to Operate

We are making equipment that will be handled by people that may not have a technical background. Because of our intended users, we must consider safety issues that may come from using our device outside of "normal operation." The team realizes that safety is relative and in our designs, we will be mindful about safety, but we also plan to have hazard labels on the device to further identify our concerns to the user. To address the safety risks of electronics, we will require that the electronics be fully enclosed to reduce the risk of electrocution.

8. Durable

During our interviews with Claire and Jane Smith we found that the students in the AACIL like to repurpose the devices and as a creative tool they may be handled in different ways by different people [9,10]. Because of this we recognized durability as an important requirement for our device. We found that ASTM standards for toys offered good methods for verifying the safety and durability of devices, and because we expect multiple users we set a minimum number of cycles at 30.

9. Operates on Household Power

During our interview with Claire, she pointed out that students may not have access to or may not want to work with difficult-to-find power sources [8]. We agreed that the device should operate on a standard home outlet.

10. Includes a Textile

This requirement is similar to a challenge posed given to ARCH409 students, and Professor Ahlquist encouraged us to keep this requirement for our team. The textile serves as an additional challenge for us to incorporate, as well as an opportunity for more creative expression.

Concept Generation

Our team began concept development individually and then came together as a group. Our team met three times in the concept generation phase and used the concept generation methods shown in Table 3. We had two initial concept generation sessions. The first session consisted of various brainstorming methods and the second session employed analogical thinking and SCAMPER.

Table 3. Concept generation methods explained with their respective result

Concept Generation Method	Result of Concept Generation Method
Brainstorming (primarily individual)	Give a space to write down all the ideas that we originally had in mind
Analogical Thinking (primarily group)	Challenged us to come up with more creative ideas that did not show up in individual brainstorming
Scamper (primarily group)	Iterated on existing ideas to create more nuanced changes, allowing for different ways of manipulating current solutions

Brainstorming

By beginning with individual brainstorming, we were able to immediately document all the ideas formed during problem definition. According to IDEO, brainstorming is a great place to start the concept generation process because the sessions produce a large number of ideas and build enthusiasm. Concepts were documented on individual Google Jamboards. The initial brainstorming process was set to last an hour and a half. The session concluded with an hour of group brainstorming, which encouraged iterating on current concepts and improved team collaboration. An individual's brainstorming board can be seen in Figure 5.

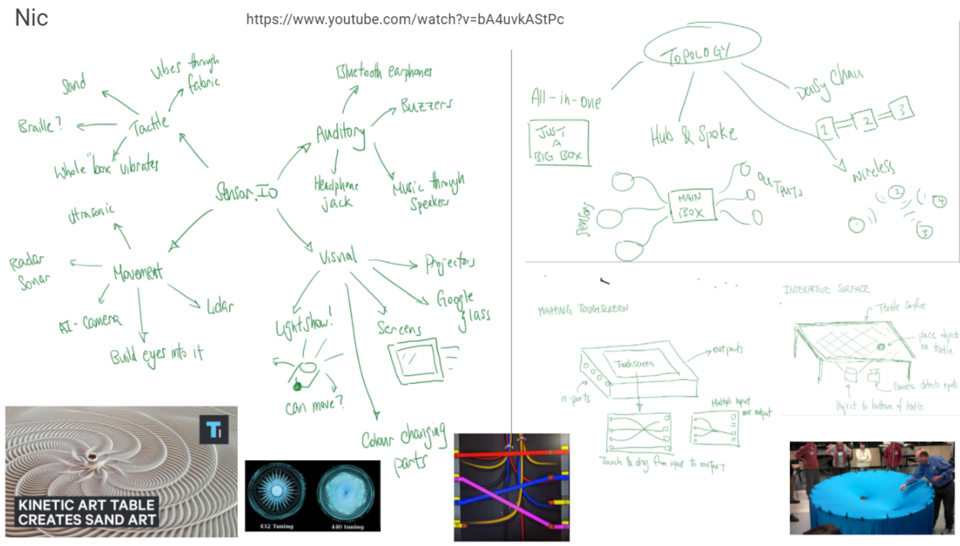


Figure 5. Example of one individual's Jamboard participation that occurred during the individual brainstorming session. Rudimentary sketches and a mind map allowed this team member to communicate their ideas.

It is important to note that the brainstorming process heavily relied on each team member deferring judgement. This meant embracing all ideas and not inherently comparing them against personal biases or the project's requirements and specifications. The team also took into account building ideas off of others. In our second session, we intentionally worked as a group, having one conversation at a time, to create a more diverse set of concepts.

Analogical Thinking

Analogical thinking draws from what is familiar. Novice designers often try to ignore what they know from daily life in order to create "new and exciting" concepts. However, sometimes the most brilliant ideas come from what is right in front of us. We conducted analogical thinking in a collaborative environment once again through Jamboard. A subspace of concepts can be seen in Figure 6. We wanted to document natural versions of tactile or visual inputs and outputs. Analogical thinking helped us investigate those examples that may have gone overlooked.

Figure 6. Example of a set of ideas that were created using analogical thinking. From left to right: a Venus flytrap, a sensitive plant, and a pill bug. All of these things, found in nature, react in some way to motion. [13-15]

SCAMPER

The main charm of SCAMPER is how it creates small changes to existing concepts that allow designers to further investigate the design space. As a team, we went through each aspect of SCAMPER and created another Jamboard page. Once concept derived from the “Modify” portion of SCAMPER can be seen in Figure 7.

Figure 7. Example of an idea created from the “Modify" portion of SCAMPER. The idea centered around how we could change a standard ant farm into a mechanical system that would make interesting designs. [16-18]

Morphological Chart

A morphological chart is a great way to generate concepts based on the different ways to achieve the subfunctions of a device. After exploring our large solution space, the morphological chart shown in Table 4 was our first attempt at placing the design concepts into bins representing the requirements they met (left column). The mapping, accessibility, engagement, safety, durability, and use of household power requirements did not have direct features in our morphological chart, as these requirements pertain to the performance of the design as a whole and were not suitable for use in the morphological chart, but they manifested later in our concept generation process. In our input row, we had to select three different types of inputs per our specification and requirement in Table 2. Similarly, we required at least two outputs from the output row. After realizing the quantity of combinations the morphological chart could produce, the team decided to screen our ideas, and this process is discussed in the next section.

Table 4. Morphological chart. Highlighted concepts correspond to the legend below the table.

Requirement	**Concepts**						
Inputs	Speaking	Tapping/ drumming	Pitch sensitive	External speaker	Connecting personal music/sound	Flashlight	Pressure
	Drawing on a screen	Heart rate	Breathing	Proximity	Joystick motion	Moving objects/ tokens	Friction
	Color sensor	Ice	Using an iron	Flame/ candle	Pulling	Pushing button	Rubbing
	Body temperature	Sunlight	Gesture Recognition	Scanned image			
Outputs	Instruments	Voices	Layered sound recordings	Volume dependent on input	Build up of inputs	Fluid/waving tactile structures	Kaleidoscope
	Movement of sand or magnetic filings	Image/art	Rotation	Projections	Moving mechanical structures	Fans	Vibrations
	Color changing surfaces	Printer	Piezoelectric patch	Tone warp based on input			
Transport	Rigid plastic boxes	Soft-shell enclosure	Stuffed animal	Deconstruct-able into pieces	Hanging on the wall	Built into a portable box	Connected modules
Textile	Light shining through fabric	Fabric manipulation	Fabric suspended/ taut	Fabric used as gloves	Ribbons/ streamers	Objects moving through fabric	Fabric being colored or dyed
	Conductive textile						

Screening Criteria Legend

Safety	Stakeholder Impact	Feasibility	Team Strengths

Initial Screening of Morphological Chart

Due to the large concept space represented by the morphological chart, we decided to undergo an initial screening stage. We screened by evaluating and eliminating individual subfunctions on the basis of safety, stakeholder impact, feasibility, and team strengths. These screening parameters are directly related to our requirements and specifications, as well as the implicit requirement of feasibility. The initial screening allowed us to narrow our focus into a sufficiently large yet practically explorable space to generate our preliminary concepts. The rationale behind each evaluation criteria is explained below.

Safety. Concepts that posed an immediate hazard for the end user of the device were eliminated, as we were unlikely to develop any concept that involves significant safety risks. Input concepts of using a flame, candle, or iron were eliminated as these inputs could cause burns or ignite fires. Inputs with ice/water were also removed due to concerns for electrical safety.

User Engagement and Accessibility. Concepts were screened based on engagement and accessibility, eliminating ideas that would result in minimal engagement or raise accessibility concerns. The eliminated ideas and related justifications are:

- Sunlight/body temperature as inputs: These inputs are not user-controllable, taking away the user's agency to influence the device. This would likely reduce user engagement with the device.
- Fabric being colored or dyed: This concept was eliminated as it was similar to previous ARCH409 projects that were considered too-prescriptive, and would not be sufficiently engaging.
- Pulling/pushing/rubbing as inputs: Inputs that require significant physical exertion may negatively impact stakeholders with mobility limitations, making it difficult for users to engage with the device. These inputs were eliminated from further consideration.

ME450 Feasibility. Our initial screening also considered feasibility with respect to time, cost, and technology readiness. As we are limited by both explicit stakeholder requirements and implicit project constraints, screening by feasibility allows us to focus on concepts that fall within the scope of ME450. Concepts that were eliminated for feasibility include:

- Conductive textiles: While conductive textiles are technologically feasible, we eliminated this concept as the time required to develop this concept will likely fall outside the scope of ME450.
- Gesture recognition: Concepts involving gesture recognition inputs were eliminated because of the high cost of sensors and the time required to implement such systems.
- Printer as an output: This concept was eliminated on the basis of cost.
- Color changing surfaces: Surfaces that changed color were eliminated due to technological infeasibility within the scope of this project.

In addition to the screening above, we screened ideas on the basis of our team strengths. In this case, strengths lend themselves more towards what our team has the ability to learn or implement in one semester, rather than what we consider easy to achieve. Ideas that were screened based on these criteria included scanning images into the device, warping the tone of sounds based on user inputs, and the use of piezoelectric patches as tactile outputs. While these ideas are feasible, these concepts lend themselves towards software solutions rather than mechanical ones. We eliminated these ideas because software-based projects would not align with our team strengths and the goals of ME450.

Preliminary Concepts
Using the morphological chart, each team member individually generated preliminary concepts. These concepts were then presented to our stakeholders, Sean and Jane Smith, and the feedback was taken into account in future iterations. Four detailed concepts are presented in this section with comments immediately following, for clarity. The remaining concepts and sketches can be found in Appendix A on page 61.

Sensory Roomscape
The sensory roomscape concept (Figure 8) consists of three inputs: audio from the user's phone, a motion sensor, and a touchpad. The outputs include kaleidoscope-like light projections and a textile canvas on which the light will be projected, whose position can be manipulated by adjusting the wooden dowels which hold the textile. The audio input will be played through the speakers.

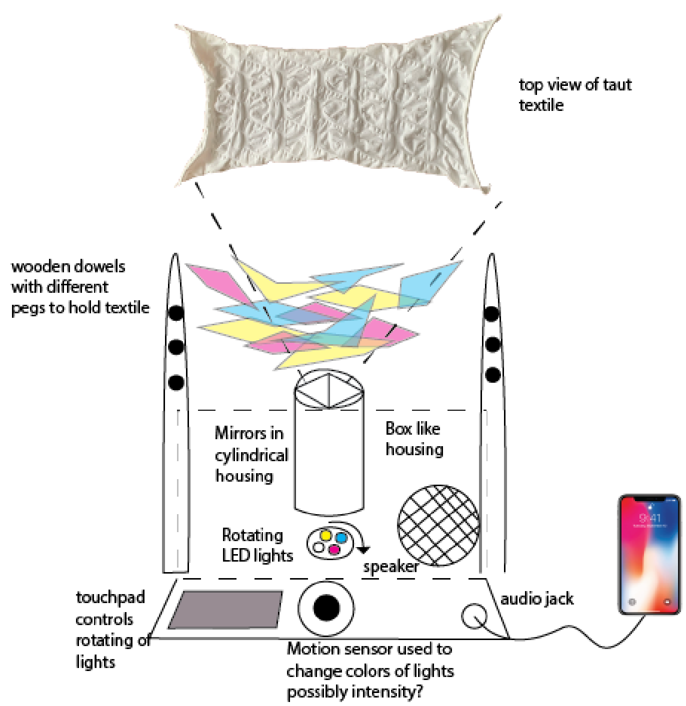


Figure 8. Sketch of sensory roomscape concept

Our stakeholders generally had a positive impression of this concept, but had a few criticisms. Sean and Jane Smith both enjoyed the light projection aspect of this concept, but Sean specifically criticized the limitation of the projections by projecting onto a 2-dimensional fabric canvas [19]. He emphasized that our device should be able to transform the nature of the user's surroundings, even while being a relatively small device.

Infinity Box

The infinity box concept is based on infinity mirror rooms such as the one displayed in Figure 9, where an image is reflected to create the illusion of an infinitely large room. The inputs to the infinity box are a touch screen drawing surface, a Bluetooth connection for inputting personal music, and fabric surfaces which can be squeezed to manipulate the displayed images. The outputs are the image displayed in the box (which can be created or altered using the touch screen drawing surface and fabric surfaces), and the music played through speakers.

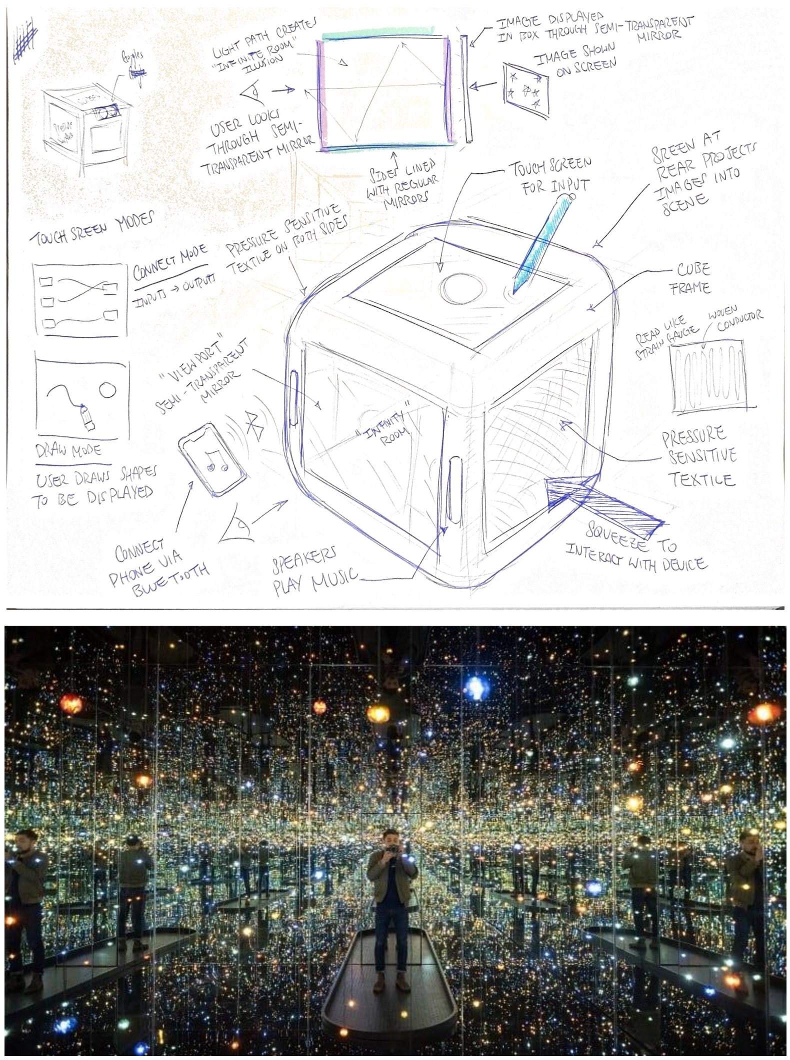


Figure 9. Infinity box concept and infinity mirror room example [20]

From our stakeholders, we learned that it may be difficult for the user to look into the box from one direction and manipulate the fabric from another direction, without being able to see the surfaces they are touching. Additionally, Sean challenged our team to think outside of the box and use the textile in a more 3-dimensional manner, rather than 2-dimensional [19]. After presenting this concept to Jane Smith, we found that an inward-facing spatial output was less engaging than an outward-projecting output [21].

Oswald the Octopus

In Oswald the octopus (Figure 10), the tentacles are used for inputs and the face is used for outputs. The inputs include a color sensor which can capture the color of an object, a microphone or Bluetooth sound input, and an accelerometer or inertial measurement unit (IMU) that can sense the speed and orientation of the device. The outputs are produced by the "face" of the device, including a light projector and speakers.

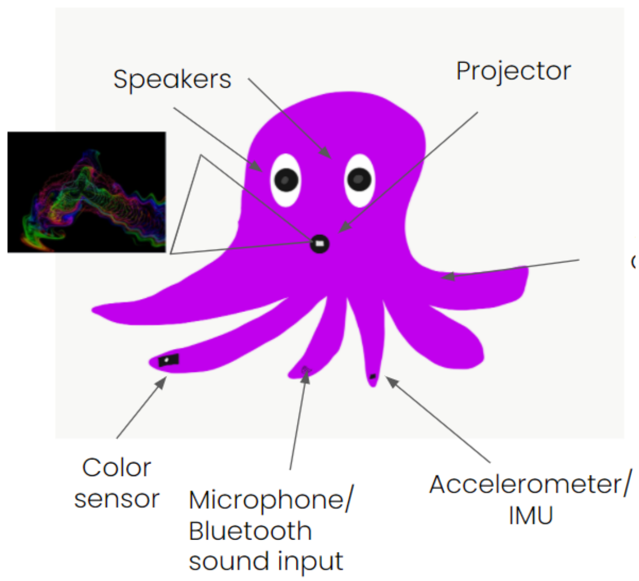


Figure 10. Oswald the octopus concept

Sean's main criticism of this concept was the housing: he warned that because our users are adults, presenting the device in an animal figure may be insulting, implying that we equate our users with children [19].

Magnetic Landscape

The magnetic landscape (Figure 11) uses three inputs: a fabric surface as a drawing surface, a laser sensor to measure frequency of hand waving, and a light projector which can be adjusted based on intensity or color. These inputs are mapped to an output device, which uses an electromagnetic field generator and magnetic filings to draw the figures that were inputted on the fabric surface. The output device also has piezoelectric patches to generate vibrations at the frequency measured by the laser sensor.

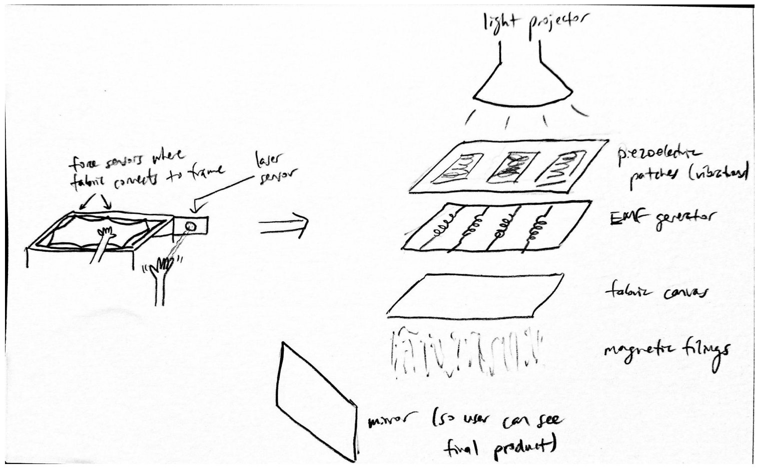


Figure 11. Magnetic landscape concept

Sean's feedback for this concept was similar to the infinity box and the sensory roomscape. He challenged us to alter the user's surroundings and create an immersive experience, and to use the fabric in a more complex, 3-dimensional manner [19]. Jane Smith also indicated that she would prefer a device that creates a larger spatial experience, rather than a device that creates one specific, smaller-scale output [21].

Concept Development

After screening the morphological chart for safety and seeking stakeholder feedback, we further narrowed down our solution space using user engagement as the main criterion. Jane Smith, our representative user with auditory sensitivities and mobility limitations, communicated that designs which were more confined were less interesting to her. Thus, she was more likely to engage with designs that projected outwards. To meet our requirement that the device is engaging for the user (and the corresponding specification that the user engages with the device for more than 15 minutes), we eliminated ideas and concepts that did not align with Jane Smith's preferred device functions. Additionally, because our device is for those with auditory sensitivities and mobility limitations, we removed all pure sound inputs and outputs. For example, an output like a fan can make sound, but the sound is not the main feature or appeal of the output.

Our new design space is captured in the morphological chart in Table 5 on the next page. For this chart, we only considered the input, output, transportation, and textile requirements. We did not include the mapping, accessibility, engagement, durability, safety, and power requirements because these requirements pertain to evaluating our designs as a whole, rather than individual subsystems.

Table 5. Narrowed design space, based on user engagement feedback.

Requirement	Concepts						
Inputs	Heart rate	Proximity	Tokens	Color sensor	IMU	Anemometer	Movement
Outputs	Projections	Kaleidoscope	Rotation	Color changing	Fluid/waving tactile structures	Fans	
Transport	Connected modules	Deconstruct-able into pieces	Soft-shell enclosure				
Textile	Light shining through fabric	Fabric suspended/taut	Fabric manipulation	Ribbons/ streamers			

From this narrowed design space, we then generated three final concepts, one of which is an iteration of the sensory roomscape concept presented earlier in this report and the other two of which are new.

Design 1: Kaleidoscopic Dream Fortress

Our first design incorporates the following features from Table 6:

Table 6. Features from the morphological chart, shown in Table 5, that are incorporated in Design 1

Inputs	Outputs	Transport	Textile
Heart rate, Tokens, Movement	Rotation, Kaleidoscope	Soft-shell enclosure	Light shining through fabric

A sketch of this design is shown in Figure 12 on the next page. This design incorporates a base structure with two rotating kaleidoscopes and lights below the kaleidoscope's housing. The device creates a projection onto the user's surroundings, as well as onto a fabric knit cover of the device. The inputs for this device are a heart rate sensor and a token panel that incorporates touch and movement inputs.

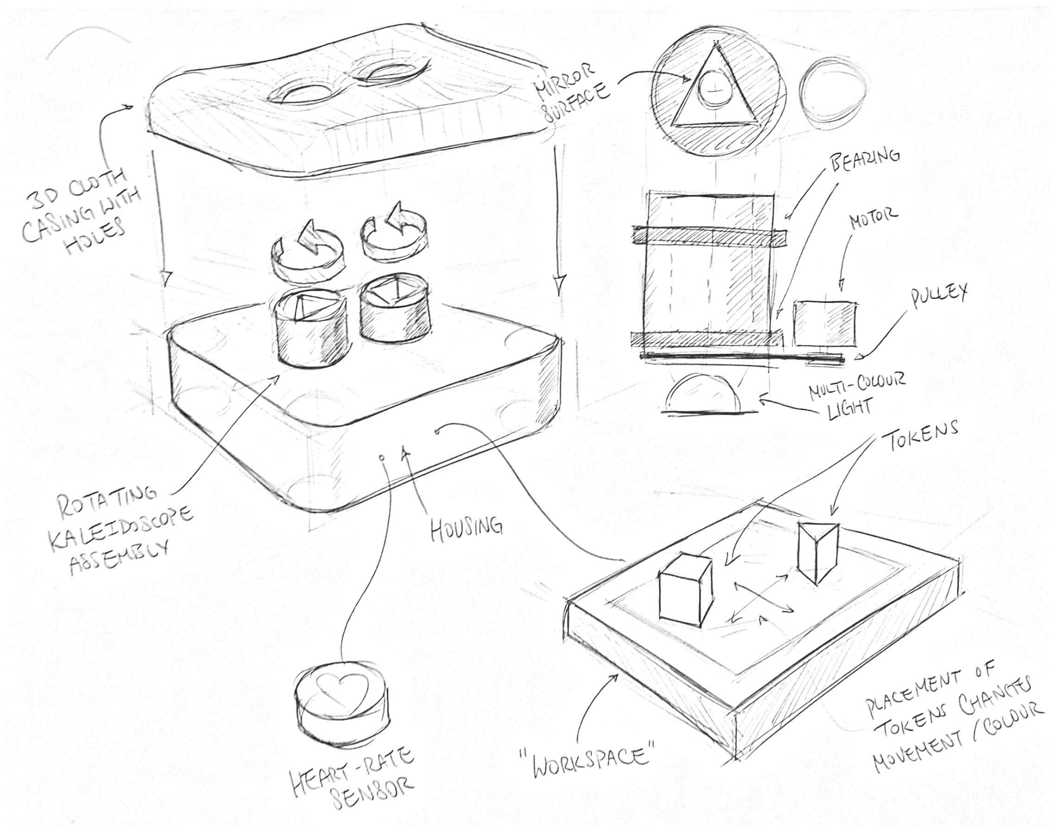


Figure 12. Sketch of Design 1

This design was selected from the revised morphological chart because we believe the combination of a token board and light projection will adequately satisfy the user engagement requirement, as supported by direct feedback we received from Jane Smith.

Design 2: Dancing Air Anemone

Our second design incorporates the following features from Table 7:

Table 7. Features from the morphological chart, shown in Table 5, that are incorporated in Design 2

Inputs	Outputs	Transport	Textile
Color sensor, IMU, Anemometer	Projections, Fan	Connected modules	Ribbons/streamers

A sketch of this design is shown in Figure 13 on the next page. The main feature of this design is an almost fluidic, waving textile structure that users can interact with in a tactile manner. Fans are used to inflate the tubular structures, and a grid of LEDs below the fabric provides lighting. Inputs to this device are incorporated into a handheld controller, which include a color sensor, anemometer, and IMU. These inputs can be used to control the color of light, speed of fans, and direction of airflow.

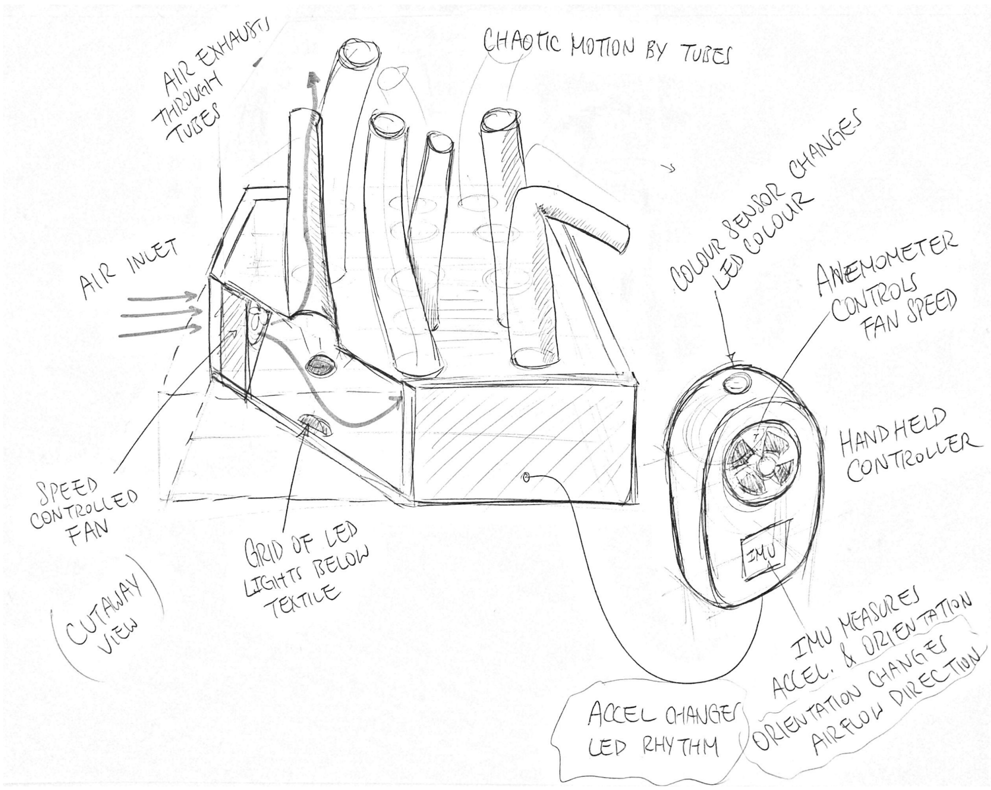


Figure 13. Sketch of Design 2

This design was selected from the morphological chart because it demonstrated a diverse set of inputs and outputs. The level of complexity of the device supports our user engagement requirement, as it would provide many options for the user to explore.

Design 3: Spinning into the Light

Our third design incorporates the following features from Table 8:

Table 8. Features from the morphological chart, shown in Table 5, that are incorporated in Design 3

Inputs	Outputs	Transport	Textile
Proximity, Heart Rate, Movement	Projections, Rotation	Connected modules	Fabric suspended/taut

A sketch of this design is shown in Figure 14 on the next page. This design consists of a cylindrical main structure, with a rotating and translating platform supported by a shaft. A 3D knitted textile is stretched across the base and platform with user-adjustable attachment points. Lights placed within the cylindrical structure shine through the knit, casting shadows onto nearby surfaces. The shape of these shadows change as the platform stretches and skews the fabric. Inputs include proximity sensors that control the movement of the platform, a heart rate sensor, and a slider.

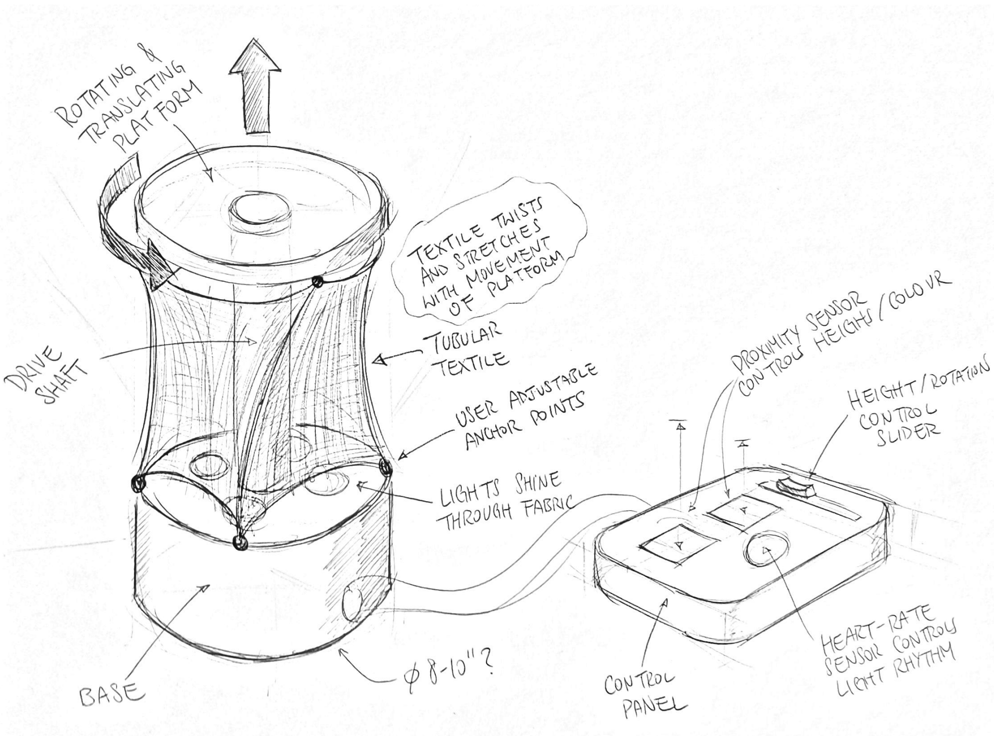


Figure 14. Sketch of Design 3

This design was selected from the morphological chart because users can interact with the stretched textile in both a visual and tactile manner. The movement of the platform also generates dynamic movements in the textile. Both these aspects would make the device more engaging for the end user.

Concept Evaluation and Selection

To choose a design to move forward with and continue to refine, we will evaluate our final three designs using a Pugh chart, shown in Table 9 on the next page. The criteria are directly converted from our requirements and specifications, shown in Table 2 (Page 9). Additionally, we will evaluate our concepts on manufacturability, as we will need to have ample time to conduct user tests.

Table 9. The final three designs were evaluated using a Pugh chart, where the first design was used as a datum and other designs are compared against the datum. +1 represents better performance compared to the datum, while -1 represents worse performance.

Criteria	**Weight**	**Design**		
		1	**2**	**3**
3 Inputs	5	0	0	0
2 Outputs	5	0	0	0
Mappable	4	0	0	0
Accessible	4	0	-1	+1
Engaging	5	0	-1	+1
Transportable	2	0	+1	+1
Safe	3	0	-1	-1
Durable	2	0	0	-1
Operable on household power	3	0	0	0
Manufacturable	5	0	+1	+1
TOTAL		**0**	**-5**	**+7**

Engineering Analysis

Our chosen design concept features rotary and linear motion to manipulate light projections (Figure 14 page 25). In order to effectively build a prototype, we needed to make informed design decisions that improve our chosen concept. The team achieved this through several analyses, such as modeling the system theoretically, analyzing projections, determining static loads, and calculating power requirements. These analyses informed us in modeling our design in CAD, using SolidWorks.

System Modeling

A spring-mass system model of our chosen concept was created to characterize the required performance of device actuators and determine critical dimensions. To create this model, we made the following assumptions:

- Textile achieves a maximum of 50% vertical extension and 90^{o} rotation: Based on preliminary experimentation with the textiles from Professor Ahlquist's lab, we found that an approximately 50% extension and 90^{o} rotation resulted in a sufficient deformation in the knit for the device to be engaging.
- Textile can be modeled as linear spring: Within the 50% extension detailed above, we observed the textiles to act similarly to linear springs.
- Rotating platform weight: We make a conservative estimate that the rotating platform will weigh 1kg.

- Friction can be neglected: We assumed that the friction is negligible in all calculations in comparison to forces exerted by the stretching of the textile.

We considered the extending motion and rotary motion with separate free-body diagrams, shown in Figure 15 below.

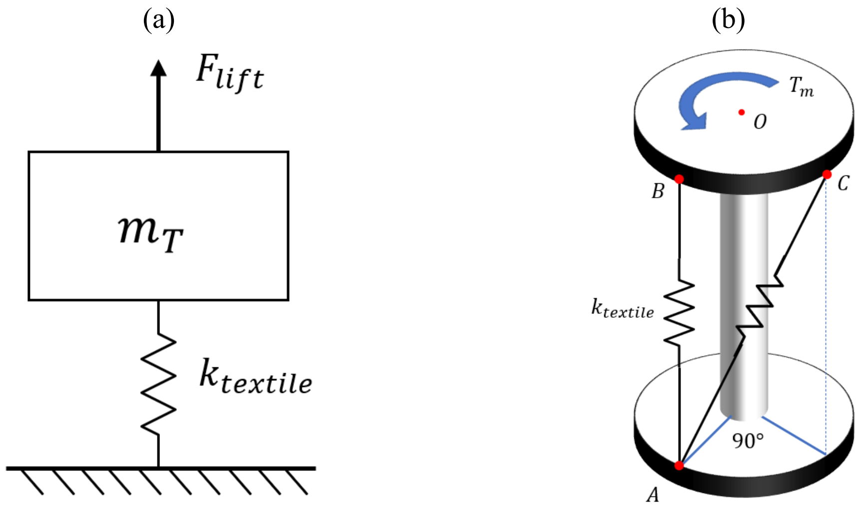


Figure 15. Free body diagrams for the (a) extension motion and (b) the rotary motion components of the system. The spring stiffness $k_{textile}$ is kept constant for both systems. Also shown are the force exerted by the lift motor, F_{lift}, the weight of the rotating platform, m_T, and the torque exerted by the rotation motor, T_m.

We performed a static load experiment to determine an approximate spring stiffness, $k_{textile}$, wherein we progressively added load to the textile specimen while measuring the extension. A photograph of the experimental setup is shown in Figure 16 below.

Figure 16. Experimental procedure to measure textile stiffness. A water bottle was used to apply various loads to the textile and a tape measure was used to measure the extension of the textile. The bottle was weighed using a kitchen scale.

A plot of applied load against textile extension, shown in Figure 17 below, was used to determine the equivalent spring stiffness.

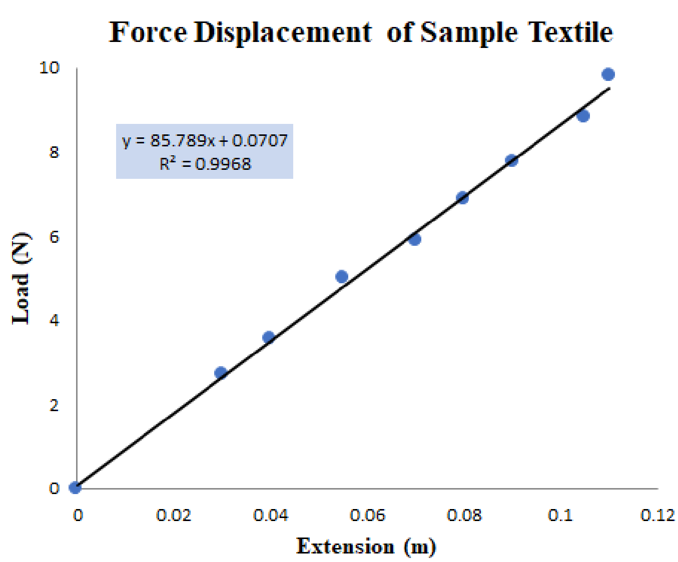


Figure 17. Plot of textile extension against applied load. The data closely resemble a linear relationship, validating our approximation of the textile as a linear spring. The spring constant found was $K = 85.8\ N/m$.

To account for the differences in geometry between the test sample, we normalized the spring constant by the width of the test specimen (100mm):

$$K' = 857.89\, N/m^2 \quad (1)$$

To find the performance requirements of the lift motor, we assumed that the device would extend from an initial height of 250mm to a final height of 380mm and have a diameter of 200mm. These values were chosen based on the 50% extension rate and feedback from stakeholders about overall device size. The adjusted spring constant for the given diameter is given as:

$$K_{adj} = K' \times W = K'\pi(0.2m) = 540\, N/m \quad (2)$$

The force required to lift the rotation stage is a combination of the weight of the platform and the force exerted by the textile:

$$F = K_{adj}\Delta x + m_T g = 80\, N \quad (3)$$

Applying a safety factor of 2, we will design the lift stage to support a design load of 160 N.

For the rotary stage, we will use the same adjusted spring stiffness to calculated the torque required to achieve a $\pm\ 90^{o}$rotation from the neutral position. The calculation is shown in Equations 4 through 6:

$$\hat{r}_{CA} = \frac{1}{|\vec{r}_{CA}|} \quad (4)$$

$$\vec{F} = -K_{adj}(|\vec{r}_{CA}| - l_0)\hat{r}_{CA} \quad (5)$$

$$T_m = (\vec{r}_{CO} \times \vec{F}) \cdot \hat{k} \quad (6)$$

where $\vec{r}_{CA}$is the position of C relative to A in Figure 15, $\vec{r}_{BA}$ is the position of Brelative to A in Figure 15, $l_0$is the unstretched spring length, and T_m is the required motor torque. Substituting all values yield a design torque of 2.1 Nm. Applying a safety factor of 2, we will design the rotation stage to support a design torque of 4 Nm.

Mechanism Choice

To achieve the 160 N lifting force, mechanisms we considered using include a rack and pinion, crank and slider, pneumatics, and a lead screw. We calculated the torque required for each of these mechanisms, details of which are available in Appendix B on page 66. Pneumatics were eliminated early on due to noise concerns for the compressor, which would violate our 4th requirement of accessibility. Table 10 below summarises the torque requirements using each mechanism.

Table 10. Summary of torque requirements for various lift mechanisms to achieve a lifting force of 160 N. The lead screw has the greatest mechanical advantage and only requires 0.40 Nm of torque.

Mechanism	Torque Required (Nm)
Rack and pinion: 10mm pinion	1.60
Crank and slider: 65mm crank	11.0
Lead screw: 8mm lead, 8mm pitch	0.40

We eliminated the crank and slider because the large crank radius would be impractical to package. We chose the lead screw mechanism over the rack and pinion because the greater mechanical advantage of the lead screw will allow us to choose smaller motors.

Motor Choice

Our device features two motors: one motor acting as a linear actuator to raise and lower the top section and one motor driving rotary motion of the top section. Our mechanism selection resulted in the lead screw. When looking for a motor on Pololu, we found a packaged linear actuator (Figure 18), which is internally the same lead screw mechanism that we planned to build from scratch. We chose to buy the 6” linear actuator because the stroke contained our needed motion of 5” and could supply the necessary lifting force, and would be simpler to implement within our limited manufacturing capabilities due to COVID.

Figure 18. The Glideforce LACT6P-12V-05 light-duty linear actuator with feedback: 25kgf and 6" stroke.

Our device needs to achieve a 90º rotation in two directions. Therefore, continuous spinning is not necessary. Due to the nature of our device, the motor will need to effectively stall at user set positions. We decided to use a stepper motor (Figure 19) based on its ability to safely stall and the effective position control incorporated in the motor. The chosen motor meets the required 4Nm of torque.

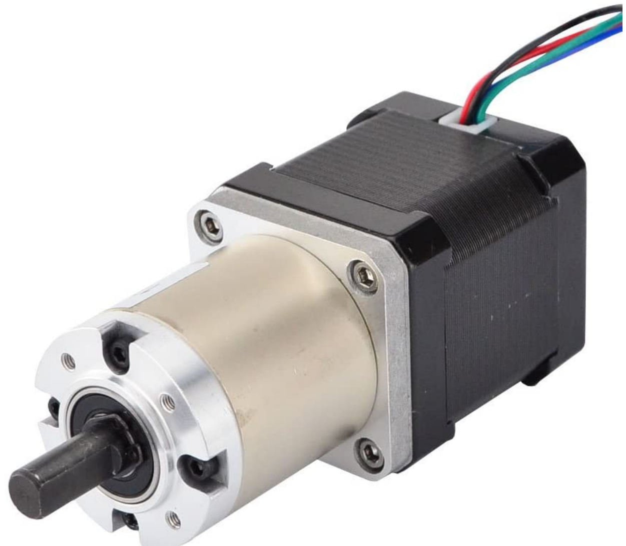


Figure 19. The selected 51:1 planetary gearbox high torque stepper motor.

Light Analysis
Our selected concept relies on shadows to create an immersive experience. The 5th requirement quantifies user engagement as a quality that can keep the user engaged for at least 15 minutes. Since the concept relies heavily on projections, we completed a series of tests in order to determine the brightness of light necessary to create projections that will be engaging for the user.

We began by creating a testing plan in order to find the necessary lumens range. The parameters were as follows:

- Light is approximately 3ft away from wall (number derived from ISO 14738:2002(E) §6.3 [6])
- Room is not fully dark in order to simulate a room having natural light (all lights in room are off)
- Fabric is held approximately 200mm away from light source
- Photographs are taken on wall that is 3ft away

Our variable textiles and light sources can be seen in Figure 20 and 21 below:

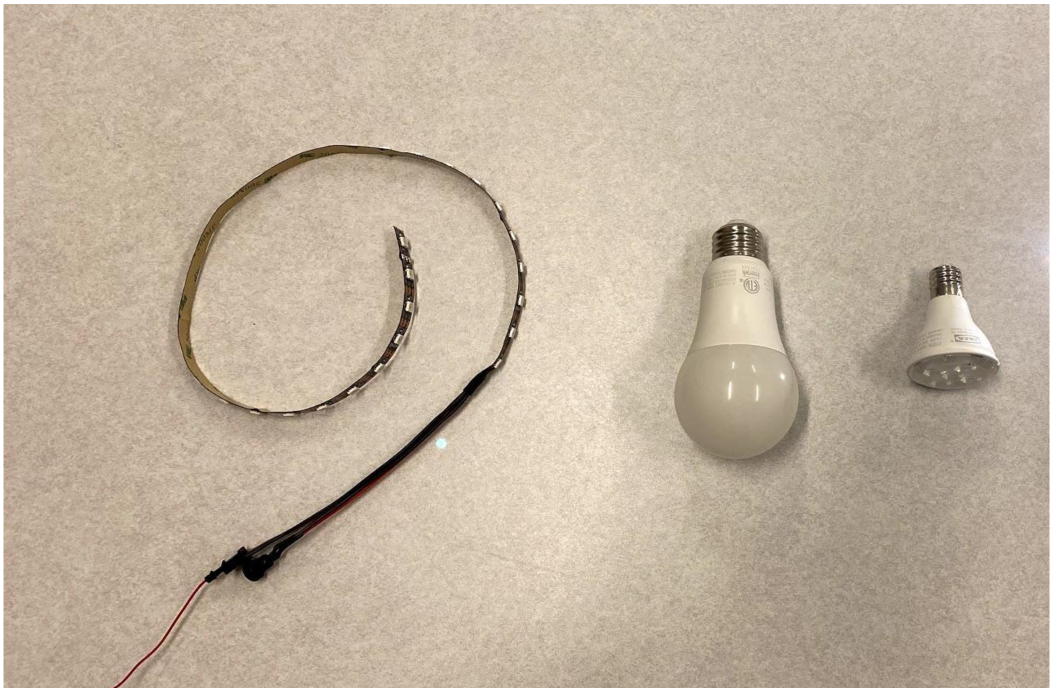


Figure 20. Lights tested from left to right with respective lumen rating: LED strip lights (217lm total), light bulb (1000lm), LED light bulb (400lm)

Figure 21. Textiles being tested from left to right: Mesh bag, nylastic and plastic filament textile, polyester knit, chunky knit scarf. The center two textiles were provided by Prof. Ahlquist's textile lab at Taubman.

We completed 12 experiments, pairing each textile with each light source. The LED strip lights had the ability to change color, so we took additional photos with different colors. Figures 22 through 24 capture each light source paired with a fabric. For conciseness, not all combinations are shown.

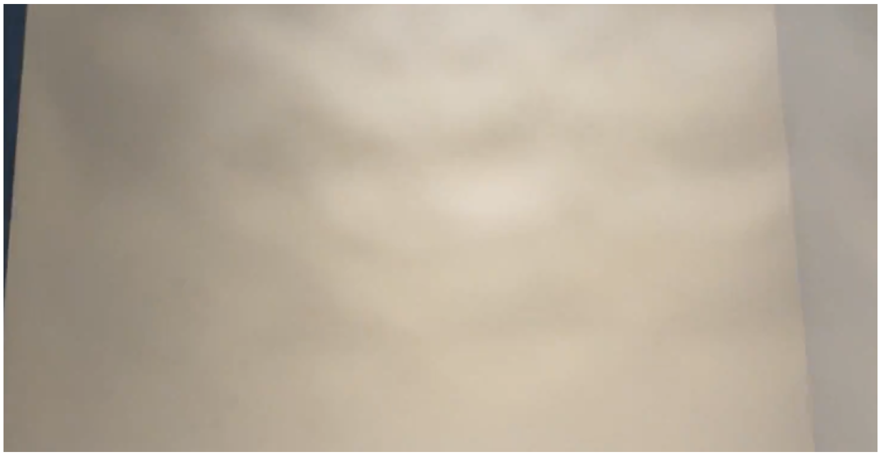


Figure 22. Shadow produced with the 1000lm light bulb and textile lab fabric. The shadow was very undefined due to the diffusivity of the light source.

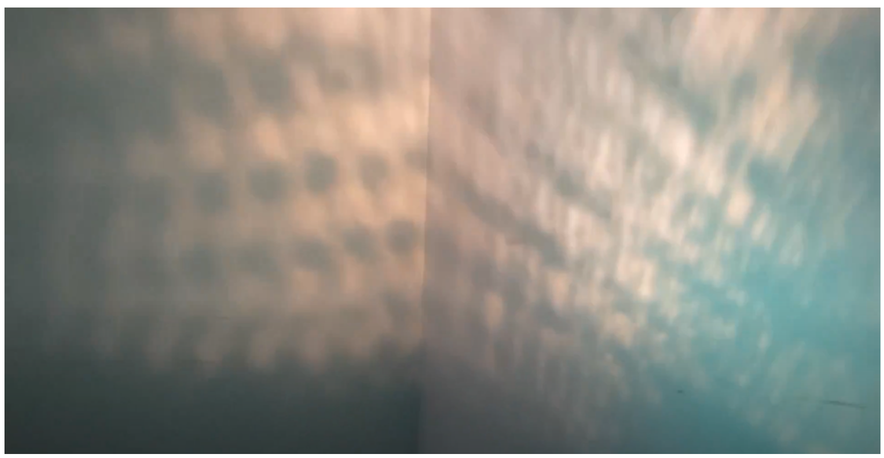


Figure 23. Shadow produced with the 400lm light bulb and chunky knit scarf. The color of the scarf transferred into the projection. The shadow created was well-defined.

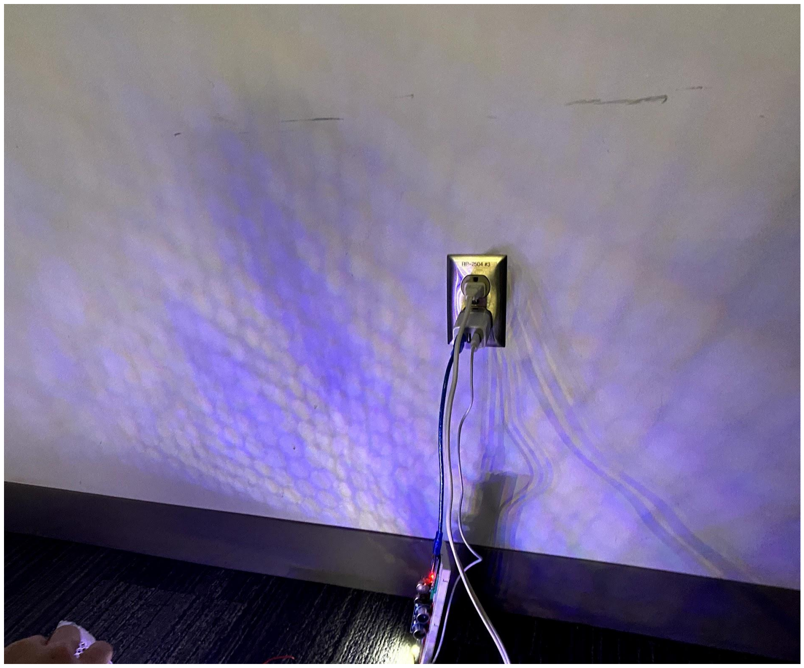


Figure 24. Mesh bag and 217lm LED lights. In this case, the lights were alternating purple and white. Due to the lower lumen rating, the projections were captured on a closer wall in order to gauge projection quality.

From initial testing, we found out that our updated design should include the following:
- Multiple lights instead of one bright light
- Lights that can vary in color
- Lights that can achieve a range between 200lm and 400lm

Due to COVID-19 restrictions, we were unable to perform these tests in front of our user. Instead, we captured each experiment through photo and video and shared it with Jane Smith. She conveyed that colorful projections were more engaging, which agreed with our assessment. She also gravitated towards the shadows produced by the 400lm light bulb. The LED lights created adequate shadows but had less range. Therefore, using our experimental results and user feedback, we believe the 400lm rating of the light bulb combined with the versatility of the LED lights will lead to an engaging design. We found chainable LEDs on Adafruit (part number: WS2811) that serve this function with 48lm per each RGB set.

Static Analysis

Our 8th requirement and specifications are related to durability. To ensure our design is durable, our team used the ASTM-F963-17 toy safety standards for tension and torque to characterize the minimum strength specifications for our device. In order to size our structural components (particularly the center tube structure) the team set the minimum internal radius to 25mm to fit the stepper motor, and then solved for outer radius simulating a bending moment of 160N at the end of the support (100mm from the fixed end) and a compressive load of 160N. Figure 25 below demonstrates the load modeled on the beam.

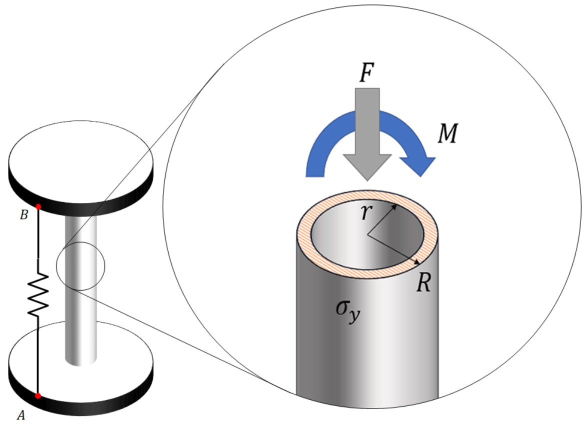


Figure 25. The largest forces experienced on the device are in the center structure. We modeled a worst case scenario of a direct load and a bending moment.

Using the principle of superposition to combine the direct load and the bending load, the two stresses were set equal to the yield stress to solve for the minimum radius with a safety factor (detailed in Table 11) on the yield strength. The resulting radii and parameters used are shown in Table 11. Equation 7 below was used to solve for the radii.

$$\frac{\sigma_y}{SF} = \frac{F}{\pi(R^2 - r^2)} + \frac{(0.1m)\times Fr}{\frac{\pi}{4}(R^4 - r^4)} \tag{7}$$

The outer radii were calculated for all of the prospective materials with safety factors based on the material and manufacturing process. 3D printed plastics were given a higher safety factor to combat lower shear and axial strength due to layer bonding.

Table 11. The material thickness for a tube to support our "worst case loading" is less than 4 mm with a safety factor. The calculations present 3D printed materials as a viable structural material for the application.

Material	Yield Strength (MPa)	Safety Factor	Wall Thickness (mm)
Aluminum 6061-T6	276	2	0.06
PLA	26.4	10	3.24
PETG	50.0	10	1.76
PVC	37.9	2	0.47

After these calculations we found that under the maximum loading, the minimum wall thickness is less than 4mm, and that we can consider 3D printed components. We are also aware that any axial load onto the shaft will be supported by our actuator, which is capable of carrying that load. Based on this analysis the team has decided to use PLA material for the tube shafts in the final device, as this material was readily available.

Electrical Analysis

Our 9th requirement requires that our device operates on household power. The maximum amount of power that can be drawn from a household outlet is approximately 1400 Watts, so the power requirement of the electrical components in our design needed to be below that threshold. All of our devices also operate on DC power at various voltages, so we wanted to determine what would be the best power supply voltage and max current to operate on. Table 12 combines the published current and voltage for all of our electrical components, and the power is calculated as the product of voltage and current.

Table 12. The table lists all of the device's electrical components, and uses the published voltage and current values to determine power. The theoretical max power draw of our device is 80.3 Watts, well below the maximum available from a household outlet.

Component	Voltage (V)	Continuous current (A)	Power (W)
Pololu 2321 Linear Actuator	12	3.2	38.4
Nema 17 Stepper Motor	12	1.4	16.8
RGB Color Sensor	3.8	3.30E-04	1.25E-03
Ultrasonic Sensor	5	1.50E-02	7.50E-02
10K Linear Potentiometer	5	0	0
LED Lights (x10)	5	5	25
		Total Power:	**80.3 W**

From this analysis we determined a power supply operating on 12V with a minimum power output of 85W would be ideal for our device. We will finalize our power supply choice based on cost considerations.

3D Modeling

Using the results from static analysis and the chosen motors, we modeled the rotating column structure and the user input control panel in SolidWorks. The models for the rotating column and control panel are shown in Figure 26 through 30.

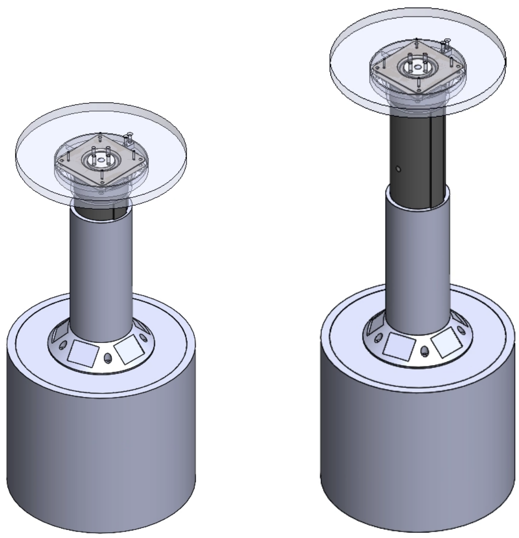


Figure 26. SolidWorks model of the rotating column structure. The base houses the linear actuator, which drives the dark grey inner tube. The top of the base has rectangular pockets which will house the LED lights. A stepper motor, which is mounted to the inner tube, drives the rotation of the top disk. The structure is shown at its least and most extended states.

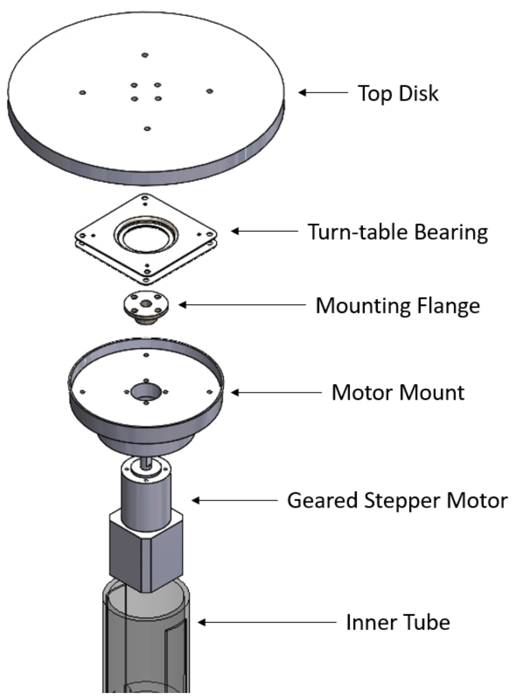


Figure 27. Exploded view of interface between the stepper motor and top disk. The stepper motor is attached to the inner tube with a motor mount, and attached to the top disk with a mounting flange and turn-table bearing.

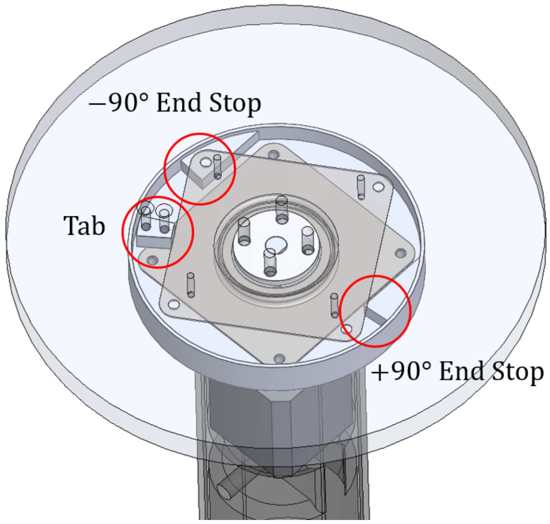


Figure 28. Transparent view of the top disk to show -90º and +90º hard stops, which are integrated within the disk. The tab is integrated in the motor mount.

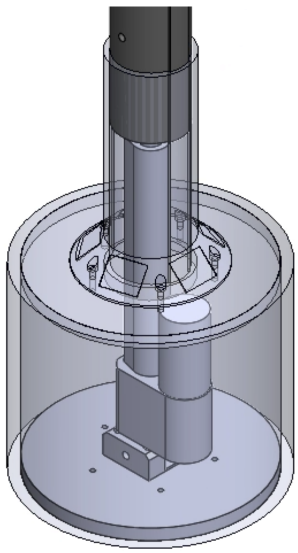


Figure 29. Transparent view of the base of the structure, which houses the linear actuator. The linear actuator is pinned to the base with a pillow block, and pinned to the inner tube. The outer tube serves to separate the user form the actuator and also houses the LED lights.

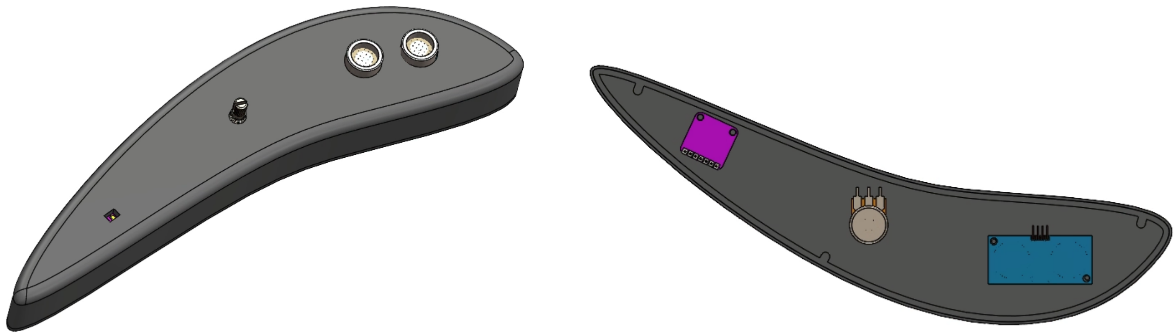


Figure 30. User input control panel, which houses the input sensors. The bottom view is also shown. From left to right: color sensor, knob potentiometer, and proximity sensor.

Rotating Column

The rotating column (Figure 26-29) features a set of telescoping shafts, which are keyed to prevent rotation with respect to each other. The inner shaft is driven by the Pololu 2321 Linear Actuator, allowing for the vertical motion of the device. The linear actuator is pinned to the structure in two locations: at the bottom of the base, using a 3D printed pillow block, and inside the inner shaft. The stepper motor sits above the upper linear actuator pin and is connected to the rotating upper platform using a mounting flange and a turn-table bearing. Two sets of hard stops allow for the angular position of the motor to be calibrated. The hard stops also prevent the motor from rotating too far and causing damage to the device. We will add two additional sets of limit switches to the rotational mechanism in the coming days. The base of the outer tube features pockets for the LED lights chosen in the Light Analysis section.

The SolidWorks model helped us design the telescoping shafts to accommodate the linear actuator, while providing enough overlap between the inner and outer tubes to counteract the anticipated bending moment, as detailed in the Static Analysis section. It also helped us select a method of attaching the motor to the rotating upper platform.

Control Panel

The control panel (Figure 30) houses the three input sensors: the color sensor (left), knob (middle), and proximity sensor (right). It also includes a power switch, to provide an emergency on/off switch that is accessible to the user during operation.

Modeling the control panel helped us envision its shape and size. Through modeling, we ultimately decided on a curved control panel, which is more aesthetically appealing and ergonomic for the user. The curve shaped control panel also provides enough separation between the color sensor input, knob to control angular position, and proximity sensor to control height.

Solution Development and Verification

After completing engineering analysis, the team moved forward to conduct a risk assessment, reevaluate sensor placement, and finalize the design. The following section introduces our risk assessment and mitigations, detailed design solution, and solution verification processes.

Risk Assessment

An early design failure modes and effect analysis (FMEA) was conducted for our detailed design solution. Our FMEA was based off of a Wilson Center design team's process where components' failure methods are described and ranked based on severity and occurrence. The full FMEA is included in Appendix C on page 67. In this section, we will discuss two high severity failures and their mitigations. The severity and occurrence ratings are defined in Table 13 below.

Table 13. FMEA ratings for severity and occurrence with relative severity

Rating	Severity	Occurrence
1	No injuries may be caused, but general safety is affected by this failure	Failure occurrence is very unlikely
2	Light injuries may be caused by this failure	Relatively few failure occurrence
3	Medium injuries may be caused by this failure	Occasional failure occurrence
4	Heavy injuries may be caused by this failure	Frequent failure occurrence
5	Fatal injuries may be caused by this failure	Persistent failure occurrence

Top Rotating Component

The top rotating component could fracture at the interface with the bearing. This could be due to too much torque applied by the spinning motor or the user using the device incorrectly. We gave this failure a severity of 4. If the user has their face near the device, this failure could cause significant injury to sensitive areas of the face. The piece was originally planned to be acrylic, however, after analyzing associated risks we went forward with a stronger material at a greater thickness. Instead of 0.125” acrylic, the current device has 0.25” aluminum. Our mitigation efforts changed the occurrence of the failure mode to a 1. After the material and design change, the risk associated with this component is now an acceptable level. Since this device is open to a user, we would still need to have adequate labeling and an instruction manual that details potential risks associated with device misuse.

Inner Structural Tube

The structural tube distributes a lot of the device’s load and upon failure would transfer load to the linear actuator in an unintentional way. The failure mode would be fracture at the pin connection point to the linear actuator or to the motor mount. The linear actuator is quite powerful, so if it became unhinged it may begin to act erratically causing unexpected injury. In order to mitigate this risk, we considered using a stronger material for the structural tube, such as solid PVC or aluminum. Due to our team’s limitations and COVID, this was not an option and these improvements are discussed in our recommendations . After this change, we believe the device is less likely to fail. The occurrence was already quite low, at a 2 rating. The tube is covered with a textile tube, so it would be difficult for the user to access or tamper with the pin.

Detailed Design Solution

Overall, our final solution was fairly similar to the design presented in the Engineering Analysis and Solution Development section. Subsequent sections will discuss how this design meets our requirements and specifications and summarize changes made since earlier design stages. Images of the final prototype are shown below in Figure 31, and dimensioned engineering drawings are available in Appendix D on page 68. The full bill of materials can be found in Appendix E on page 69.

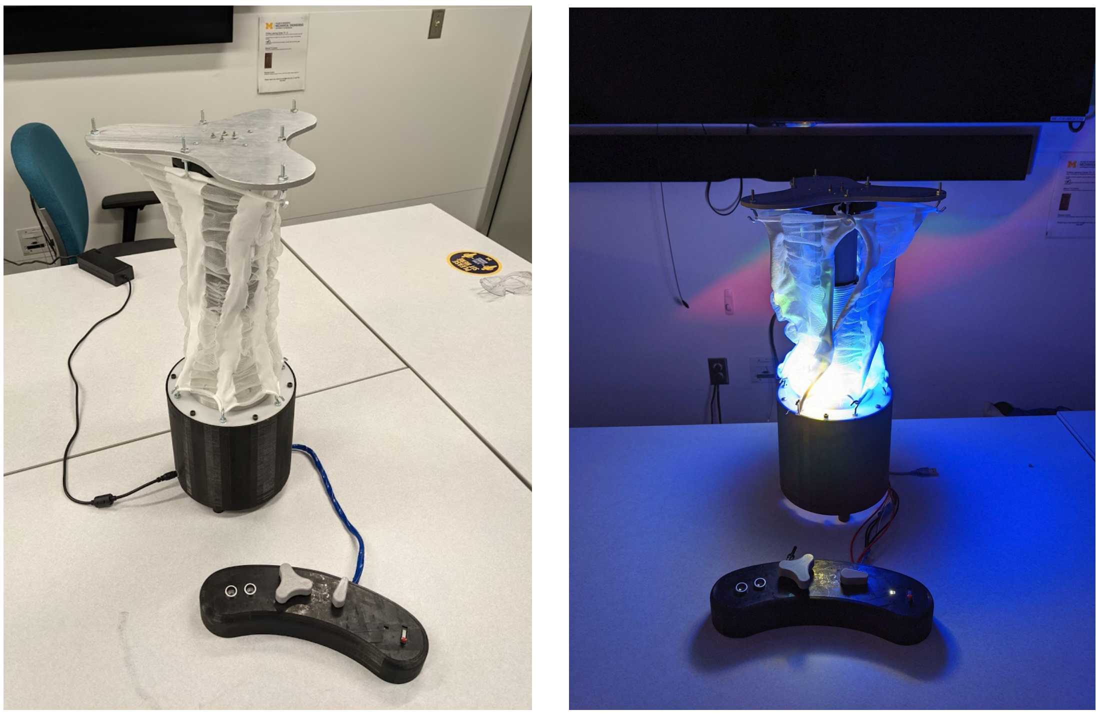


Figure 31. Final prototype when turned off (left) and when turned on in a dark room (right).

Vertical Motion Subsystem

The vertical motion subsystem remained unchanged compared to our initial design. The Pololu 2321 linear actuator is enclosed within the 3D printed columns and drives the vertical motion of the top structure. This system is capable of lifting the top structure by 130mm and aligns with our requirement for two distinct outputs, as the stretching of the fabric provides a changing tactile experience for the user.

Rotary Motion Subsystem

Compared to our initial design concepts, the final rotary motion design includes limit switches on the positive and negative extremes of the motion range. The limit switches were implemented as a safety measure to prevent over-extension of the fabric as identified in our FMEA. A rendering for the limit switch placement is shown below in Figure 32:

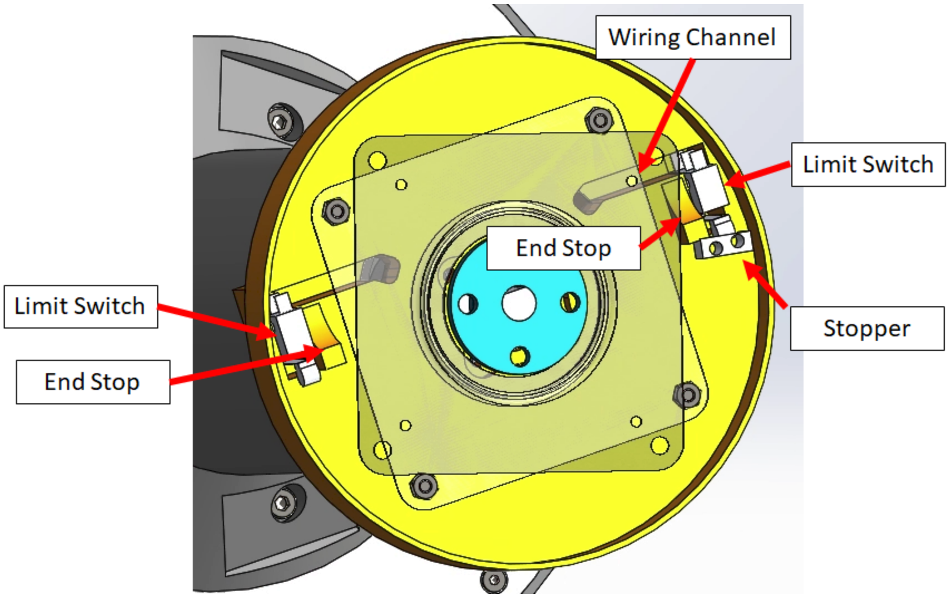


Figure 32. Labeled rendering of limit switch arrangement. Limit switches are placed at the +90 degree and -90 degree positions. A stopper fastened to the rotating plate hits the limit switches when the motor exceeds the rotation range.

Additionally, the shape and material of the top disk was also changed to address concerns over user engagement and safety. After presenting our design concept to Professor Ahlquist and Jane Smith, we learned that our stakeholders would have preferred more complex geometry from an engagement standpoint. Based on this feedback, we modified our design to incorporate a three-lobed design, shown below in Figure 33:

Figure 33. The shape of the top disk was modified to improve user engagement.

For our final prototype, we also changed the material of the top disk from 0.125” acrylic to 0.25” aluminum. This change was informed by our FMEA and sought to reduce potential risks of injury from brittle failure of the disk.

Device Main Housing

Compared to the original designs, minor changes were made to the device housing to facilitate assembly and aesthetics. Changes to the main body of the device include adding grooves for the top and bottom plates to sit flush with the top of the main body. Six tabs with pilot holes were also added to allow the top and bottom plates to be fastened directly to the main body tube. The diameter of the pilot holes were chosen such that fasteners would self-tap into the plastic. Finally, a hole was added to fit the DC power input barrel jack. These changes are summarized in Figure 34 below:

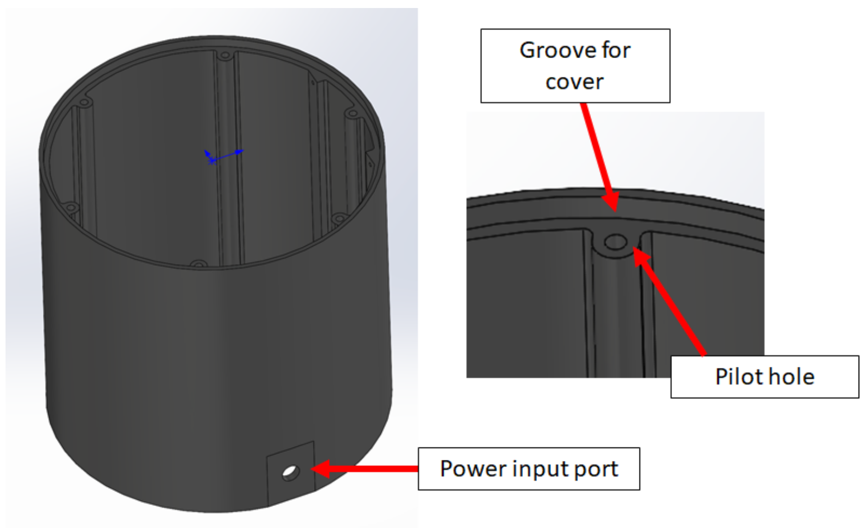


Figure 34. Changes to the main body tube include the addition of a power input port, grooves for the cover plates, and tabs with pilot holes for fasteners.

Another design change was the addition of a translucent cover for the LED lights. This component was added to satisfy our safety requirement, which specifies that all electronics must be fully enclosed. The cover 3D printed from a clear PLA filament to maximize the amount of light transmitted through the cover. Images of the cover are shown in Figure 35 below:

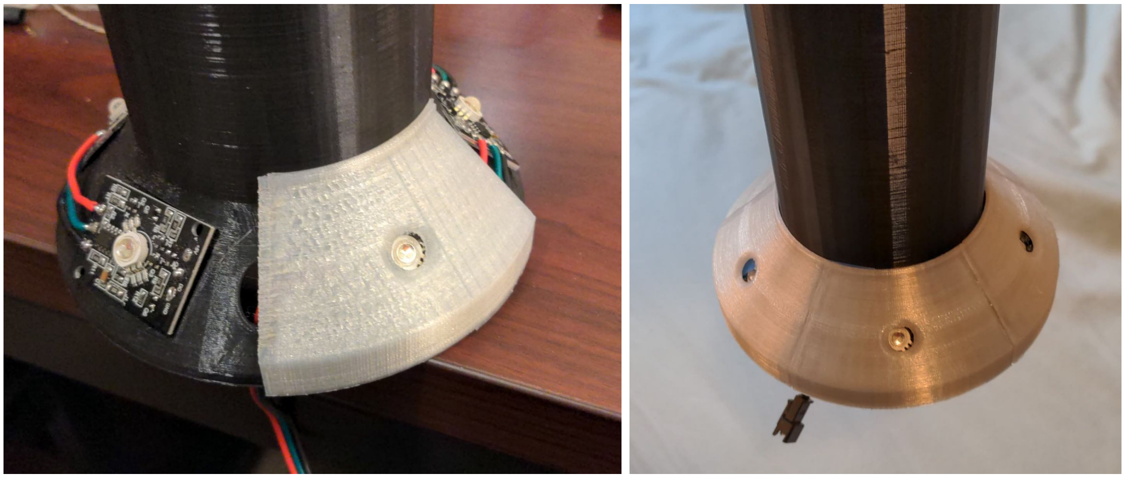


Figure 35. (Left) A single segment of the light cover. The cover sufficiently encloses all electronics while still allowing light to pass through. (Right) Fully assembled light cover consisting of five segments glued together.

Lastly, hooks (McMaster 9491T11) were added to the device as an attachment point for the textile cover. Hooks were chosen based on feedback from our stakeholders, who expressed that hooks would be the easiest to use and least damaging to the textile. The hooks are shown in Figure 36 below:

Figure 36. (Left) Hooks attached to the base of the device. (Right) Identical hooks fastened to the top of the device.

Control Box

Significant changes were made to the control box compared to the original design. Firstly, we added a second potentiometer to control the brightness of the lights. This additional control was included based on feedback from Professor Ahlquist, who expressed the importance of allowing users to have direct control over the intensity of outputs from an accessibility standpoint. The control box was subsequently made larger and rounded to accommodate the additional potentiometer knob. A comparison between the initial design and final prototype is shown below in Figure 37:

Figure 37. Initial design of control box (left) compared to final prototype (right). The final prototype is more rounded and larger than the initial design to accommodate additional components.

Additionally, the shape of the rotation control knob was chosen to match the shape of the top plate. We hoped that choosing matching shapes would make the prototype more intuitive to use and make it easier for users to engage with the device.

Electrical Systems

Our final prototype incorporates an electrical system that receives user inputs from the various sensors and drives the corresponding outputs. The electronics system directly aligns with the requirements for the device to accept user inputs and produce outputs. An overview of the electrical components used is presented in Table 14 below:

Table 14. Summary of electrical components used in the prototype. The usage of each component and a justification for why the component was selected is explained.

Component	Description
Pololu 2999 Motor Driver	H-Bridge motor driver breakout board for DC motors. Can supply 3.4A continuous in single channel mode, commensurate with the power requirements for the linear actuator.
TMC2208 Stepper Motor Driver	Stepper motor driver breakout commonly used in devices such as 3D printers. This driver was selected because it offers silent operation, helping to achieve our accessibility requirements for persons with auditory sensitivities.
Adafruit TCS34725	RGB color sensor breakout board. This sensor was selected to achieve our inputs requirement because it was low-cost and had detailed documentation from the manufacturer.
HC SR04 Distance Sensor	Ultrasonic range sensor. This sensor was selected because it offered an adequate range to satisfy the accessibility requirement at a very low cost.

Component	Description
10K Rotary Potentiometer	10KΩ rotary potentiometer knob designed for panel-mount applications. Used to achieve the user inputs requirement.
Adafruit 3W WS2811 LED	3W RGB individually addressable LED module. These lights were chosen based on our experimental analysis of light sources, which indicated that lights in this brightness range would be sufficient.
BANKEE 12V-5V 5A Converter	12V to 5V buck converter. A high power converter was chosen to satisfy the power draw of the LEDs.
Arduino Nano	We chose to use an Arduino Nano because it offered enough peripherals to support all the sensors and actuators at a low cost.

The electronics were organized in two groups: One main control board housed in the main column of the device, and a group of sensors housed in the control box. The main control board, shown in Figure 38 below, was assembled on a prototyping board with wires connecting each of the components. Our initial plan was to control the entire device from a single Arduino; however, we decided to use two separate Arduinos due to difficulties in integrating all the sensors and software to a single Arduino. A full schematic is shown in Appendix F on page 70.

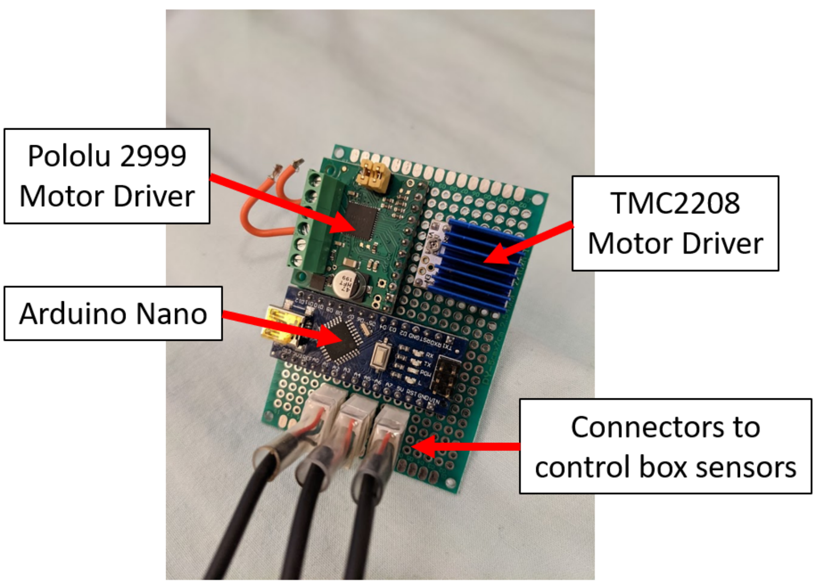


Figure 38. Main control board assembly. Carries the Arduino Nano, motor drivers, and connectors to the control box sensors.

The sensors and power switch were housed in the control box. Compared to the original design, a knob was added to allow users to adjust the brightness of the lights based on feedback from our stakeholders. A trigger switch was also added to activate the color sensor, as the color sensor would otherwise continuously sample the environment and produce random color readings. The arrangement of the sensors is shown in Figure 39 below:

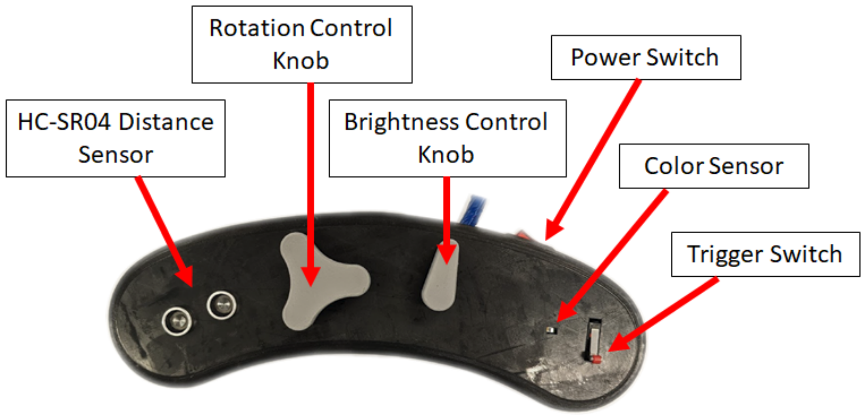


Figure 39. Control box electronics arrangement.

Software

Software was our main means of achieving the requirement that the device maps between user inputs and device outputs. Table 15 below summarizes how inputs and outputs are split across the two Arduinos.

Table 15. Summary of inputs and outputs handled by each Arduino.

Arduino	Inputs	Outputs
1	Ultrasonic distance sensor	Vertical lift motor
2	Rotation control knob Brightness control knob Color sensor	Rotation motor LED brightness LED color

For Arduino 1, the distance reading from the ultrasonic sensor is directly correlated to the position of the vertical lift motor. First, we defined a valid distance range to be within 5-31cm above the sensor. Values outside of this range are deemed invalid. When a valid distance is detected, the distance reading is directly mapped to a desired position for the linear actuator. A P-controller is subsequently used to control the position of the linear actuator using feedback from the built-in potentiometer. The P-controller was sufficient as the system is heavily damped and did not require any derivative gain. We also found the steady-state error to be sufficiently small as to negate any need for integral action. The full code for Arduino 1 is shown in Appendix G (page 71).

For Arduino 2, the rotation control knob and brightness control knob inputs are directly mapped to the desired rotary position and desired brightness level respectively. A timer interrupt is implemented to create a 8kHz square wave signal to drive the stepper motor. Pulses are continually sent to the motor until the motor position reaches the desired position. The use of a timer interrupt allows for smooth movement of the stepper motor even while the Arduino is busy processing other tasks.

Additionally, Arduino 2 monitors the state of the color sensor trigger switch. Once the switch is pressed, a color sample is taken and displayed on the LEDs. The lights are organized in two groups, such that readings from the color sensor update alternating groups of lights. This was implemented because our initial analyses showed that two distinct colors would produce more complex projections and be more engaging to the user. The full code for Arduino 2 is shown in Appendix H (page 73).

Verification

We used a wide variety of methods to verify the requirements and specifications established for our device (refer to the Requirements and Specification section on page 9 for details), which are detailed in this section. Ultimately, we verified 8/10 of our requirements and specifications (see Table 16 for details). We believe our design was successful, because the two requirements we failed to verify were failed due to time constraints (lack of safety labeling) and because our device is only a prototype (failure to pass tension tests as specified in ASTM-F963-17). The requirements and specifications we were able to verify included important user engagement requirements, such as the device accepting multiple inputs and producing multiple outputs, as well as accessibility specifications.

Table 16. Summary of verification of requirements

#	Requirement	Verified? (Y/N)
1	Device accepts multiple user inputs with electronic sensors	Y
2	Device produces outputs that address visual, auditory, and/or tactile sensory modes	Y
3	Device maps between user inputs and device outputs	Y
4	Accessible to persons with auditory sensitivities and mobility limitations	Y
5	Device is engaging for the user	Y
6	Transportable between UM and student’s home	Y
7	Device is safe to operate	N
8	Durable	N
9	Operates on household power	Y
10	Includes a textile	Y

1. Device Accepts Multiple User Inputs with Electronic Sensors

To verify that our device can accept 3 or more types of inputs, that all inputs are operable simultaneously, and that the sensor response time is less than or equal to 5 seconds, we conducted several tests of our device in operation. First, we counted the total number of inputs and total number of input types. The device has 4 total inputs, spanning 3 distinct input types: a movement input, two touch inputs, and a light input. These correspond to the proximity sensor that controls the height of the device, a knob that controls the rotation of the top, a knob that controls the brightness of the LED lights, and a color sensor that maps to the color of the LEDs. These inputs are summarized in Table 17.

To test the simultaneous specification, two users operated the device at the same time, with one operating the proximity sensor and knob 1 and the other operating knob 2 and the color sensor. The device was able to handle all four inputs simultaneously.

To test the response time specification, we operated each input separately and timed the space between the initiation of the input and the response of the device. The time between initiation and response was too short to be measured, which is indicated in Table 17 as response times of less than 1 second. Thus, each input to our device was able to achieve a sensor response time of less than 5 seconds.

Table 17. Summary of inputs, input type, function, and response times.

Input	Type	Function	Response Time
Proximity sensor	Movement	Distance from proximity sensor corresponds to height of device	<1s
Knob 1	Touch	Rotation of knob corresponds to rotation of top of device	<1s
Knob 2	Touch	Rotation of knob corresponds to brightness of LED lights	<1s
Color sensor	Light	Color inputted corresponds to color of LED lights	<1s

2. Device Produces Outputs that Address Visual, Auditory, and/or Tactile Sensory Modes

To verify that the device produces at least 2 types of outputs and that all outputs are able to operate simultaneously, we first counted the number of outputs. The device has 3 total outputs, including 2 types of outputs: two tactile and one visual output.

The simultaneous specification was tested at the same time as the simultaneous specification for the first requirement. The device was able to produce all outputs simultaneously, as the inputs were simultaneously triggered.

3. Device Maps Between User Inputs and Device Outputs

The mapping requirement was verified through user testing. We verified that each input directly caused an output. The mapping between user inputs and device outputs are outlined in Table 18.

Table 18. Mapping between user inputs and device outputs.

Input	Output
Moving hand above proximity sensor	Vertical linear motion of device
Rotating knob 1	Rotary motion of top platform
Rotating knob 2	Adjustment of LED brightness
Placing a colored object over the color sensor and pressing the switch	Change of the color of the LED lights to that of the object

4. Accessible To Persons With Auditory Sensitivity and Mobility Limitations

Accessibility to persons with auditory sensitivity and mobility limitations was verified by measuring various aspects of our device. The auditory specification was verified by measuring the sound intensity of the device at its loudest operating state, when the device is moving vertically at its maximum speed, and at its quietest operating state, when the device is stationary. The tactile specification was verified by measuring the size of the control box, which represents the working area, and measuring the force required to turn the two knobs. The movement specification was verified by measuring the range in which the proximity sensor responds to user inputs. The size of the control box and proximity sensor range were then compared to the maximal working area specified in ISO 14738:2002(E) §6.3, which is reproduced in Appendix I on page 76. The results of these tests are summarized in Table 19.

Table 19. Results of tests to verify auditory, tactile, and movement accessibility requirements.

	Specification	Test result	Verified?
Auditory	● Output sound intensity ≤80dB ● Output sound is adjustable to ≤40dB	● Maximum sound intensity: 68 dB ● Minimum sound intensity: 48 dB (Room is 43 dB)	Yes*
Tactile	● Device fits within a radius of 415mm from user ● Knobs require <5lbs of force to turn	● Size of control box: width = 10.5cm ● Force required to turn knobs: <1oz	Yes
Movement	● Motion inputs are sensitive to movements within 730mm from seat	● Range of response of proximity sensor: 43-68cm	Yes

Our results show that the device satisfies the tactile and movement specifications of this requirement, as the control box and range of the proximity sensor fit within the working area specified in ISO 14738:2002(E) §6.3. The maximum sound intensity of the device satisfies the auditory specification that the output sound intensity is less than 80dB. The minimum sound intensity is greater than the threshold of 40dB, so our device technically does not satisfy the auditory specification of this requirement. However, the sound intensity of the silent room was 43dB, which was already greater than the threshold we set for our device. Thus, we recognize that the specification may have been unrealistic, and for the purposes of this evaluation of our device, we consider that this requirement was verified.

5. User Engagement

To verify our user engagement requirement, we gathered several test users and measured the amount of time they used the device. "Using" includes actively operating the controls as well as passively enjoying the atmosphere created by the device. Some of our test users were unable to test for a period longer than 15 minutes due to scheduling difficulties. To measure their engagement levels, we asked them how long they anticipate they could use the device. Our user engagement results are summarized in Table 20, which shows that the majority of our users were engaged or anticipated they could be engaged by the device for at least 15 minutes.

Table 20. Engagement times for four test users.

User #	Engagement Time / Anticipated Engagement Time
1	< 15 min*
2	1 hour
3	45-60 minutes
4	15-20 minutes

Three out of four of our users indicated that they would be engaged with the device for at least 15 minutes. User #1 is Jane Smith, our representative user, but she was not actually able to use the device in person due to COVID-19 restrictions. Instead, we demonstrated its functions over Zoom. However, we believe that she would have been more engaged with the device if she were able to interact with and experience it in person, which is indicated by the response of the other three users. Thus, we consider this requirement and specification verified.

6. Transportable between UM and Student's Homes

To verify the requirement that the device is transportable between the University of Michigan and the AACIL student's home, we measured the size of the bounding box of the device and the control panel. We then weighed the device using a hanging scale. The device measured 20in x 10.5in x 10.5in and weighed 10.9lb, which is within the range of the specification.

7. Device is Safe to Operate

The safety requirement specified that hazards of our device were labeled according to Section 5.3.1 of ASTM-F963-17 (Appendix I on page 76) with an alert symbol, a signal word, and text to describe the hazard, and that these labels were identifiable within 1 minute. Due to time constraints, we were unable to satisfy this specification.

Additionally, the safety requirement specified that all electronics were fully enclosed. We were able to satisfy this specification, as all electronics were enclosed within the base of the device or within the control panel, and the wires running from the device to the control panel were wrapped in electrical tape.

8. Durable

The durability of the device was verified using the procedure detailed in ASTM-F963-17, Sections 8.8 and 8.9 (see Appendix I on page 76 for detailed procedure). For our intended age group of 18 to 36, the test torque and force used are 3 ± 0.2 in.·lbf (0.34 N·m) and 15 ± 0.5 lbf (66.8 N), respectively. The components that were tested were the two knobs on the control panel, the hooks on the top and bottom of the device, and the top platform. Our device was able to withstand the torque tests, but only the hooks passed the tension tests. For the tension tests of the knobs and top platform, we stopped applying force at 15.7N and 24.5N, respectively, to prevent damage to the prototype. For the torque test, we did not test the hooks because it was unrealistic to apply a moment on a component that small. The results from the tension and torque tests are summarized in Table 21, and a demonstration of the torque test on the top platform is shown in Figure 40.

Table 21. Results of tension and torque tests for the knobs, hooks, and top platform.

Component	Maximum Tension Applied	Maximum Torque Applied
Knobs	15.7N	3 lb-in
Hooks	>66.8 N	N/A
Top platform	24.5N	4.3 lb-in

Figure 40. Torque test on top platform. A force was applied at a 1 inch moment arm. The handheld force gauge reads 4.3 lb.

Ultimately, the durability requirement was not verified due to the failure of two components to pass the tension tests.

9. Operates on Household Power

The device draws 120V AC from a wall outlet and operates using 12V power, which agrees with the specification for this requirement.

10. Includes a Textile

The device includes two textiles: a ribbed nylastic tube that covers the telescoping shafts in the center of the device and a striped nylastic and monofilament sheet that stretches around the outside of the device. Thus, the specification that our device includes at least one textile is verified.

Discussion and Recommendations

Sensor.IO satisfies the overarching project goal: it is an input-output device designed intentionally for accessibility and inclusivity. After completing our initial prototype, our team identified several further improvements that could be made. Recommendations range from general device improvements to changes necessary to meet currently unmet requirements. Overall, the next steps for this project would be to secure a larger budget and spend more time post-COVID to improve the physical prototype. However, the team is satisfied with the results of the design and initial prototype and feels Sensor.IO was successful overall.

Sensor Technology
To increase user engagement, our device is controlled by the user with a separate control box, which houses several different sensors. The sensors and electrical hardware, however, have many areas for improvement. Due to budgetary constraints, many of our sensors were low quality. For example, right before the Design Expo, the color sensor failed and we were unable to demonstrate a working color sensor. Another major improvement is reducing the noise in the proximity sensor, which was reflected in user feedback that the height of the device was difficult to control using the proximity sensor. If we had a larger budget and more time, we would improve the robustness of our electrical subsystem by purchasing a higher quality proximity sensor and more rigorously testing the P-controller that translates the proximity sensor input into the height of the device. This improvement would also enhance the interactivity of our prototype by increasing the accuracy of the device's response to the user's input and creating a "smoother" overall operating experience.

User Engagement
Sensor.IO behaves as a combined tactile/technological device that strives to alter external surrounding environments. The main function of the design is to evoke engagement through light projections through a textile. While the device acts to alter the surrounding atmosphere, Sensor.IO can also be viewed as a tactile experience. The first layer of engagement is the control box. From testing, we have found users are generally intrigued by the color sensing and changing abilities, as well as the proximity sensor manipulating the fabric. The second layer focuses on tactile interactions with the outer and inner textiles, while the last layer includes interacting with the projections, patterns, and colors produced by our device. In fact, after posting images on social media, friends asked the team if they were able to get a chance to interact with Sensor.IO. Due to COVID19, we were unable to meet with our representative user in person and she felt that she would not be able to interact with it for more than 15 minutes. With other users having longer interaction times, we predict our representative user may find the device more engaging if she were able to interact with it in person. While we met our interaction requirement on average, there is still room for improvement. The light output and projections are a large part of the user experience, for users that choose to interact with that feature, more lights at the top of the spinning structure could improve the projections as well as overall textile illumination. With a larger budget and more time, the control box could be made wireless to allow the user to operate the device from farther away. Our representative user and a few spectators at the Design Expo expressed that having a wireless control box would make the device more accessible and improve user experience.

Manufacturing
The mechanical and electrical components of the project were acquired through a variety of ways—purchasing components like the hooks and motor from suppliers or 3D printing custom designed components like the concentric shafts and control box. Multiple parts that were 3D printed are better suited for other manufacturing processes. For example, the sliding tubes

covering the linear actuator require a slip fit of .002”. Large gaps were created due to 3D printing tolerances. These gaps resulted in slop and wobble that degraded device performance. In a non-COVID semester, the team would likely be more comfortable machining these parts out of aluminum or PVC pipe. The addition of stronger materials would also lead to improved device durability. One key aspect our design did not consider was design for manufacturability. This flaw manifested in our assembly where the device had to be assembled in one specific way. Later when the electronics needed to be accessed or a motor inspected, the entire device had to be disassembled. The team recognizes that threading many of our components or using clip nuts would make several assembly procedures easier and more efficient.

Safety

Another area of improvement identified was safety, as the team did not have time to develop the safety labels required. Additionally, failure to verify all of our durability requirements poses a safety risk. To resolve these issues,manufacturing processes with tighter tolerances such as milling or turning would be used, and labels would be developed.

Conclusion

Sensor.IO began as a self-proposed student project with an unbound problem space. By researching current products, we were able to get a baseline for creative technologies aimed at accessibility. With a newfound understanding, the problem led itself to be defined as an input/output device. We successfully modeled a solution with the aid of engineering analysis. Soon after, Sensor.IO began to physically take shape. As a tactile experience, the device features a variety of surface textures that react to interactions differently. Various surfaces can be explored by the user, as well as manipulated from afar. The control box features an ultrasonic sensor that controls the height of the device as the user brings their hand or other object closer or farther away. The color sensor and knobs that control rotary and linear motion achieve the same purpose of giving the user autonomy over the experience. Surfaces can be manipulated from farther away with the control box or directly by pulling and stretching the knits by hand, which subsequently alter the surrounding space due to changing light interactions. These spaces aren’t defined by the device itself, but rather become applicable through its portability. The user defines all facets of the experience like the duration, intensity, and location. The tabletop device enables users to alter the environment around them in a large scale-way through a variety of means, as well as define the emotional atmospheres around them.

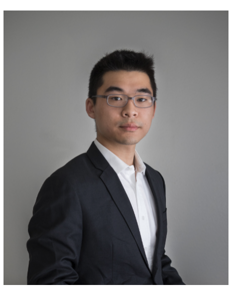
The goal of our team was to blend the needs of an engineering project with the needs of an artistic experience through an inclusive lens. The structured engineering design process helped guide us to an optimal solution. Although not all requirements were met at the end of the semester, we believe Sensor.IO was a success. Go Blue! M

Authors

Nadya Barghouty is a senior studying Mechanical Engineering with a Program in Socially Engaged Design from Rochester Hills, Michigan. The mechanical engineering department lacks forums for human conscious design, so Nadya looked towards Taubman and ME450 to learn more. After graduating in May 2021, Nadya will be moving to Seattle to work as a Program Manager at Microsoft.

Claire Huang is a senior from St. Louis, Missouri, studying Mechanical Engineering with a minor in Energy Science and Policy. She chose this project to learn more about the intersection of mechanical engineering and inclusive, accessible design. Claire has a passion for sustainable energy technology and policy and will be pursuing a career in clean energy consulting at Guidehouse in San Francisco.

Leandro Martinez is a senior studying Mechanical Engineering with a passion for aviation, and is from Chicago, Illinois. Leandro has been exposed to various facets of inclusive design in his internships, as well as in volunteer work. He chose this project to get more technical experience with inclusive design. After graduation he will be moving to Florida to work at SpaceX as an Integration Engineer.



Nicholas Chan is a senior studying Mechanical Engineering from Hong Kong. Nicholas attended UC Davis for two years before transferring to the University of Michigan, where he developed an interest in electric vehicles and biomedical engineering. After graduation in May 2021, he will be completing an internship in Chicago before returning to the university for a graduate degree in mechanical engineering.

Acknowledgements

Sensor.IO was made possible with the support of students, faculty, and community members all across Ann Arbor. Without ME machine shop staff like Charlie and Jon, our device would not have been able to be physically prototyped. Similarly, when we had 3D printing trouble two nights before the Design Expo, friends like Dan Rubio graciously printed parts for us. In the concept generation phase, we received critical guidance from Professor Daly. With her advice, we were able to move into the concept selection phase with confidence. We encountered an issue with our potentiometers and reached out to Professor Ganago. Professor Ganago connected us with the EECS lab technician Rob who gave us potentiometers to use the day before the design expo. In addition to the engineering community, we received a lot of aid from the Taubman College of Architecture. Sean Alqhuist challenged our perceptions of disability and pushed us to design with intention. He met with us frequently and worked hard to make sure we could have a meaningful experience. Taubman senior Pilar O'Hara was also a large part of the team. She worked tirelessly with us to create the narrative of the project, as well as develop the textiles. Claire Moore always had something encouraging to say and tried her best to meet with us despite her busy schedule. Jane Smith, our collaborator at the Ann Arbor Center for Independent Living, worked with us throughout the whole process and had invaluable contributions to the mechanical and textile design. We would also like to thank Heather Cooper for her dedication to the course and assistance in creating this self-proposed ME450 project. Lastly, we thank our section leader Professor Saitou for his patience and guidance throughout this term.

References

[1] Marti, P., Pollini, A., Rullo, A., Giusti, L., & Grönvall, E. (2009). Creative Interactive Play for Disabled Children. *IDC '09: Proceedings of the 8th International Conference on Interaction Design and Children,* 313-316. doi:10.1145/1551788.1551871

[2] Michalowski, M. (2011, December 13). My Keepon on the CNET Crave Podcast [Video file]. Retrieved February 8, 2021, from https://www.youtube.com/watch?v=NiZ_gjePVDU

[4] Xbox Adaptive Controller. (n.d.). Retrieved February 8, 2021, from https://www.xbox.com/en-US/accessories/controllers/xbox-adaptive-controller

[3] Swingler, T. (2013, December 12). Soundbeam, what is it? [Video file]. Retrieved February 8, 2021, from https://www.youtube.com/watch?v=AoqzhLbdo9Q

[5] SOUNDBEAM PRICE LIST. (2016). Retrieved February 8, 2021, from https://www.soundbeam.co.uk/new-page-3

[6] International Standards Organization. (2002). ISO14738 Safety of machinery - Anthropometric requirements for the design of workstations at machinery. Retrieved from https://bsol-bsigroup-com.proxy.lib.umich.edu/Bibliographic/BibliographicInfoData/000000000030192261

[7] ASTM International. (2017). F963-17 Standard Consumer Safety Specification for Toy Safety. Retrieved from https://doi-org.proxy.lib.umich.edu/10.1520/F0963-17

[8] Claire Moore, interview by authors, Ann Arbor, Jan 27, 2021

[9] Jane Smith, interview by authors, Ann Arbor, Feb 5, 2021.

[10] American Academy of Audiology. (2010). Levels of Noise in decibels (dB). Retrieved from https://audiology-web.s3.amazonaws.com/migrated/NoiseChart_Poster-%208.5x11.pdf_5399b289427535.32730330.pdf

[11] Americans with Disabilities Act. (2010). ADA Best Practices Tool Kit for State and Local Governments, Appendices 1 and 2. Retrieved from https://www.ada.gov/pcatoolkit/introapp1and2.htm

[12] Sean Ahlquist, interview by authors, Ann Arbor, Feb 18, 2021

[13] Large Sized B52 Giant Venus Flytrap. Amazon. Retrieved from https://www.amazon.com/Medium-Sized-Giant-Venus-Flytrap/dp/B00Q1UH0UG

[14] Mimosa Pudica Shameplant, Tenor. Retrieved from https://tenor.com/view/mimosa-pudica-shameplant-touch-plant-gif-17907196

[15] Pill Bug, Bugs and Insects, Animal Bugs, Pinterest. Retrieved from https://www.pinterest.com/pin/104497653824252484/

[16] Giant Ant Farm, Science Toy Store. Retrieved from http://www.sciencetoystore.com/contents/en-us/p603_Giant_Ant_Farm.html

[17] Hexbug Nano, Desert Cart. Retrieved from https://faroe.desertcart.com/products/1416313-hexbug-nano-random-color

[18] America Etch A Sketch Print, GV ART. Retrieved from https://gvartwork.com/products/american-etch-a-sketch-print

[19] Sean Ahlquist, interview by authors, Ann Arbor, Feb 24, 2021

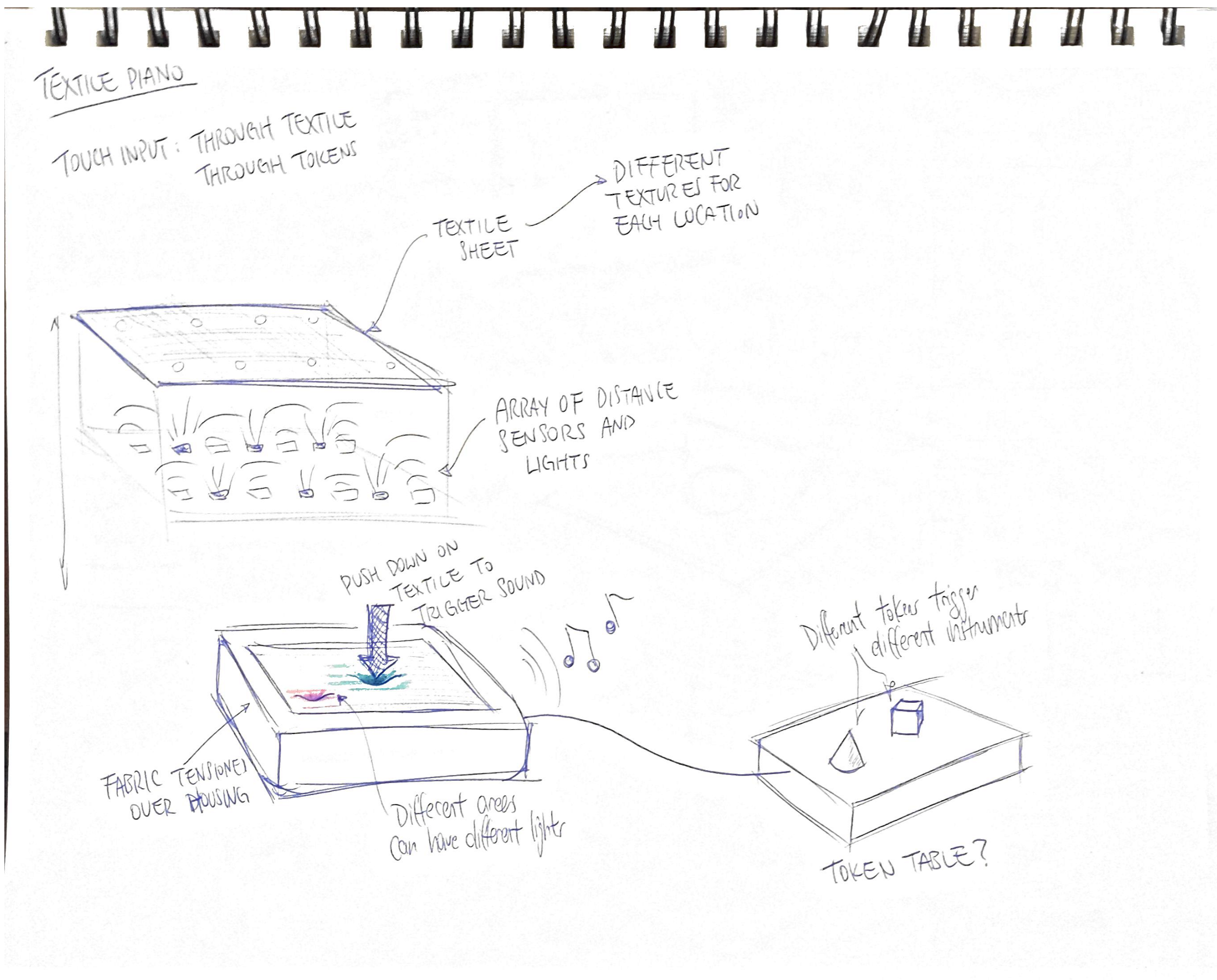
[20] Pietroni, D. G. (2019, October 12). David Zwirner will open New Yayoi Kusama 'Infinity Mirror room' in New York as it looks to have 100,000 visitors. Retrieved February 28, 2021, from https://www.art-insider.com/david-zwirner-will-open-new-yayoi-kusama-infinity-mirror-room-in-new-york-as-it-looks-to-have-100000-visitors/1147

[21] Jane Smith, interview by authors, Ann Arbor, Feb 19, 2021

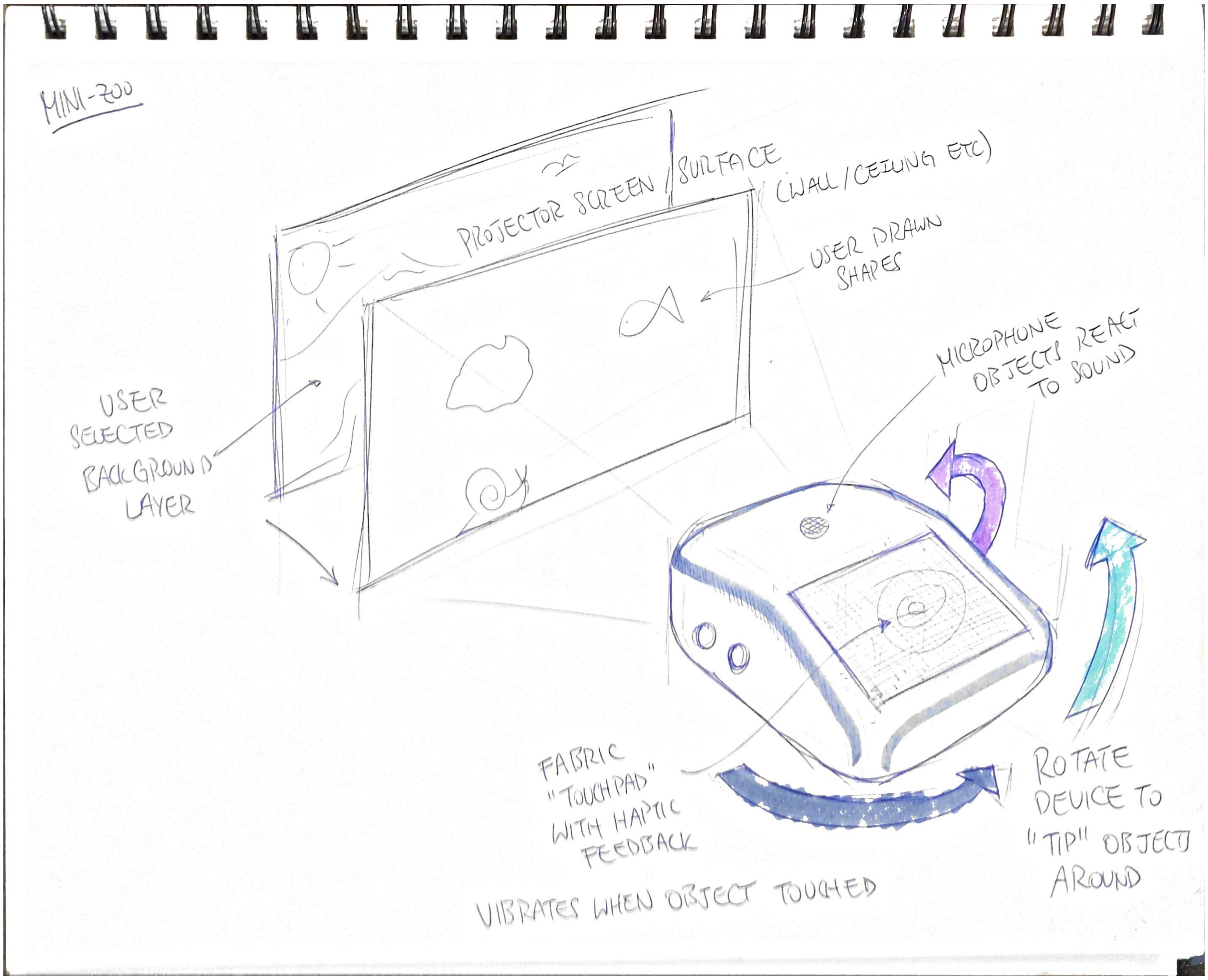
[22] Budynas, R.G., Nisbett, J.K., 2011, "Screws, Fasteners, and the Design of Nonpermanent Joints," Shigley's Mechanical Engineering Design., 9th ed., McGraw-Hill, NY, 415-422.

Appendix A: Additional Preliminary Concepts

Textile Piano

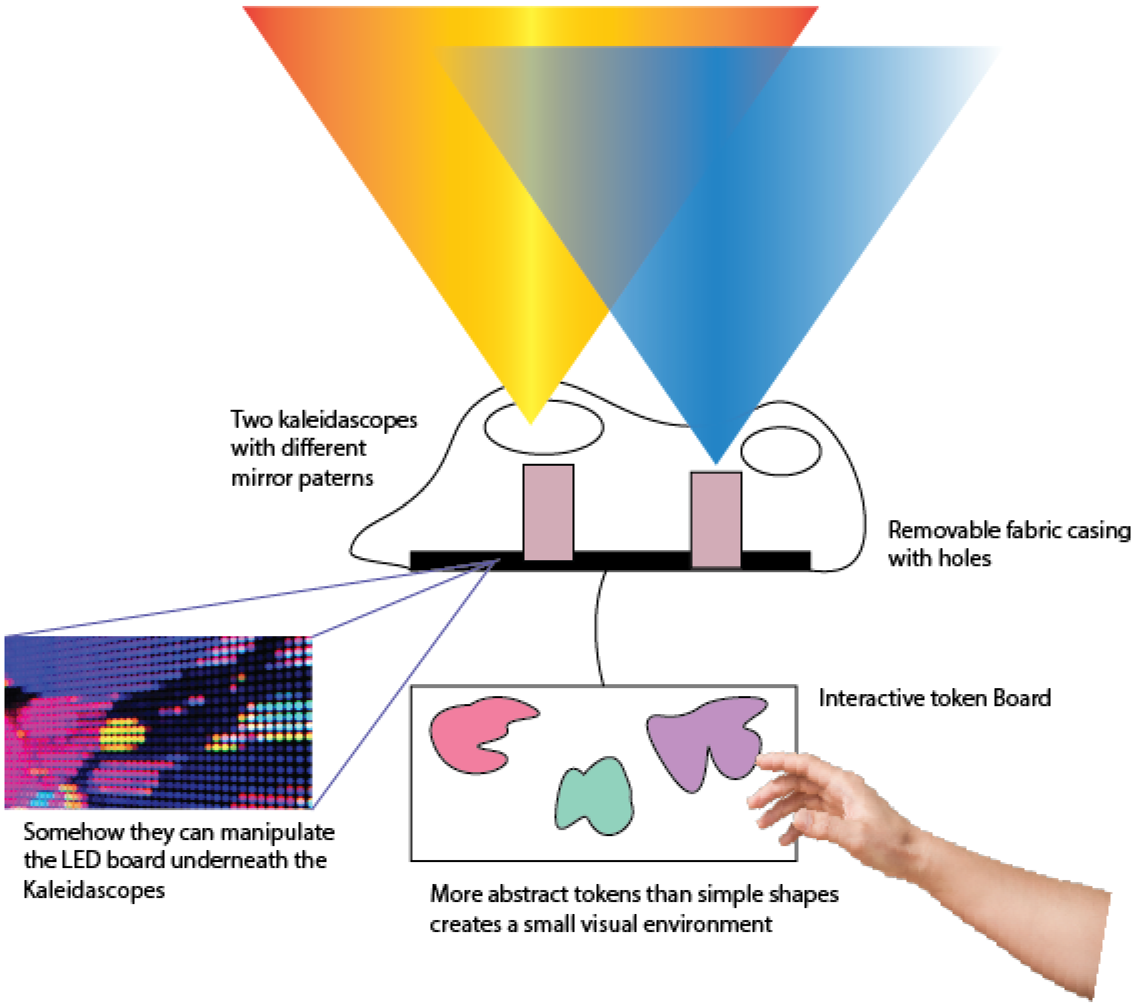


Mini Zoo

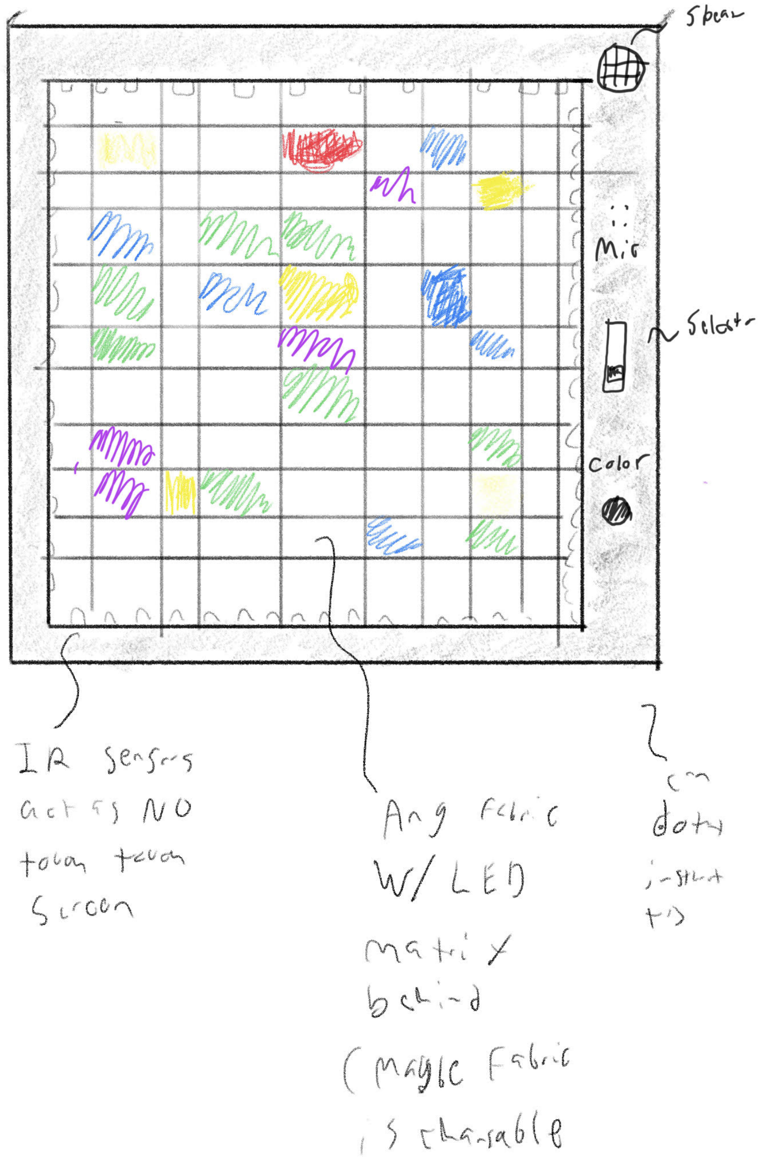


MINI-ZOO
PROJECTOR SCREEN / SURFACE
(WALL / CEILING ETC)
USER DRAWN SHAPES
USER SELECTED BACKGROUND LAYER
MICROPHONE OBJECTS REACT TO SOUND
FABRIC "TOUCHPAD" WITH HAPTIC FEEDBACK
ROTATE DEVICE TO "TIP" OBJECTS AROUND
VIBRATES WHEN OBJECT TOUCHED

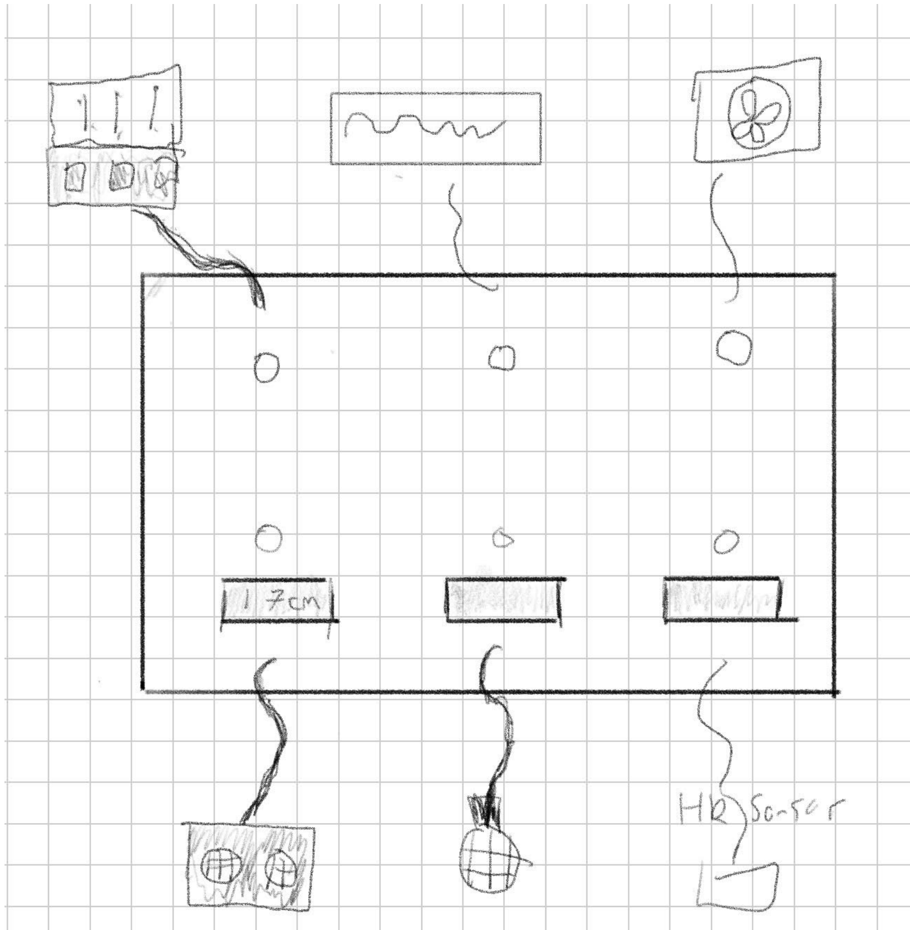
Kaleidoscopic Visions



3D Touch Screen



Switchboard



Appendix B: Lift Stage Torque Calculations

Rack and Pinion

We assumed a gear pitch for the pinion to be 10mm, as this would be near the practical limits of how small of a pinion we could choose. Based on this radius, we can simply calculated the required torque using the following equation:

$$T = r \times F = 0.01m \times 160N = 1.6\,Nm \quad \text{(B.1)}$$

Crank and Slider

For the crank to achieve the required extension of 130mm, the crank itself will also need to be at least 65mm. At the point of maximum for needed, the crank will be at an angle of 12° with respect to the slider. We can use a similar equation to B.1 to calculate the required torque.

$$T = \frac{r \times F}{\cos\theta} = \frac{0.065m \times 160N}{\cos(12^o)} = 11.0\,Nm \quad \text{(B.2)}$$

Lead Screw

For the lead screw, we used the raising torque equation from Shigley's Mechanical Design [22]:

$$T_R = \frac{F d_m}{2}\left(\frac{l + \pi\mu d_m \sec(\alpha)}{\pi d_m - \mu l \sec(\alpha)}\right) \quad \text{(B.2)}$$

In this equation, $F$is the vertical load, d_m is the mean diameter of the screw, l is the screw lead, μ is the friction coefficient between the nut and the screw, and α is the thread angle of the screw. The following values were used for the torque calculation.

Table B.1: Parameters and their corresponding values for the lead screw calculation.

Parameter	Value
F	160 N
d_m	8 mm
l	8mm
μ	0.23
α	29°

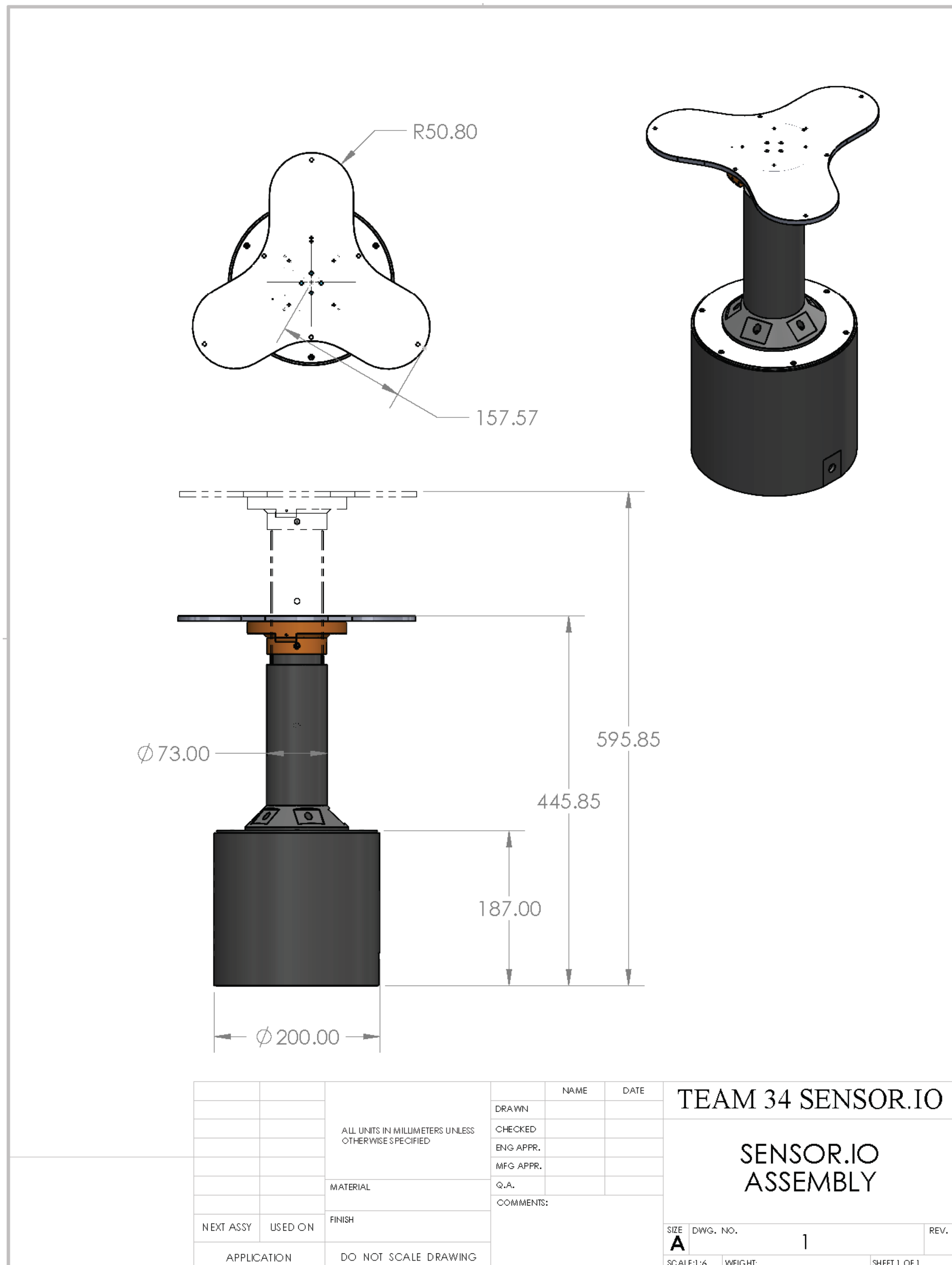
The screw parameters are chosen from a standard T8x8 lead screw, as these are standard parts and readily available. The friction coefficient was adapted from Shigley [22] and represents the friction between a steel screw and a brass nut. The resulting torque is:

$$T_R = 0.38\,Nm \quad \text{(B.2)}$$

Appendix C: Full FMEA Analysis

Component name	Failure mode	Failure cause	Severity	Severity reasoning	Occurrence	Occurrence Reasoning	Methods for Avoidance
Linear actuator motor	Overheating	Stalling	3	An overheated motor could cause plastic to melt	1	Linear actuator is well-contained and not in a situation where it would easily stall	Programmable stops; internally the screw can only advance so far
Spin motor	Overheating	Stalling	3	An overheated motor could cause plastic casing to melt, also is relatively close to the surface and could cause burns	3	The spin motor is meant to hold pieces of fabric in tension and would theoretically need to stall in order to do this	Programmable stops; mechanical hardstops; limit switches
Inner structural tube	Fracture at pin point to linear actuator or to motor mount	Too much torque	4	The structural tube distributes a lot of the load and upon failure would transfer load to the linear actuator in an unintentional way	2		The team considered stronger tube materials, but were unable to implement due to COVID limitations
Top rotating component	Fracture at interface with bearing	Too much torque	4	Failure of the top flat component could result in an injury to the face. This is because the textile would pull down on the fractured piece and be launched into the user	1	The amount of torque necessary to break the aluminum is very large and would not occur unless user is purposefully attempting to break the top, even then failure would occur at the 3D printed part	Changing the original material of acrylic to 0.25" thick aluminum to mitigate any risk of cracking
Acrylic top component fasteners	Rotational self-loosening	Shock/ vibrations	2	When screws become loose the top part may fall off or be more likely to crack	1	There won't be too much excessive shock or vibration at the top part of our system to encourage rotational self loosening	We plan to have enough screws, where one loose screw will not lead to catastrophic failure, also screws can be secured with poly lock nuts

Appendix D: Full Assembly Drawing

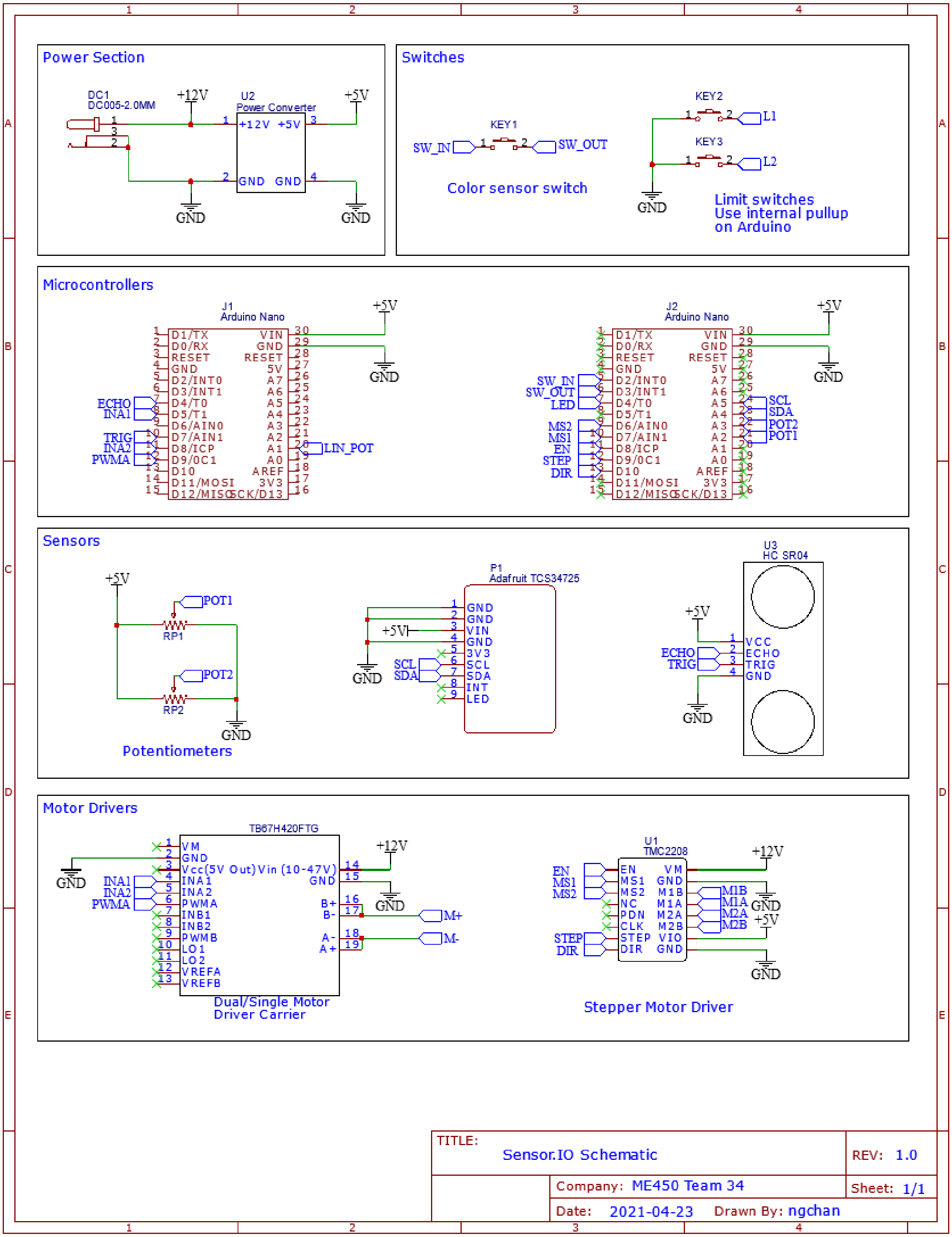


Appendix E: Bill Of Materials

Table E.1: Working bill of materials with purchased and manufactured components

Sensor.IO Bill Of Materials					
Part Number	**Part Name**	**Model**	**Quantity**	**Supplier/ Method**	**Cost**
001	Aluminum Top Spinner	--	1	Water Jet	
002	5/8" Hooks	9491T11	12	McMasterCarr	
003	Thrust Bearing	6031K16	1	McMasterCarr	$2.59
004	Motor flange	UXCell 8mm	1	Amazon	$9.99
005	Motor Stopper	--	1	3D Print	
006	Motor Mount	--	1	3D Print	
007	Stepper Motor	Nema 17	1	Amazon	$44.26
008	Inner Tube	--	1	3D Print	
009	Outer Tube	--	1	3D Print	
010	Top Plate (Delrin)	--	1	Laser Cut	
011	Linear actuator	LCT6P-12V-05	1	Pololu	$129.95
012	Base Cover	--	1	3D Print	
013	Pillow Block	--	1	3D Print	
014	Bottom Plate (Acrylic)	--	1	Laser Cut	
015	Feet	--	4	450 Shop	
016	Electronics sled (Acrylic)	--	1	Laser Cut	
017	Control Box top	--	1	3D Print	
018	Control Box Bottom	--	1	3D Print	
019	Color Sensor	TCS34725	1	Adafruit	$7.95
020	Limit Switch	URBEST AC250V	3	Amazon	$7.41
021	Proximity Sensor	HC-SR04	1	Adafruit	$3.95
022	Potentiometer	Adafruit 562	2	Adafruit	$4.00
023	Arduino Micro	ATmega328P	2	Amazon	$14.83
024	Buck converter (12V-5V)	BANKEE 12-5V	1	Amazon	$9.49
025	Linear Actuator Driver	TB67H420FTG	1	Pololu	$9.95
026	Stepper Driver	TMC2208	1	Amazon	$7.99
027	DC Power supply (12V)	BIZNET HTY-120100000	1	Amazon	$20.95
028	Power Jacks	DC-099	1	Amazon	$7.99
029	Power Switch	--	1	Home Depot	$7.39
030	LED Pixels	Adafrit4544	5	Adafruit	$31.50
031	LED Cover	--	1	3D Print	
032	Wiring Harness	--	1	Soldered	
033	Large Knit	--	1	Taubman	
034	Tube Knit	--	1	Taubman	
Fasteners					
035	4-40 1"	--	8	450 Shop	--
036	4-40 Nut	--	20	450 Shop	--
037	4-40 .5"	--	14	450 Shop	--
038	10-32 1"	--	16	450 Shop	--
039	10-32 nut	--	4	450 Shop	--
040	.25" Diameter pin 2" Length	91595A154	2	McMaster	$5.00
TOTAL			**120**		**$325.19**
Note: Cost does not include Tax and shipping for all components, Total Amount spent with standard shipping and tax is $395.51					

Appendix F: Electronics Schematic



Appendix G: Arduino 1 Code

```
/*
   Sensor.IO Main Code
*/
#include <HCSR04.h>

#define BRIGHTNESS_POT_PIN A2
#define POSITION_POT_PIN   A3

#define TRIG 7
#define ECHO 4

HCSR04 hc(TRIG,ECHO);

// Ultrasonic sensor variables
float distance;

void setup() {
  Serial.begin(115200);                   // Begin serial COM port
  linear_actuator_init();                 // Initialize linear actuator
}

void loop() {
  distance = hc.dist();                   // Read ultrasonic sensor
  linear_actuator_update(distance);       // Move linear actuator
}

//Pins for the linear actuator
#define INA1    5
#define INA2    8
#define SPEED   6
#define LINPOT A1

// Potentiometer conversion constants
const float minMotorPosition = 27.0;    //
const float maxMotorPosition = 884.0;   // Bits (potentiometer's scale)
const float minProxRange = 5.0;         // cm
const float maxProxRange = 26.0;        //

// Location tracking variables
float desiredPosition  = 0; // [encoder counts] desired motor position
float motorPosition = 0;

float positionError = 0;
float integralError = 0;
float motorSpeed = 0;
float P = 14;
float I = 0;

/*
 * Initialization function: Sets INA1, INA2, SPEED as outputs
 * Sets potentiometer pin as input
 */
```

```
void linear_actuator_init() {
   pinMode(INA1,  OUTPUT);
   pinMode(INA2,  OUTPUT);
   pinMode(SPEED, OUTPUT);
   pinMode(LINPOT,INPUT);
}

/*
 * Update function for linear actuator. Runs a P controller
 */
void linear_actuator_update(float distance){
  desiredPosition = distance;                                  // Set desired
position
  motorPosition = ((analogRead(LINPOT)-27.0)/884.0)*26.0+5.0;   // Convert linear
potentiometer value to position
  positionError = motorPosition - desiredPosition;             // Calculate position
error
  integralError += positionError;                              // Accumulate error
  motorSpeed = P * positionError + I * integralError;          // Calculate output
speed signal with P gain

  if(distance > 31 || distance < 5){                           // Enforce
extension/retraction limits
    analogWrite(SPEED,0); // stop motor if out of range
  }
  else{
    if(abs(desiredPosition-motorPosition)<2)                   // Deadband for
position error
    {
      analogWrite(SPEED,0);
    }
    else if(desiredPosition-motorPosition > 0){                // For positive error,
move one way
      // move up
      digitalWrite(INA1,LOW);
      digitalWrite(INA2,HIGH);
      analogWrite(SPEED, abs(motorSpeed));
    }
    else if(desiredPosition-motorPosition < 0){                // For negative error,
move another way
      // move down
      digitalWrite(INA1,HIGH);
      digitalWrite(INA2,LOW);
      analogWrite(SPEED, abs(motorSpeed));
    }
  }
}
```

Appendix H: Arduino 2 Code

```
#include <Wire.h>
#include "Adafruit_TCS34725.h"
#include <Adafruit_NeoPixel.h>

#define USE_TIMER_1     true
#define USE_TIMER_2     false
#define USE_TIMER_3     false
#define USE_TIMER_4     false
#define USE_TIMER_5     false

#define DIR 10
#define STEP 9
#define EN   8
#define MS1  7
#define MS2  6

#define BUTTON_LOW 2
#define BUTTON_HIGH 3

#define BRIGHTNESS_POT A2
#define PIN 4
#define NUMPIXELS 5 // Popular NeoPixel ring size

float contrast = 1.6;

Adafruit_NeoPixel pixels(NUMPIXELS, PIN, NEO_GRB + NEO_KHZ800);
Adafruit_TCS34725 tcs = Adafruit_TCS34725(TCS34725_INTEGRATIONTIME_50MS,
TCS34725_GAIN_1X);

long desired_pos = 10200;

// Variables will change:
int buttonState;             // the current reading from the input pin
int lastButtonState = LOW;   // the previous reading from the input pin

// the following variables are unsigned longs because the time, measured in
// milliseconds, will quickly become a bigger number than can be stored in an int.
unsigned long lastDebounceTime = 0;  // the last time the output pin was toggled
unsigned long debounceDelay = 50;    // the debounce time; increase if the output
flickers

int group = 0;

#include "TimerInterrupt.h"

void setup() {
  // put your setup code here, to run once:
  pixels.begin(); // INITIALIZE NeoPixel strip object (REQUIRED)
  pinMode(BRIGHTNESS_POT, INPUT);
  pinMode(BUTTON_HIGH, INPUT_PULLUP);
  pinMode(BUTTON_LOW, OUTPUT);
  digitalWrite(BUTTON_LOW, LOW);

  pinMode(EN, OUTPUT);
  pinMode(MS1, OUTPUT);
  pinMode(MS2, OUTPUT);
  digitalWrite(EN, LOW);
  digitalWrite(MS1, LOW);
  digitalWrite(MS2, LOW);
  Serial.begin(115200);
```

```
  ITimer1.init();
  if (ITimer1.attachInterrupt(8000, TimerHandler0)) {
    Serial.println("Starting timer");
  }
  else
  {
    Serial.println("Timer can't start");
  }
  pinMode(BRIGHTNESS_POT, INPUT);
  pinMode(A3, INPUT);
  pinMode(DIR, OUTPUT);
  pinMode(STEP, OUTPUT);
  pinMode(13, OUTPUT);
  //desired_pos = 81600;
}

void loop() {
  int reading = digitalRead(BUTTON_HIGH);
  if (reading != lastButtonState) {
    // reset the debouncing timer
    lastDebounceTime = millis();
  }

  if ((millis() - lastDebounceTime) > debounceDelay) {
    if (reading != buttonState) {
      buttonState = reading;
      if (buttonState == HIGH) {
        uint16_t r, g, b, c, colorTemp, lux;
        tcs.getRawData(&r, &g, &b, &c);

        float max_val = 0;
        max_val = max(r, g);
        max_val = max(max_val, b);

        float red=r/max_val*255.0;
        float green=g/max_val*255.0;
        float blue=b/max_val*255.0;

        red = 255-(255-red)*contrast;
        green = 255-(255-green)*contrast;
        blue = 255-(255-blue)*contrast;
        if(group == 0)
        {
          pixels.setPixelColor(0, pixels.Color(green, red, blue));
          pixels.setPixelColor(2, pixels.Color(green, red, blue));
          pixels.setPixelColor(4, pixels.Color(green, red, blue));
          group = 1;
        }
        else if(group == 1)
        {
          pixels.setPixelColor(1, pixels.Color(green, red, blue));
          pixels.setPixelColor(3, pixels.Color(green, red, blue));
          group = 0;
        }
        Serial.print(red);
        Serial.print('\t');
        Serial.print(green);
        Serial.print('\t');
        Serial.println(blue);
        pixels.show();
      }
    }
```

```
  }
  lastButtonState = reading;
  pixels.setBrightness(map(analogRead(BRIGHTNESS_POT), 0, 1023, 10, 255));
  pixels.show();
  desired_pos = map(analogRead(A3), 0, 1023, 0, 40800);
}

void TimerHandler0()
{
  static long current_pos = 0;
  static int stat = LOW;
  stat = !stat;

  if(abs(desired_pos-current_pos) < 800)
  {
    return;
  }
  if(desired_pos-current_pos > 0)
  {
    digitalWrite(DIR, HIGH);
    digitalWrite(STEP, stat);
    current_pos++;
  }
  else
  {
    digitalWrite(DIR, LOW);
    digitalWrite(STEP, stat);
    current_pos--;
  }
}
```

Appendix I: Details from Standards Used

ASTM-F963-17

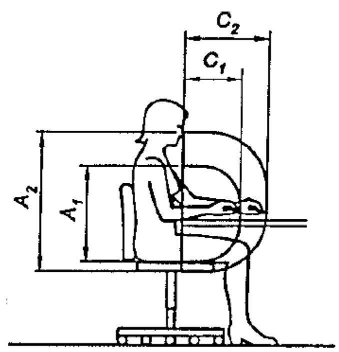
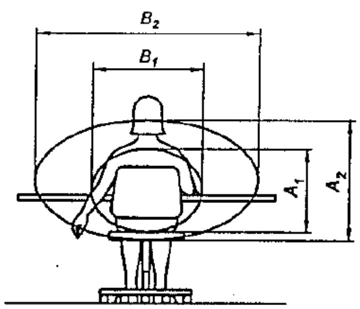
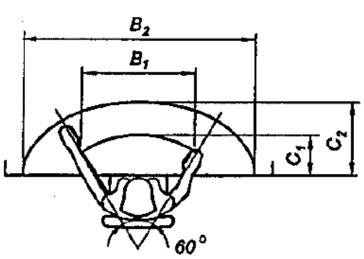
5.3.1 Required safety labeling shall consist of an alert symbol (an exclamation mark within an equilateral triangle), a signal word (CAUTION or WARNING), and text that describes the hazard that is present. Additionally, safety labeling may contain text about what to do or not to do to avoid injury (for example, "Keep out of baby's reach"). The signal word shall be in all upper case sans serif letters not less than 1/8 in. (3.2 mm) in height and shall be center or left aligned. The alert symbol shall directly precede the signal word. The height of the triangle shall be at least the same height as the signal word. The height of the exclamation point shall be at least half the height of the triangle and be centered vertically in the triangle. Text describing the hazard(s) and hazard avoidance behavior(s) shall appear in sans serif lettering and shall be either left aligned or center justified. Capital letters shall be no less than 1/16 in. (1.6 mm). Recognizing space constraints, it is recommended, that where possible, such text begin on the next line below the signal word, and that a new line be used for each subsequent statement or separate thought.

8.8 Torque Tests for Removal of Components—Any toy with a projection, part, or assembly that a child can grasp with at least the thumb and forefinger or the teeth shall be subject to this test. The amount of torque shall be determined from Table 5, according to the age group for which the toy is intended. The loading device used in the test shall be a torque gauge, torque wrench, or other appropriate device having an accuracy of ±0.2 in.·lbf (±0.02 N·m). A clamp capable of holding the test component firmly and transmitting a torsional force shall be used. The clamp is fastened to the test object or component with the toy fastened rigidly in any reasonable test position. The torque shall be applied evenly within a period of 5 s in a clockwise direction until either (1) a rotation of 180° from the original position has been attained, or (2) the required torque is exceeded. The maximum rotation or required torque shall be maintained for an additional 10 s. The torque shall then be removed and the test component permitted to return to a relaxed condition. This procedure shall then be repeated in a counterclockwise direction. Projections, parts, or assemblies that are mounted rigidly on an accessible rod or shaft designed to rotate along with the projections, parts, or assemblies shall be tested with the rod or shaft clamped to prevent rotation. If a component that is attached by a screw thread that has been assembled by the manufacturer, or that has been assembled to the manufacturer's instructions, becomes loosened during application of the required torque, continue to apply the torque until either (1) the required torque is exceeded, or (2) the part disassembles. The test should be terminated if it becomes obvious that the part under test will continue to rotate at less than the required torque limit and will not disassemble.

8.9 Tension Test for Removal of Components—Any projection of a toy that a child can grasp with at least the thumb and forefinger or the teeth shall be subjected to this test. The tension test shall be performed on the same components of the toy subjected to the torque test described in 8.8. The amount of force used shall be determined from Table 5, according to the age group for which the toy is intended. A clamp capable of applying a tension load to the test component shall be applied in a manner that will not affect the structural integrity of the attachment between the component and the toy. The loading device shall be a self-indicating gauge or other appropriate means having an accuracy of ±0.5 lb (±2 N). With the test sample fastened in a convenient position, an appropriate clamp shall be attached to the test object or component. The required tensile force shall be applied evenly, within a period of 5 s, parallel to the major axis of the test component, and maintained for an additional 10 s. The tension clamp shall then be removed, and a second clamp suitable for applying a tension load perpendicularly to the major axis of the test component shall be attached to the test object component. The required tensile force shall be applied evenly, within a period of 5 s, perpendicularly to the major axis of the test component and maintained for an additional 10 s.

6.3 Sitting - measurements

Table 4: Sitting, working area limits for arms

Posture	Notation	European Value (mm)[a]	Explanation of mesurements
	A_1	505	Preferred working area, height $A_1 = h_{13}$(P5) (from seat to shoulder height; centred around elbow height)
	A_2	730	Maximal working area, height $A_2 = h_{12}$(P5) + h_{17} (from 50 mm below seat to eye height)
	B_1	480	Preferred working area, width $B_1 = t_2$(P5) + a_2(P5), sides of area defined by the angle between the arms = 60°
	B_2	1170	Maximal working area, width B_2 = 2 t_3(P5) sin 60° + a_2 (P5) (provision for body movement can extend this zone, see annex B)
	C_1	170 290	Preferred working area, depth $C_1 = t_2$(P5) for work with unsupported arms = up to t_2(P5) + 120 mm for work with sup-ported arms
	C_2	415	Maximal working area, depth $C_2 = b_2$(P5) - 190 mm (fixed value, taking account of body movement) NOTE: Measurements are based on a horizon-tal seat surface
NOTE: For an explanation of notations see Annex A			
[a] Value of other regional areas of the world (for example East Asia, South East Asia and North America) will be incorporated when available (see clause 5)			

Supplemental Appendix

Engineering Standards

Engineering standards were very important to our project and design process. The premise that led to Sensor.IO was very broad and we lacked many of the requirements that were provided to many of the other teams as part of the problem statement. For example we questioned: 'how big it should be' and 'how strong it should be' and most importantly 'what IT should be. While Engineering Standards could not help us answer what our product should be, they did help us set measurable and verifiable standards for our project. The ASTM-F963-17 toy standards, particularly for tension and torque were chosen to help quantify how durable our device should be. The inclusive nature of our product meant that people of all ages should be able to use it, the most rigorous safety standards we expected to see were for childrens toys. Later these standards were used to size critical structural components. Another consideration was size, as discussed in the next section, engineering inclusivity was at the core of our project, and one of our stakeholders had mobility limitations, we also wanted to consider people who used a wheelchair. This meant that the inputs of our device should be close together and accessible sitting down. The team used the ISO 14738:2002(E) §6.3 standard to specify the working area that our controls had to be housed in. This influenced our choice to have the controls separate from the entire unit, so they could be moved to an acceptable work area. Later the standards were used again to recommend ways of testing those requirements.

Engineering Inclusivity

Our project revolved around engineering inclusivity. Jane Smith was not only a user for our device, but also a collaborator on the narrative and design. Jane Smith made critical design decisions with the group and contributed to narrowing down our design space. Our process could have been more inclusive if we involved Jane Smith more frequently. There were times where the team was bogged down by mechanical design and inadvertently did not check in with Jane Smith. We also made sure to discuss our identities with our stakeholders. In order to really know each other and have an inclusive working environment, we made sure to have discussions that highlighted individuality. Besides stakeholder interaction, the premise of our project was to design with inclusivity in mind first. We did this by creating a device that focuses on giving sensory experiences, rather than being an assistive tool to overcome the built environment. The team also studied disability theory and inclusivity principles to ensure we were approaching the project with the right mindset.

Environmental Context Assessment

Our project addresses the lack of attention to accessibility and disability in engineering design. While the prototype itself may not make significant progress towards an unmet and important social challenge, the way in which it was designed progresses society by centering accessibility and inclusivity in the design process. By working with Jane Smith, our representative user, and incorporating accessibility in our project from the start, our design process produced a final prototype that was made to be accessible to a wide range of users, including those with auditory sensitivities and mobility limitations.

The potential for our project to lead to undesirable environmental consequences in its lifecycle that overshadow the social benefits it provides is low. The environmental impacts of our design are minimal: beyond the environmental costs of manufacturing the materials and components necessary to construct the device, the device does not negatively impact the environment. The device uses outlet power, which only adds a small load to a building's total electricity consumption. Thus, the risk of adding a large enough electricity load to cause a significant amount of greenhouse gas emissions from energy generation is negligible. Overall, our project meets the first two necessary conditions to be considered a sustainable technology.

Social Context Assessment

In its current form, we do not believe this design meets the remaining three conditions for sustainability as outlined in the Social Context Assessment learning block. The first condition is whether the system is likely to be adopted and self sustaining in the market. We believe our design would not be self sustaining in the market because of its high cost. Material costs for the prototype alone are $325.19, and the acquisition costs for the consumer would be greater than this value once transport, inventory, and production costs are considered. Additionally, as the device is artistic/experiential in nature, the private benefit to a consumer may be difficult to quantify and consumers will likely find the costs of ownership to exceed the benefits.

As described above, the system is not likely to succeed in such a way that planetary or social systems will be worse off, as we believe that the system would not be self-sustaining in the market.

Finally, we believe the device is not resilient to disruptions in business as usual. As the device is a novelty item, demand for the device will likely be eliminated by disruptions such as natural disasters or economic downturn.

Ethical Decision Making

Engineering ethics are ingrained in every decision in the design process. Due to the nature of our project, we had to make sure our stakeholder was respected in situations she was not present in. In society, people with disabilities are often spoken for in a demeaning way. We used ethical tools like imagining ourselves as the stakeholder in order to better understand their needs. We also had to be honest with our architecture partners about technological limitations in the project. For example, rather than telling them we could do anything they wanted, we had to be honest in our personal ability and the nature of the technologies we are working with.