The Design and Optimization of a Lighted Kinetic Art Surface Display

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Table of Contents

Introduction

Mechanical engineering is an ever-changing and developing field of study, and in recent years a shift in ideology has occurred to coincide with recent improvements in technology. In both education and industry, the focus has shifted away from complex mechanisms towards a mechatronic approach to create desired motions and to control smart systems. Mechatronic principles combine many areas of expertise, most notably computer science, electrical engineering, and mechanical engineering, through the design of controllable, adaptable, and efficient systems. Similarly, the push towards mechatronics in mechanical engineering is accompanied by another shift towards more efficient and optimized designs and systems. However, this accompanying shift lags behind in engineering education, where the focus is mainly centered on the more traditional concepts that lay the groundwork for design and application. Optimization of engineering design and mechatronic systems will continue to grow in importance in the future as technology improves and systems are developed to handle more complex tasks. To highlight the shift in engineering thought and to emphasize the importance of other disciplines and optimization in design, the capstone team decided to create a mechatronic display to intrigue and inspire future mechanical engineering students.

Background

The team determined the need for a mechatronic display to succinctly combine mechatronic principles and design optimization in an educational setting to provide inspiration for the future of mechanical engineering. More specifically, the focus of the project was to create a mechatronic display that focused on minimizing manufacturing costs and time while also providing educational potential in an aesthetic and mystifying way. During background research, the team found two areas of kinetic art that the team believed to represent mechatronics and provide educational potential.

The first consists of suspended kinetic sculptures that move in pre-programmed patterns to create various surfaces, pictures, and waves. Two kinetic sculptures in particular inspired the initial design of the team's project: the sculpture developed for the Bavarian Motor Works (BMW) Museum in Munich and the Build UP LLC piece in Dubai. These kinetic sculptures, shown below in Figure 1, utilize actuatable suspended spheres to create shapes and motion ("Kinetic sculpture," 2018; *Kinetic sculpture timelapse*, 2015). The piece in Dubai additionally used LED spheres so that the suspended system could also create awe-inspiring light displays. These two systems use string-and-pulley systems to raise and lower the metal and colored spheres, respectively.

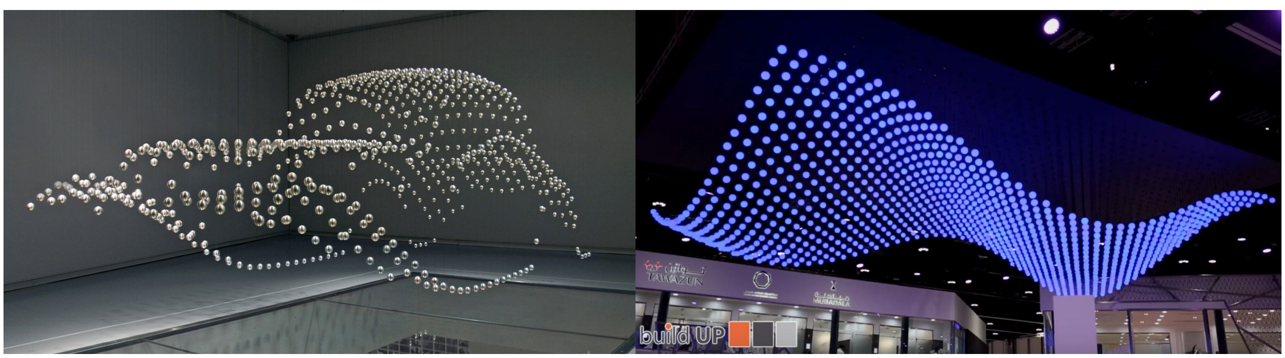

Figure 1. BMW Kinetic Sculpture (Left) and Build UP LLC Lighted Kinetic Sculpture (Right)

The other area of kinetic art researched was into interactive, programmable, and actuatable tables such as the inFORM table (shown in Figure 2 below) created at the Massachusetts Institute of Technology (MIT) and the shapeShift project created at Stanford. Unlike the suspended nature of the aforementioned kinetic sculptures, these tables actuate rod-like structures vertically to interact with their environment. The inFORM table uses a compact linear actuator coupled with a slide potentiometer for positional feedback to actuate each rod-like structure to create a digitally-configurable surface (Follmer, Leithinger, Olwal, Hogge, & Ishii, 2013). Stanford's shapeShift table, on the other hand, uses a screw drive (shown in Figure 2 below) to move each rod vertically (Siu, Gonzalez, Yuan, Ginsberg, & Follmer, 2018). These two products, as well as the kinetic art sculptures mentioned above, had unique design considerations, constraints, and limitations that the team believed were consistent with the aim of the project and upon which could be improved.

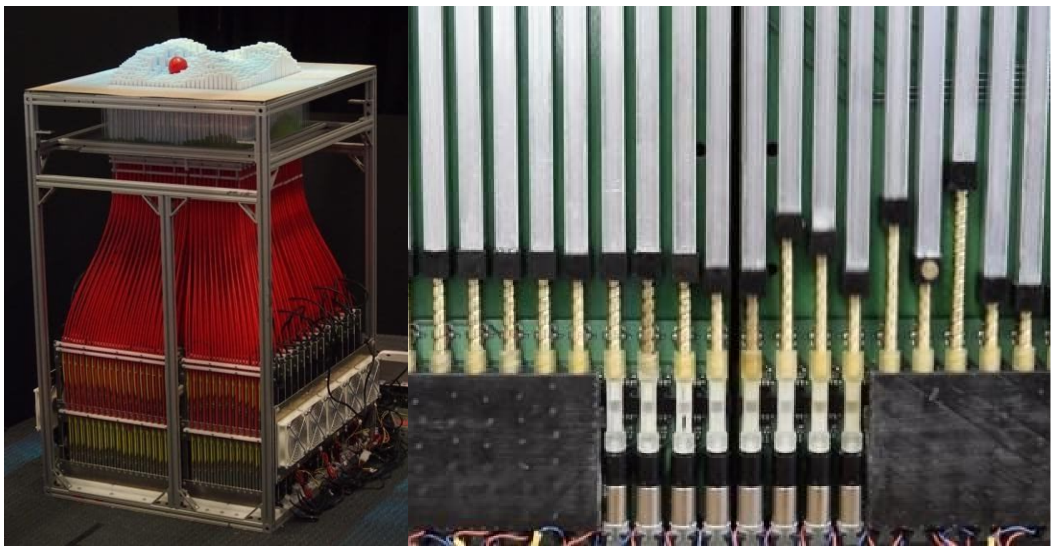

Figure 2. MIT inFORM table (left) and the actuating screw drive from Stanford's shapeShift table (right).

In terms of limitations, the string-and-pulley systems created by BMW and Build UP LLC are notably underconstrained. Each suspended sphere only has one point of contact at the ceiling, and so nothing prevents each sphere from swinging or becoming tangled due to interference from external factors. Additionally, the string-and-pulley actuation system can only actuate in one direction, as they rely on gravity to pull each sphere down. Over time, wear on the system and varying frictional effects will compromise the ability of the string-and-pulley actuation system to consistently move each sphere. The actuation systems of the inFORM table and the shapeShift project remove the reliance on gravity and result in a much more reliable final result. However, these actuation systems are more costly, require more space, are more difficult to assemble, and have a limited range of travel in comparison to the string-and-pulley system. The team used these constraints to create design goals and project objectives for the technical project.

Objectives and Timeline

Upon the conclusion of background research, the team had narrowed the focus of the project to a programmable kinetic art display that utilized similar components from the pieces of prior art while reducing their associated limitations and adapting the final product for use in an educational setting. The primary purpose of the project was to create a kinetic art sculpture that emphasized the importance of mechatronic design and optimization and could be installed in the Mechanical Engineering Building (MEC) to inspire future students. The team set a goal of creating and optimizing a modular, actuatable, and programmable kinetic structure using acrylic rods with programmable lights that could be reproduced at relatively low cost to create a captivating final display assembly. Other goals included creating infrastructure so that the final assembly could be used in education by allowing different functions and patterns to be programmed and updated over time, expanding production of the modular unit to create a larger programmable display, and ensuring project longevity of the mystifying display.

With these objectives in mind, the team determined a rough timeline for the entire project, with the overarching deadline of the end of the Fall 2019 semester to have the final assembly prototype complete. Below, in Figure 3, is the final timeline projection, organized in a Gantt chart. The original Gantt chart was updated several times throughout the course of the project (shown in Figure 1 in the Appendix), which converged to the final Gantt chart as project deadlines and tasks were revised. With such a short timetable, the focus of the project was further narrowed to mechanical design optimization, leaving electrical subsystem and programming to be completed as a tangential timeline to the main project. This can easily be seen in the final Gantt chart in Figure 3 by the duration of the electromechanical subsystem design task, which took place over the majority of the design and production timeline. However, this focus led to possible problems with the timing and testing of final components after final assembly when time would be short and possible bugs in the electrical subsystem and code would need solving.

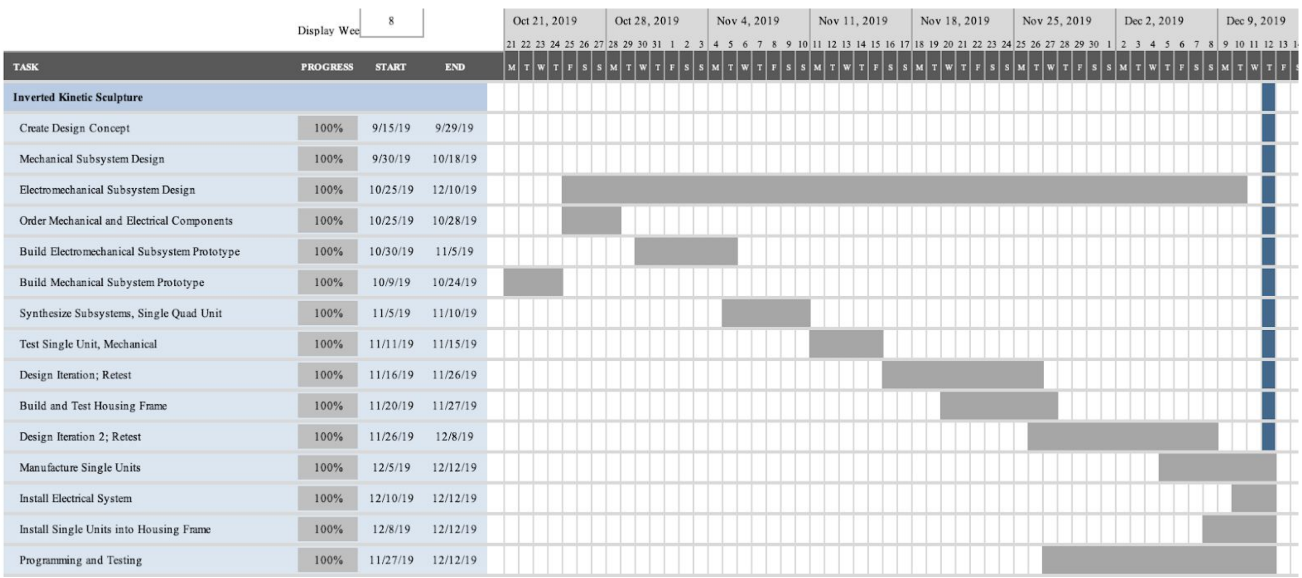

Figure 3. Final Gantt chart outlining project timetable. The blue column represents final project deadline. Note only weeks after 10/21 are shown.

Budgeting

For this project, the team's budget was constrained in two different ways. For one, each student in capstone is given the equivalent of around $175 to complete their project. Therefore, the team had $525 of total funding for completion of the project. Additionally, the team and advisor decided that for this project to be economically feasible and for future expansion to include more units, the cost per actuating rod must be under $20.00. The team and advisor also decided that the calculation of cost per actuating rod would be calculated excluding any costs relating to 3D-printed materials. This is an important fact as the most expensive component for the final assembly would be the amount of 3D printed material used. With these monetary constraints in mind, the team set to work.

A complete bill of materials is shown in Table 1 in the Appendix with a calculated cost per actuating rod. It should be noted that the project was over budget in both constraints. The final assembly created cost approximately $813.33, a total of $288.33 over budget. Additionally, the estimated final per unit cost of each actuating acrylic rod (therefore one-fourth the cost per absolute unit) was $20.21, which is a meager $0.21 over budget. However, this means that additional external funding would be required for future expansion of the project to include more lighted rods.

One major objective of the project was to optimize both manufacturing times and costs. The team did meet this objective despite finishing over budget; the final estimated cost per actuating acrylic unit was around 17.6 percent less than the initial prototype, as the cost fell from $24.54 to $20.21 per unit. To better illustrate this fact, a complete bill of materials for the first prototype is shown in Table 2 in the Appendix from which comparisons can be made. While the final project remained fully over budget, it is important that the team kept one of the main objectives in mind throughout the duration of the project.

Initial Design

After analyzing previous work, the team created a matrix containing various design options and evaluated each option on cost, complexity, and reliability. The design matrix, shown in Figure 4 below, was intended to help the team choose components that would allow the kinetic sculpture to best meet the goals of elegance, minimize expenses, and simplify assembly.

CATEGORY	TYPE	COST	COMPLEXITY	RELIABILITY
ACTUATOR	Servo	4	4	2
	Stepper	3	2	5
	Pneumatic	2	2	2
	Hydraulic	1	1	1
BODY MATERIAL	3D-printed	5	5	3
	Acrylic	3	4	4
BODY SHAPE	Telescoping	3	2	2
	Solid	4	4	5
	Flexible	2	3	1
LIGHT FEATURE	Acrylic tip (w/plastic body)	2	3	4
	Acrylic body w/LED at top	2	2	5
	Diffused cap	4	1	3
ACTUATION SYSTEM	Pulley	4	5	4
	Rack & Pinion	3	3	4
	Piston	1	3	4
	Screw	3	2	4
LINEAR CONSTRAINT	Rollers w/rubber	4	2	4
	Linear bearing	1	3	4
	Soft Material	5	5	2

Figure 4. Initial Design Matrix

The design matrix primarily addressed the display's structure, actuation, and constraints. The team chose to use a rigid acrylic rod as the structure because raising/lowering an acrylic rod instead of 3D-printing a structure would decrease per unit manufacturing time, and diffused light from an LED held at the top of the rod will create a unique visual effect. Although servo motors provide limited motion, they were chosen for actuation instead of stepper motors because of the low cost and simple control. However, since the servo motor only achieves 120-180 degrees of motion, the team planned to increase the range of motion using a gearbox to create a mechanical disadvantage. The MG996R Servo Motor was selected because of its low cost and robust metal gearing. Using the rack and pinion for linear actuation was simple to manufacture and implement in the framework of the design. It also gave us the ability to control both the raising and lowering of the acrylic rod, which provided an advantage over previous work that used ball and string system. In order to maintain the desired visual effect, the team planned to incorporate a stationary rack extended into the ceiling out of view (see Figure 5). The servo motor and gearbox attached to the pinion would move up and down, carrying the acrylic rod up and down the rack. Since stationary racks would be shared between multiple units, the moving system could be added to the next in a truly modular way. For the constraints, the team decided to plan on incorporating rollers with rubber to limit cost and prevent scratching the acrylic.

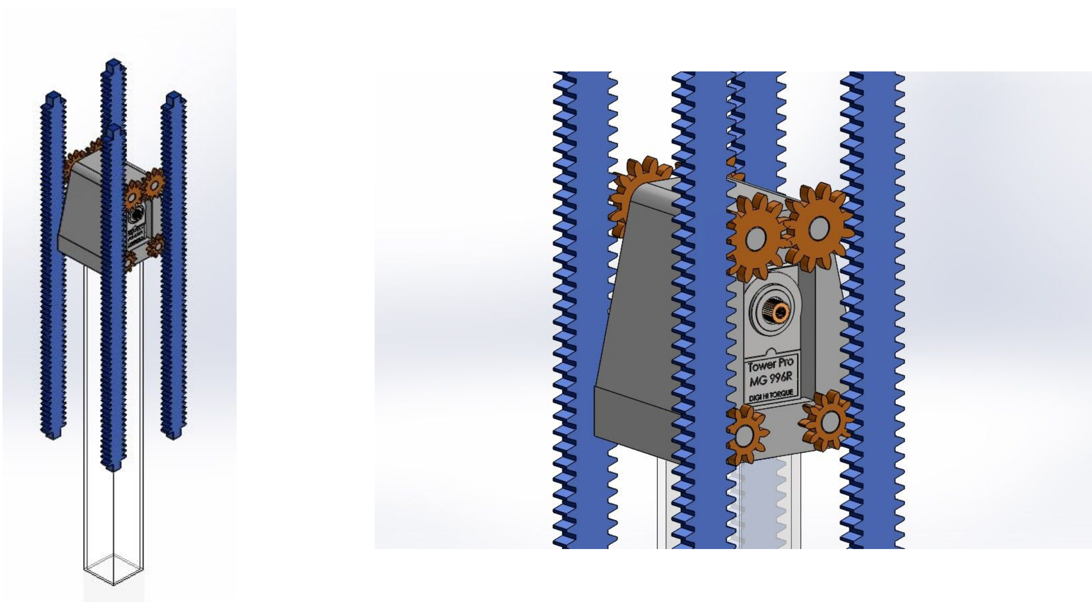

Figure 5. Early concept with fixed racks

Proceeding from the design matrix, the team created a basic model of the proposed unit system in SolidWorks and began work developing a complex gearbox shown in Figure 6 that would allow the servo motor and acrylic rod to move farther along the rack. The team prioritized linear travel at this stage of design because of the interesting visual effect it would create, and great effort was put into designing the gearbox as a result. The team decided to use a gear pitch of 20, based on the limitations of the 3D printer and laser cutter, and calculations were performed to determine the diameters of each gear and the overall gear ratio required to get the desired linear travel, as shown in Table 1. FEA analysis was also conducted on the gears, and the results justified creating a physical prototype to test.

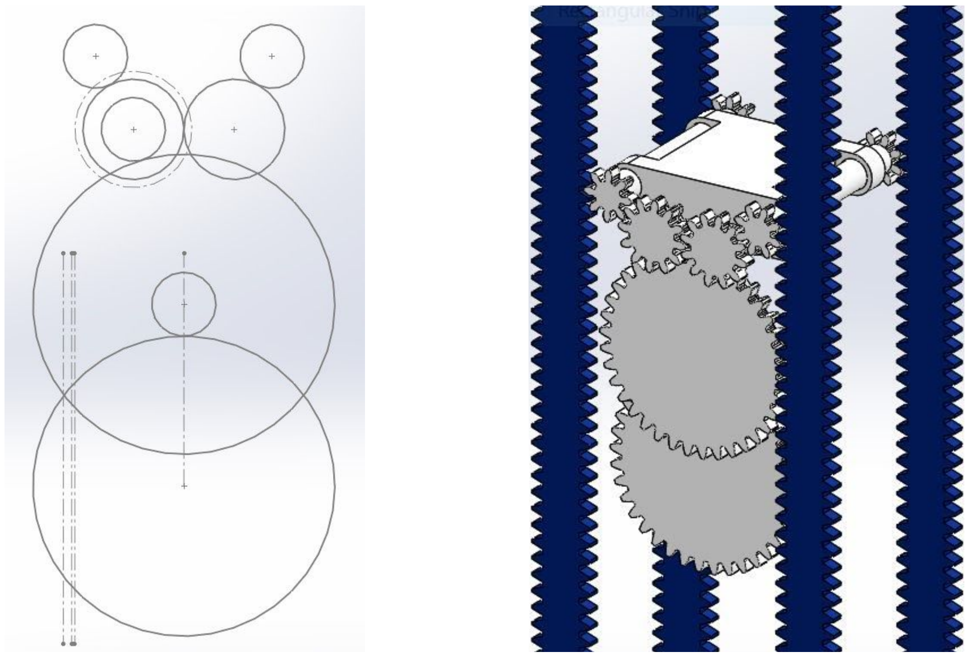

Figure 6. Compound gear concept with extended linear travel

Table 1. Drivetrain parameters and calculated values

Gear Pitch	20 teeth/in
Driving Gears	{37,37,12} teeth
Driven Gears	{8,8,8} teeth
Train Ratio	32.09
Linear Travel (120° servo input)	13.44 in
Torque at Input (for 0.5lbf load)	3.21 in-lbf

The simple model was then modified to incorporate the gearbox design, and the first gearbox prototype was 3D printed for testing. The first print was completely immobile. The gears were unable to turn because the spacing between gears and housing was too small, so layers of material from the 3D printer had attached, binding the surfaces together and making rotation impossible. The team developed a new design that increased spacing between gears and the housing, added a second point of contact on the gear shafts, and modified the position of the small gears so that they could fit between the racks in one unit of the design. A slot was also added in the housing to aid support material dissolution. The second iteration yielded a gearbox that turned, but with difficulty. The gears did not rotate smoothly as a result of improper spacing between gear teeth as well as binding with the housing at some points. Test prints like that in Figure 7 were made to determine proper shaft clearance and distance between gear teeth, and a third iteration was produced. The gearbox still did not spin well, and the motors would not have been able to turn the gears with so much binding between teeth and with housing.

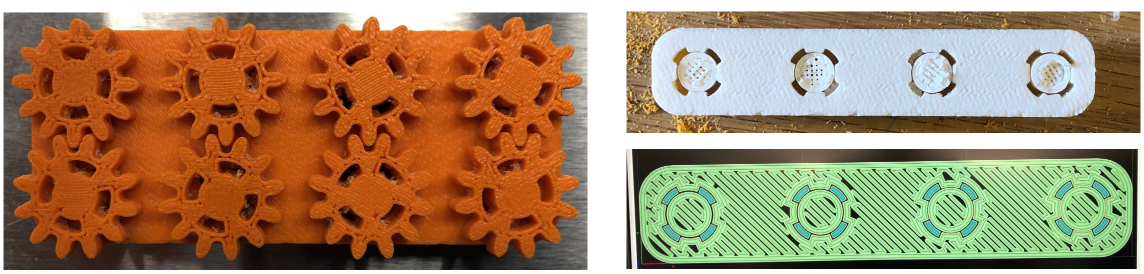

Figure 7. Testing 3D printed shaft and gear spacing clearances

The team decided that the gearbox idea needed to be changed in order to produce a large number of units that worked very well. However, a new model had to be developed that would retain the small unit size and distance between rods found in the initial design. After realizing that the unit could extend further vertically into the ceiling, the team decided to develop a design that incorporated four stacked servos. The stacked design, referred to as the "absolute unit," launched the team into the next phase of prototyping.

Prototyping

The Absolute[1] Unit

The first prototype of this design incorporated the concept of stacked servo motors, as shown in Figure 8. Even though the overall unit became larger with this design, the effective unit size decreased since four single-rod units were joined into an absolute unit. Spacing between the rods at the bottom of the sculpture was less than a quarter inch in this model. The absolute unit concept allowed the team to achieve the desired mystifying visual effect.

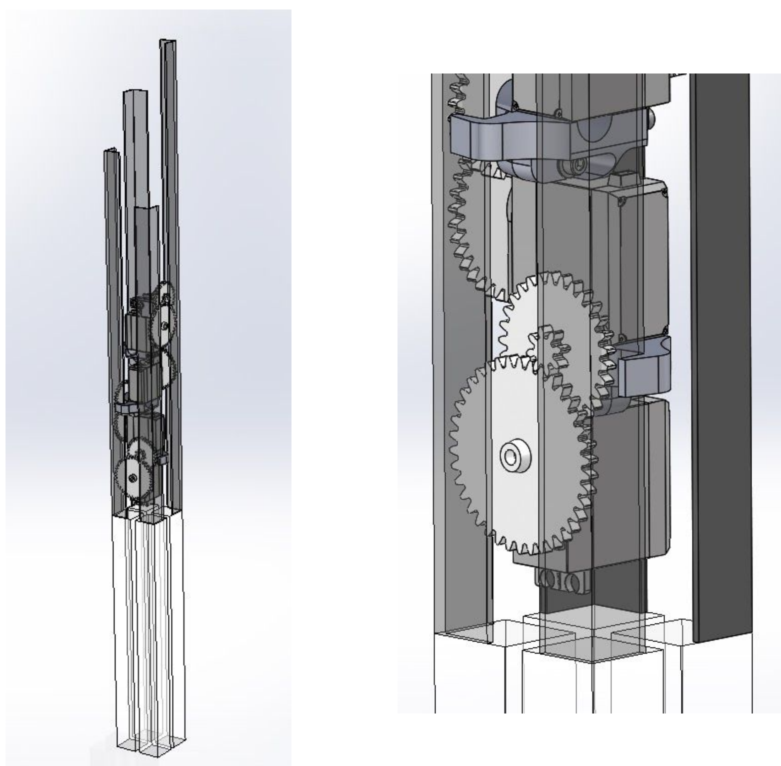

Figure 8. CAD model for initial prototype

In this prototype, the servo motors were used as structural components and were connected by smaller housing pieces that incorporated the gears and a linear guide. The design included a plan for slotted racks attached or cut into PVC L-channels that would be attached to the acrylic rods. By creating the rack using the CNC, the team would be able to produce enough racks for a large display, which would not be possible using the laser cutter to make acrylic racks. The gearbox was also simplified to include only three gears.

The team constructed the preliminary prototype in Figure 9 to test the slotted rack concept, gear ratio and travel, linear guides, and ability of the servo motor to actuate the acrylic rod. For this prototype, the gears and slotted rack were quickly fabricated using the laser cutter to prove the concept before attempting to cut the rack using a CNC machine or 3D print the gears.

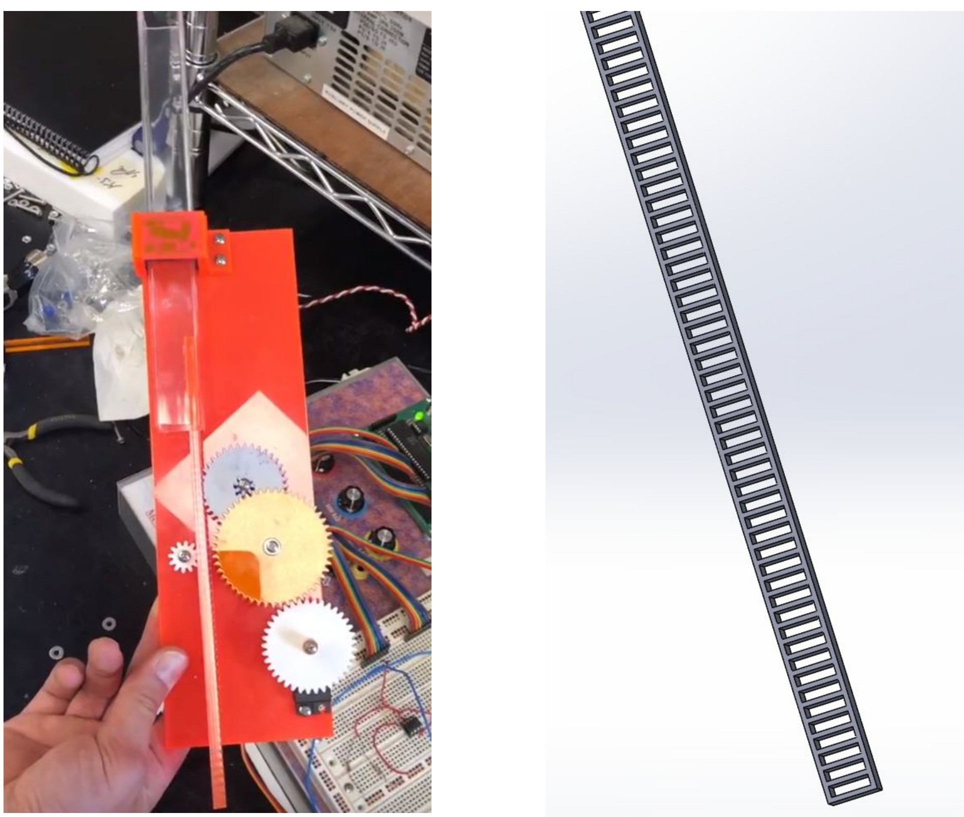

Figure 9. Testing rack design and gear ratios

The results of the tests showed that the gear ratio provided a good amount of linear travel, and the gear teeth meshed well with the slot rack. The team also gathered that felt worked well as a linear guide at the bottom of the rod, and the guide did not need to be very long to constrain the motion well. A free spinning gear was required to prevent the teeth on the actuating gears from pushing the rack away. With simple tests completed, the team proceeded to construct the prototype of the absolute unit. The team also designed a floor on which the bottom servo motor would sit as well as a bottom and top layer of linear guides. Felt was removed from the guides after proving that the acrylic guide did not scratch the rod.

Figure 10. First prototype unit

The absolute unit was able to successfully lift and lower the acrylic rods. However, the team identified many issues with the design. Overall, the unit failed to meet the larger goal of minimal manufacturing because it required a significant amount of time to assemble. This long assembly time was primarily a product of the many smaller housing components and the difficulty of wiring the LEDs. The other big issue was tolerance stackup from servo motor dimensions and 3D printing. The dimensions diverged from what we expected, and the team concluded that the servo motors should no longer be used as structural components for future models. The structure also appeared to be overconstrained, and the top ceiling layer was removed to allow the rods space to align themselves. The gearbox design, while improved from the more complex design, still experienced some binding and transmission problems. The team identified that the problems were likely a result of the cantilevered second gear piece. Finally, a smaller issue that limited functionality was incorrect sizing on the LED caps – rubbing between the caps hindered rod motion and suggested that a smaller cap would be advantageous for the next iteration.

Although there were issues, the team was able to confirm that the servo motors provide enough torque to lift the solid acrylic rods through the structure, and the visual effect achieved as a result of the acrylic and stacked servo motor design was beautiful. The solid acrylic rod diffused light very well, and the LEDs were easily controllable. Moving to the next iteration, the team focused on simplified the housing and gearbox further to address the major issues with the first absolute unit prototype.

The Absolute² Unit

The main goal for the second major prototype was to make a fully-functioning model. In order to achieve this, the team strove to create a very simple design, converging on the model shown in Figure 11. A key element of this simple design was a single housing into which servo motors could easily slide and snap into place. The lower guide was also incorporated into the single housing. The gearbox was reduced to a single gear with a pitch of 6 and a much larger radius of 1.25in. Because the gears were so large to achieve an acceptable travel distance, the units were set up in a parallelogram shape so that they could fit together and share the overhang space created by the larger gear. In this iteration, the team chose to CNC the rack profile and illuminated rod out of a solid piece of acrylic. A pitch of 6 was chosen so that the ShopBot CNC machine could effectively create the rack profile with larger bits. Three separate operations were used in an effort to make the process more efficient. On the first pass, an adaptive clearing operation with a ⅛" bit removed the bulk of the material. A second adaptive clearing pass with a 1/16" bit cut the rack profile. A final parallel toolpath operation with the 1/16" bit smoothed the vertical step artifacts created by the previous pass. Unfortunately, securing the raw material into the machine was cumbersome and time consuming. Also, the machine needed to be re-zeroed between the first and second passes since the ShopBot lacked an automatic tool changer. A smaller cap, which didn't interfere with other components, was designed to hold the LED module in place on top of the solid section of the acrylic rod. The linear guides extending from the housing were retained from the previous model.

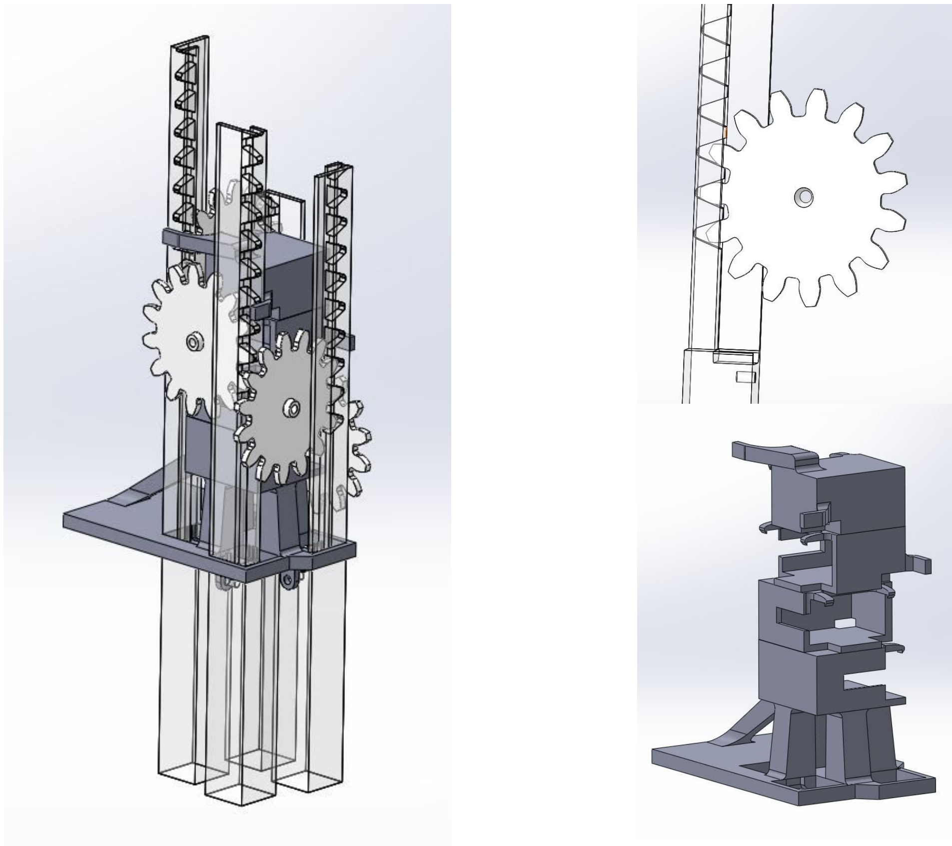

Figure 11. CAD models for Absolute² prototype

Overall, this second prototype was simple and effective. Assembly time was very short, a benefit largely attributable to the one-piece housing. Wiring was also much easier with improved access. The CNC rack was beautiful; however, the LED still could not be placed at the very top of the rod because light did not diffuse through the rack well. Therefore, the difficulty of using the CNC machine was not justified, especially because the team began to consider creating a smaller display. Because the actuating gear was so large in this model, the unit appeared large and lost the contained look of the previous prototype. Although the simple design was functional, the team decided to return to compound gearing in the next iteration to improve linear travel and unit aesthetics.

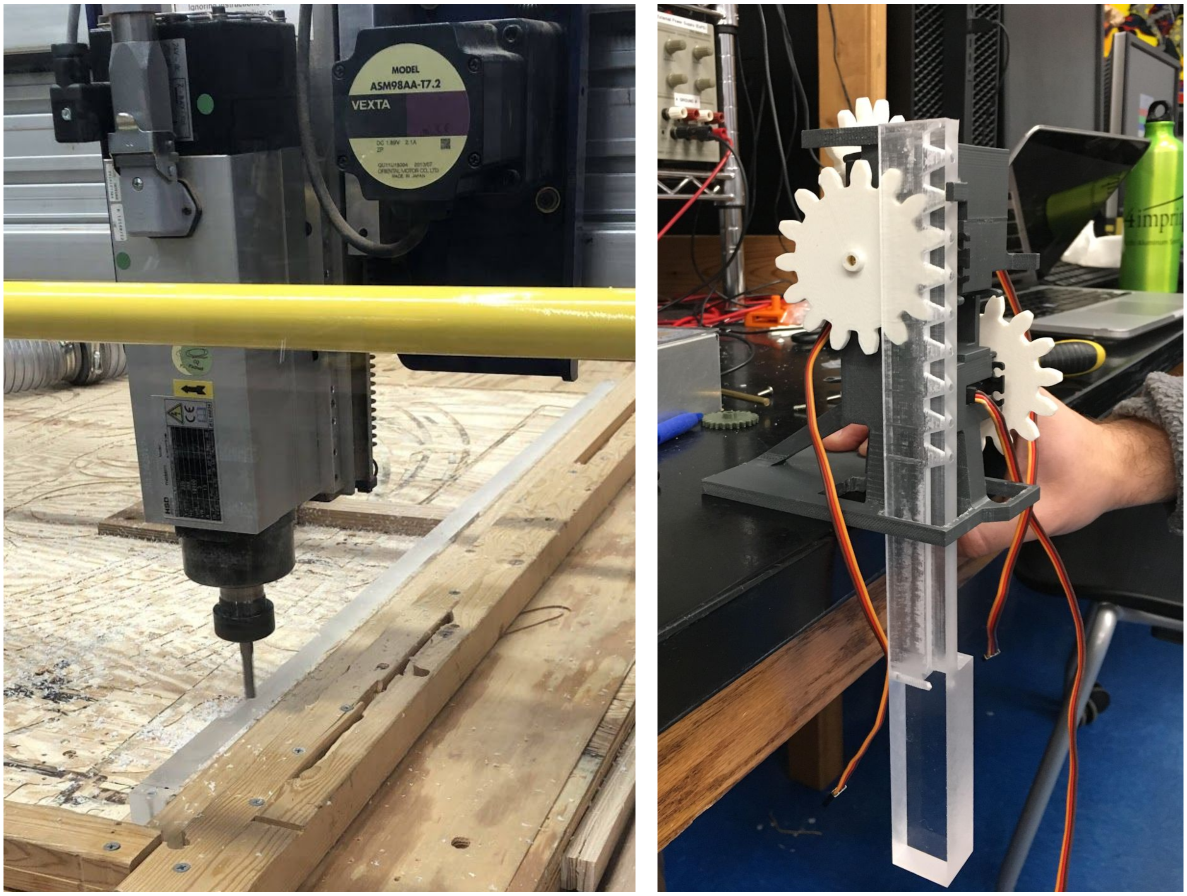

Figure 12. CNC Routing of racks (left) and partially assembled Absolute^2 Unit prototype (right).

Final Design

The Absolute^3 Unit

For the final absolute unit prototype in Figure 13, the compound gear train was reintroduced. A housing was also designed to wrap around the front of the second gear component so that the gears would no longer be cantilevered. However, the team sought to preserve the simplicity of the previous prototype as much as possible. Since the single housing from the second prototype was crucial to short assembly time, the team retained the streamlined housing that allowed the servo motors to be easily attached.

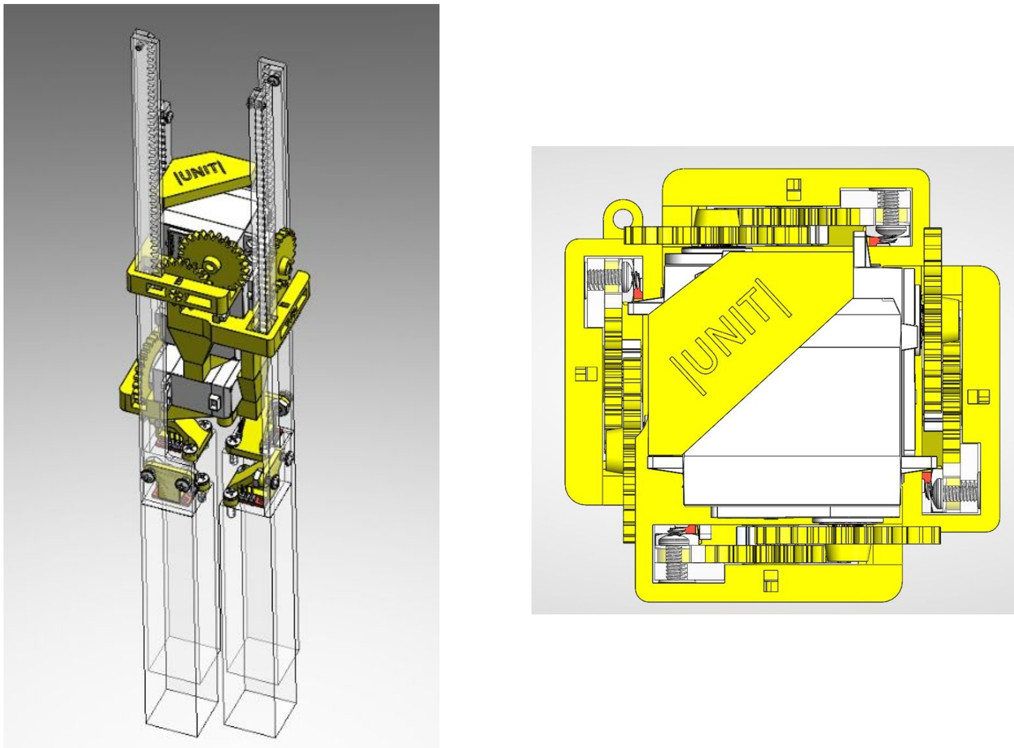

Figure 13. Absolute[3] unit design

Before introducing a new rack design, the goal of the project was reevaluated. The team decided that the absolute unit would serve as a smaller display above the entrance to the Mechatronics Lab or the MEC Lounge. The piece would then still be able to meet the goal of increasing interest in Mechanical Engineering, and completion would be feasible before the end of the semester. With a smaller display, it became possible to use the laser cutter to fabricate the racks and connecting bars that were connected to the acrylic rod by a simple cap that also held the LEDs.

Final Assembly/The Absolute[4] Unit

The team first tested one absolute unit of this third prototype design, and the unit was working well: rods were actuated relatively smoothly and the compact unit looked mystifying with the LEDs changing colors as the rods changed direction. With one functioning unit, the team decided to scale up to a display of four absolute units in a row, oriented to maintain consistent spacing between rods (Figure 14). The intention was to actuate the rows of acrylic rods to create interesting wave patterns. The team created new floor layouts that would constrain racks and rods for all four units. The acrylic sheets connecting the floors was increased in width, but still only attached at eight points to limit assembly time. Once the larger floors were created, units were added modularly. Assembly and lighting were successful, but inconsistencies in 3D printing and problems with new servomotors led to some remaining challenges in the final prototype for this project, which will be addressed in future work.

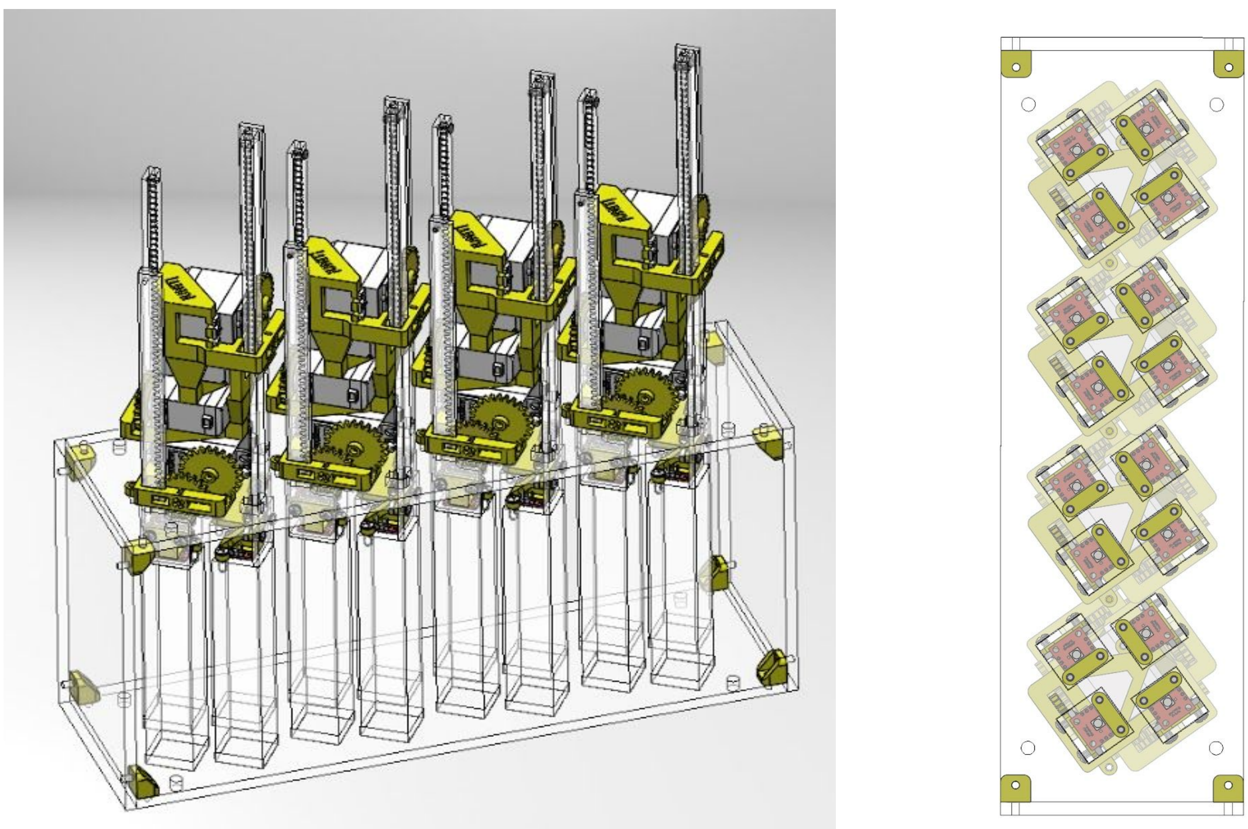

Figure 14. Final assembly with units arranged in an optimal layout

Circuitry and Software

Circuitry and Electronics

In order to meet the team's primary purpose, the final design required an external circuit board. By pairing an external circuit board with the final design, the finalized kinetic display could be installed into a variety of locations in the Mechanical Engineering Building within reach of an electrical outlet. During initial prototyping, circuitry was built on breadboards connected to the Mechatronics Lab Experimenter Board (shown below in Figure 15), a development board used to design and test circuits using the Parallax Propeller Microcontroller chip.

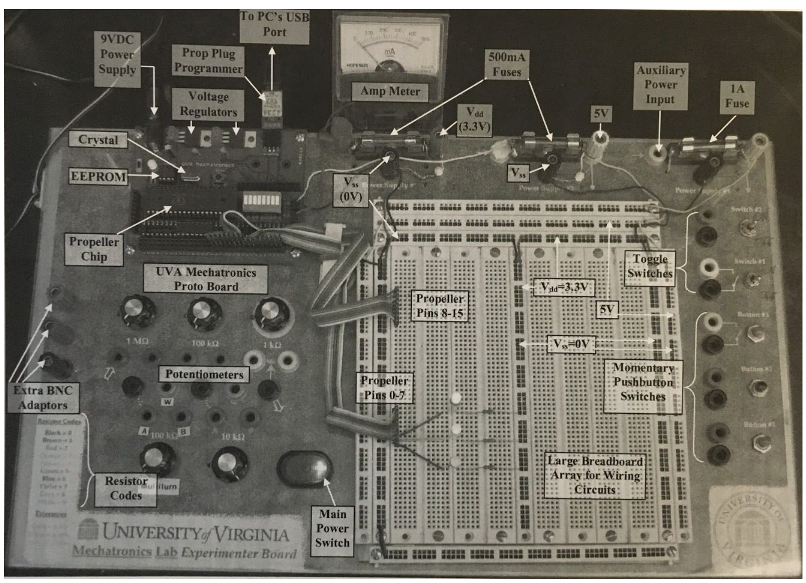

Figure 15. Development board used for early prototyping (Garner, 2019)

For the final prototype, a perfboard was created to house all electronic circuits, fuses, and relays so that the entire assembly was independent of the Mechatronics Experimenter Board. The final circuit design is shown below in Figure 16, and has many features similar to that of the experimenter board. With the final assembly having sixteen servo motors and similarly sixteen addressable RGB LED lights, the overall assembly needed a five volt, 20 ampere power supply.

To satisfy this requirement, an AC to DC power converter would be used to convert 120V, 60Hz AC power from an electrical outlet to the usable DC voltage. However, during final testing, only a 5V, 4A power supply was available, and as such the team was only able to test parts of the assembly at any given time. To control the servo motors and LEDs, a Parallax Propeller FLiP microcontroller chip was used, which contained a port for connection to a computer's USB port, an electrically erasable programmable read-only memory (EEPROM) chip, and an onboard voltage regulator so that the entire chip could be powered from a 5V supply. The EEPROM chip was absolutely necessary for meeting the team's primary objective, as it allowed software to be stored in non-volatile memory onboard without the need for a computer connection at runtime.

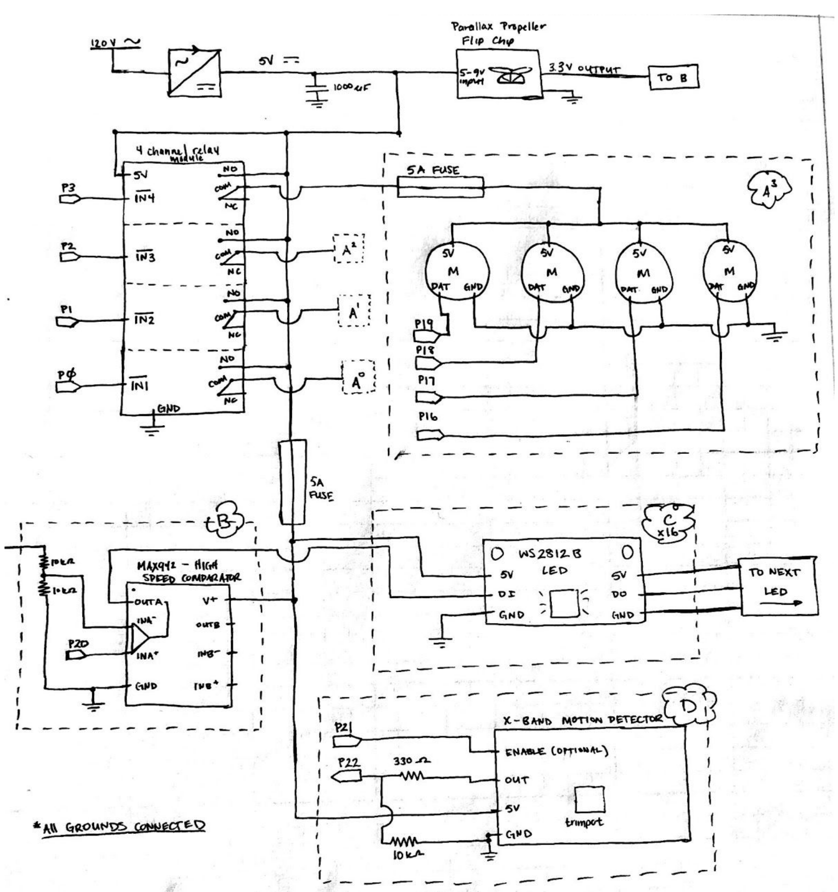

Figure 16. Electrical diagram used in final prototype

The Propeller FLiP microcontroller was connected to a four-channel relay module, which connected each absolute unit (denoted in Figure 16 by the symbol A^n) of servo motors to the 5V power supply. The relay module allowed for precise control over when the 5V power was supplied to each of the servo motors. By entirely cutting power to each servo motor when not in use, the lifespan of each servo motor could be drastically improved. Each absolute unit of four servo motors was wired through a single 5A fuse to act as a safeguard against short-circuiting, servo motor stall conditions, and other conditions that could potentially lead to complete assembly failure or fire. The servo motors, under normal operating conditions, consume between 400 and 900 mA of current, and at least 2500 mA of current during a stall condition. Theoretically, if a servo motor enters a stall condition, or short-circuits, the fuse will break first, protecting more expensive and sensitive electrical components from damage and preventing serious harm resulting from a fire hazard. All servo motors received data signals from a single pin of the Propeller FLiP microcontroller to control their motion and were connected to a single ground. A separate circuit was designed to power and control the addressable WS2812B RGB LEDs without the use of a relay. The team decided that the LEDs could continue to display different patterns even while the servo motors were inactive, as this would continue the mystifying effect while saving power and increasing the average servo motor lifespan. The WS2812B LEDs use a serial interface to transfer data from a microcontroller to each of the individual LEDs, but require a 5V data signal, which is more than the 3.3 volts that the Propeller FLiP can output from any pin. Therefore, a high-speed comparator (MAX942 chip seen in section B of the circuit diagram in Figure 16) was used to increase the voltage of the output signal from 3.3V to 5V. When connected together serially, the microcontroller can address each

LED individually so that unique and programmable patterns can be created with the LEDs. The addressable LEDs were wired as depicted in section C of Figure 16, and all were connected in series with one another. This wiring setup proved to be difficult during assembly, as connecting the LEDs together while they were placed in the context of the greater assembly was hindered by the close proximity of adjacent acrylic units. In theory, however, only the data connection needs to be connected serially among the addressable LEDs and so the power and ground connections could be made individually rather than linked to one another.

Lastly, an X-band motion detector was included in the circuit diagram (section D in Figure 16) and in the final prototype design so that, in the future, the programmable motion and lighted display could be triggered with motion in the Mechanical Engineering Building. This sensor could be placed near the final assembly and facing common walking paths within the building or placed on the assembly facing bystanders so that the motion of onlookers triggers the motion. Due to the level of motion within the building, activation of this sensor would also have to be paired with a form of timer to prevent the motion and light display from cycling continuously and instead force it to wait a specified amount of time before restarting.

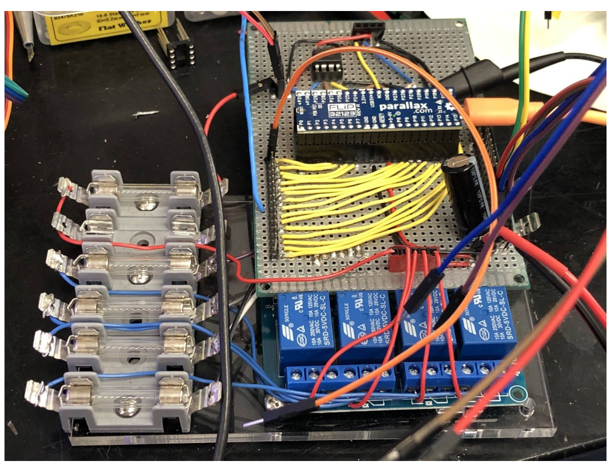

Figure 17. Final perfboard with fuses, relay module, servo and LED connectors, and the Propeller FLiP microcontroller chip.

To improve circuit durability and transportability, the circuit design above needed to be moved away from the Mechatronics Experimenter Board. Therefore, the team soldered a perfboard that contained all of the above components with connectors for easy assembly with the final unit. The perfboard, as shown in Figure 17 below, included screw holes for mounting alongside or atop the final assembly.

Software and Code

For the final assembly to be both programmable and controllable, especially without a continuous direct connection to a computer, the system would need to run software continuously. Fortunately for the team, the Parallax Propeller FLiP chip runs on a Propeller-specific object-based programming language called Spin, which was used to create programs that utilizes the FLiP chip's functionality and efficiency to control each servo motor and acrylic rod assembly. For the purposes of the final demonstration of the assembly, a default program was uploaded to the FLiP chip's attached EEPROM so that when power was applied to the system, this code would be run automatically. The default EEPROM code (shown below in Figure 18; initialization code for this program shown in Appendix A, Figure 2) was created to control only the LEDs of the total assembly in a specific pattern, one of an ascending and descending cascade of orange and blue blocks, so that in case of malfunction or power failure a fail-safe default program would run that would still provide an aesthetic appeal.

To ensure the highest degree of safety in the default EEPROM code, all relays are defaulted to be off and only code relating to the function of the LED chain is run. The Main method in Figure 18 initializes the LED driver and ensures all LEDs are turned off before entering into the Cascade public method. This method, as explained in the comments in Figure

18, turns on LEDs sequentially while subsequently turning off LEDs earlier in the chain. This code repeats in both directions, first snaking up the chain in orange then descending down the chain in blue.

```
PUB Main
  's.start
  rgb.start(LEDPin, numLED)
  'coginit(2, Cascade, @Stack)
  'maxAddress := numLED - 1
  rgb.AllOff
  Cascade

PUB Cascade  | i, j, k, m, last, value

  repeat
    repeat i from 0 to maxAddress      'turn on the LEDs in sequence, turning off the first LEDs
      rgb.LED(i,rgb#orange)            'as the later LEDs turn on to create a cascade of orange lights
      waitcnt(clkfreq/4 + cnt)
      last := i - 3  #> 0
      rgb.LED(last,rgb#off)

      value := maxAddress - i
      if value =< 3
        last := i - value
        rgb.LED(last, rgb#off)

    waitcnt(clkfreq*1 + cnt)

    repeat j from maxAddress to 0     'repeat the light sequence in the opposite direction in blue
      rgb.LED(j,rgb#blue)
      waitcnt(clkfreq/4+cnt)
      last := j + 3 <# maxAddress
      rgb.LED(last, rgb#off)

      value := maxAddress + j
      if value >= 3
        last := j + value
        rgb.LED(last,rgb#off)
```

Figure 18: Default EEPROM code with cascade light display

```
PUB Main | maxAddress

  maxAddress = numLED - 1
  rgb.SetAllColors(rgb#blue)

  repeat

    repeat until go_flag                            'run through when motion detector is tripped

    waitcnt(clkfreq*2+cnt)
    'repeat
    outa[Relay1..Relay4]~~
    dira[Relay1..Relay4]~~
    waitcnt(clkfreq+cnt)
    outa[Relay1..Relay4]~                          'turn on relay

    repeat motor from Motor1 to Motor16            'adjust sequence for rod motion and lighting
      rgb.LED((motor - Motor1), rgb#orange)
      s.Set(motor, CW)
      waitcnt(clkfreq/2+cnt)
      rgb.LED((motor - Motor1), rgb#blue)

    waitcnt(clkfreq*2)
    outa[Relay1..Relay4]~~                        'cut power to servos
    rgb.AllOff
PUB MotionDetector | count

  count := 0
  dira[MotionSignal]~
  repeat
    if (ina[MotionSignal]==1 and count > 60)     'when the motion detector is tripped and more than 60s has passed since it was last tripped,
      go_flag := true                             'set go_flag to run through sequence relays, servos, and LEDs
      waitcnt(clkfreq+cnt)
      count := 0
    else
      go_flag := false
      count:=count+1
```

Figure 19. High-level overview of programmable code for final assembly

Additionally, another program was set to be uploaded to the final assembly that controlled both the servo motors as well as the addressable LEDs. This program was not able to be tested with the final assembly due to several challenges listed in the section below, but a high-level outline for the code (as shown in Figure 19 below) was created for demonstrative purposes. Initialization code for this program is shown in Figure 2 in Appendix A.

The public method MotionDetector runs on a separate cog of the Propeller FLiP microcontroller chip and controls the setting of a global variable “go_flag.” This method takes input from the X-band motion detector to determine when a pedestrian has walked by the display so that the assembly can begin its routine. Additionally, MotionDetector waits for a minimum of 60 seconds between positive signals from the X-band motion detector before it resets the go_flag to true, which lets the Main loop continue its preprogrammed motion. For the purposes of demonstration, the Main loop simply turns on the power to all servo motors by switching the relays, changes the color and height of each acrylic rod, and then turns the relays back off to cut power to the servo motors before turning all the LEDs off. The team plans to use this Main method to call other preprogrammed methods that describe the specific motion and lighting pattern to make up different waves and functions to fully utilize the assembly’s ability to create a mystifying effect.

Manufacturing

The team took full advantage of rapid manufacturing tools to quickly create high-quality components for the final design. The central part of each unit is the 3D printed housing, which secures the servos, supports the second and third stage gears, supports the rack through its range of motion, and provides mounting points. The Stratasys Uprint’s dissolvable support material allowed the team to integrate the second and third stage gears into the housing without additional assembly.

Figure 20. Stratasys UPrint 3D Printers used for the housing and other components

In general, the 3D printed part had satisfactory gear motion with clearances determined in earlier stages of the prototyping process. One downside of the integrated gears is that at least two of the four sets of gears are aligned orthogonally to the print head no matter the part's orientation in the printer. This had an adverse effect on the smoothness of rotation for those gears. Additionally, the small feature size of the housing's moving components exacerbated any printer inaccuracies. The team noticed deviations in print quality and smoothness of rotation for the same part printed on different printers. Calibrating each of the printers would likely improve quality and consistency. Other 3D printed components include the first stage gear attached to the servo motors, brackets used to connect the solid acrylic rod to the rack subassembly, and corner brackets for the housing. These components provided plenty of structural support when printed with solid infill.

Despite the team's success milling the rack and rod out of a single piece of acrylic, this process wasted a lot of material and was overly complex given the small number of units to be produced. Therefore, the team opted for a four-piece rack and acrylic rod subassembly, consisting of the solid acrylic rod, a rack laser cut from ⅛ in. acrylic, a connecting bar laser cut from ⅛ in. acrylic, and a 3D printed bracket to attach the connecting bar to the solid acrylic rod. Laser cutting the rack and connecting bar was much faster and simpler than CNC milling, but it required a few additional manual manufacturing operations. The connecting rod required two tapped holes to secure the rack with 6-32 screws. This was a simple operation given that appropriately tap-sized holes were pre-cut in the correct location. The most involved process was drilling and tapping two 6-32 holes, used to attach the rod to the bracket, into the top of the acrylic rod. These holes had to be located and drilled manually with a drill press, leading to significant error in their position. Additional tolerance was granted to these components to account for this.

Four more laser-cut components were used to support the individual units and to guide the rods through their range of motion. These parts were cut out of ¼" acrylic for its additional stiffness. Eight holes were tapped in the mounting plate so that the units could be easily attached with 6-32 screws.

Assembly

Assembly of the individual units, as well as the four-unit assembly, was a straightforward process. Having learned from previous prototypes, adhesives and other permanent fasteners were avoided so that assembly mistakes could be corrected without penalty. First, first-stage gears were attached to each of the servo motors. Then, the three uppermost servo motors were secured in the housing with 6-32 screws. Care was taken to ensure proper gear alignment and clearances. Each of the housings were then secured to the mounting plate, and the bottom servo motors were installed. The mounting plate was connected to the guiding plate via the 3D printed corner brackets, side plates, and 6-32 screws and nuts.

For the rack and acrylic rod subassemblies, the acrylic rack was first secured to the connecting rod with two 6-32 screws in the connecting rod's tapped holes. The connecting rod was then bolted to the bracket with two screws and nuts. With the LED module positioned on top of the acrylic rod, the bracket was placed in a way that held the module in place and secured to the acrylic rod via two screws in the rod's tapped holes. Once these subassemblies were completed, they could be fed into the unit from the bottom and coupled with the stage-three gear on the housing. Before mating the rack with the gear, the gear train was rotated to its counterclockwise limit. The rack was then mated with the gear and the drivetrain was turned to bring the rack and rod to its uppermost position. Finally, pre-made connecting wires were attached between the LED modules, with a longer set running from the first LED to output pins on the perfboard. The final assembly is shown in Figure 21. For a complete list of materials and costs, refer to the bill of materials in Appendix A, Table 1.

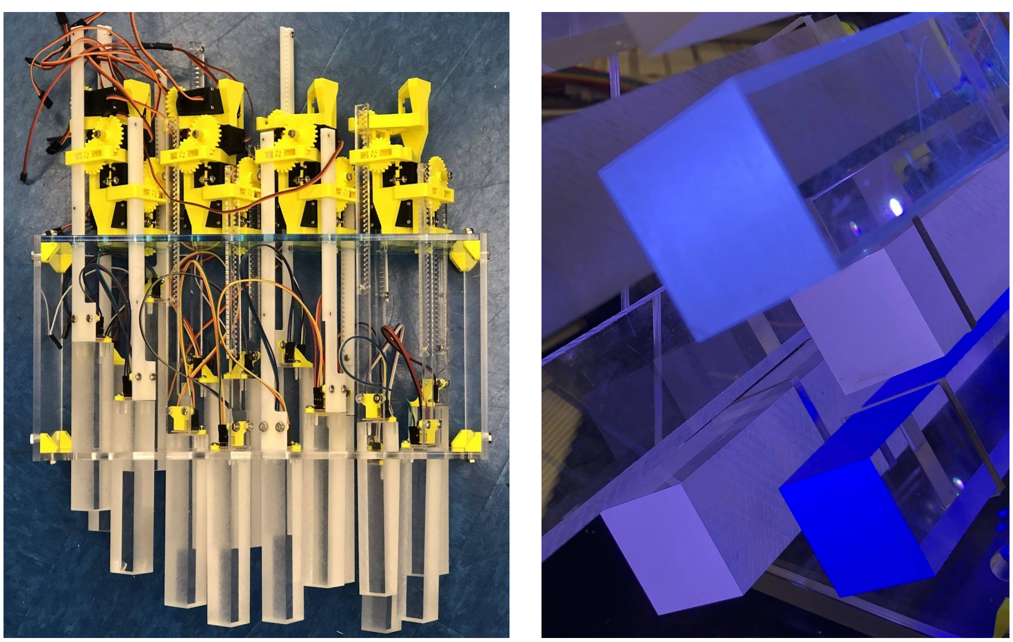

Figure 21: Final Absolute[4] Unit Assembly (left) with illuminated rods (right)

Future Work

Future work on the project would first address the challenges that accompanied the final assembly as well as organizational issues that arose during design and production. The team identified inconsistencies between housings created by different 3D printers, as well as between the gears printed in different orientations, which led to binding in the housing gears. The servomotors were not able to actuate the rods smoothly as a result. The servomotors, which were inexpensive models, burned out easily. The code also did not control the motors consistently, leading the team to suggest more expensive and reliable servo motors for future work on the display. With the display scaled down to 16 units, obtaining better motors is feasible. If the gears in the housing still do not rotate well when actuated by the new servomotors, the housing will be redesigned with increased clearance between the gear shaft, gear face, and housing body. Another option is to alter the housing design so that two pieces could be printed in the same orientation and then snapped together to create the unit of four stacked motors.

The team predicts that the lack of functionality is due primarily to the poor quality of the servomotors; however, further design improvements can still be made to improve performance. For the housing model, the team will add a feature that wraps around the back of each servo motor to prevent the servo motor from moving as a result of its own torque. Another connection point will also be added between the housing and the base of the housing to minimize the rocking motion from the overall unit.

Regarding improvements to the electrical subsystem, pull-up resistors will first be added to the inputs of the relays on the perfboard in order to ensure that the relays are off when the motors are not being controlled. Since the default EEPROM program serves as a safe state for the device, a line of code will be added to the program to set all the relays high (off) as an additional failsafe. A larger power supply must also be obtained in order for installation of the final assembly into the Mechanical Engineering Building to occur. However, before installing the display, it is necessary to test the longevity of the setup by running the display for as long as possible at full functionality. This testing will help decide if the display will be able to remain functional for an extended period of time before the MEC building is altered and labor is put into installation. The current design has several features to optimize the longevity of the system, such as the motion detector and relays, but further testing is necessary to determine estimates of assembly lifespan. Further changes must be made to the electrical subsystem if a larger assembly is to be made with more units. When the display is scaled up to more than seven absolute units, a servo motor driver would be required to control the large number of servomotors and address each one individually, which would change the setup of the electrical subsystem. Additionally, a larger system will require a larger power supply, where multiple 5V, 20A power supplies are wired together in parallel to provide sufficient power to the system.

The next step of future development will focus on user interaction with the smaller display. The motion detector code will first be tested to trigger the LEDs and movement of the acrylic rods when one passes by the display. The second step in increasing user interaction will be allowing the user to select from a few pre-programmed motions or even program in their own function to display. The team is aiming to allow users to visualize their own functions in order to meet educational goals by increasing interest in problems from MEC courses as well as the mechatronic design of the display.

Conclusion

The capstone team assembled a 16-rod display with the potential to be installed in the Mechanical Engineering Building. The display met the primary goals of the project despite difficulties with the actuation system. A modular system was created with individual units optimized for size and cost, and the unit's aesthetics have the capacity to spark onlookers' interest in mechatronic engineering. With better servo motors and adjustments to the housing, the team will produce a kinetic piece that balances simplicity, functionality, and visual appeal. Once full functionality is reached, the team will focus on scaling to a larger display and developing a user interface for educational purposes.

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Appendices

Figures

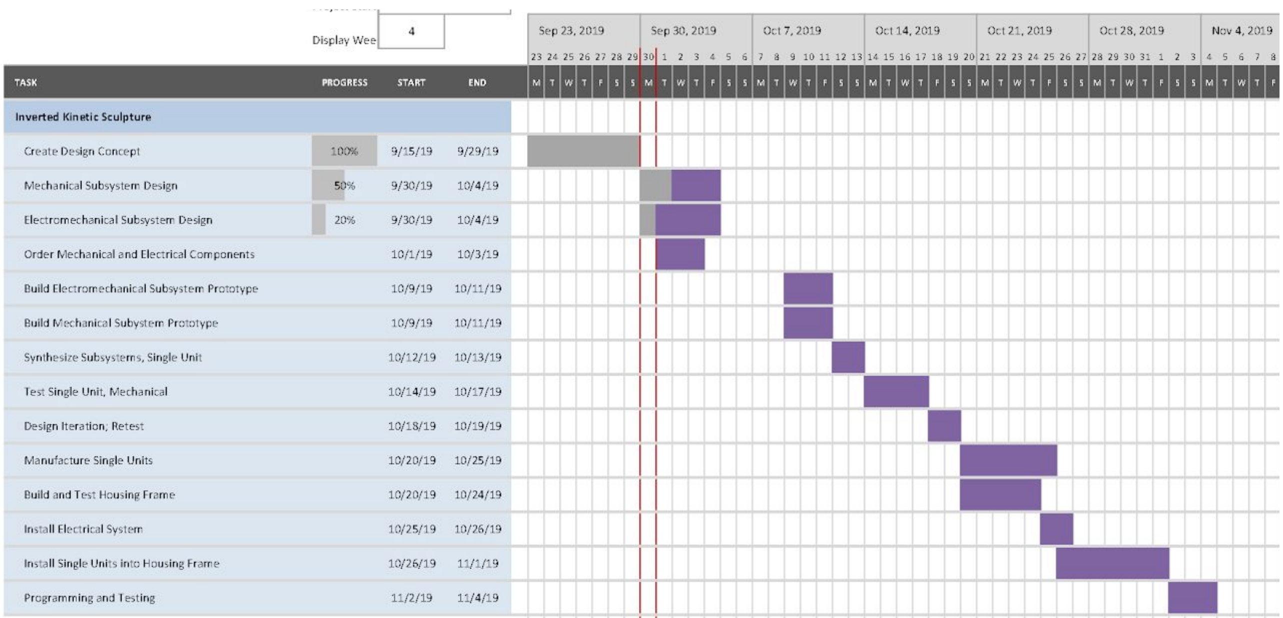

Figure 1. Initial Gantt chart outlining project timeline. Dates and tasks were updated regularly until the timeline converged to the final Gantt chart in the above report.

Figure 2. Constants (left) and Initialization code for Default EEPROM code (middle) and Final Assembly Demonstration (right)

Tables

Table 1. Bill of Materials for Final Assembly (of 4 absolute units) of 16 lighted rods. All values are estimates.

					Final Assembly Costs	
Absolute Unit Costs					*Absolute Units/Assembly:*	4
Item	*Distributor*	*Cost/Unit*	*Units/Absolute Unit*	*Cost/Absolute Unit*	*Units/Assembly*	*Cost/Assembly*
1/4" Clear Acrylic Sheet, 12"x24"	McMaster-Carr	$29.77	0.25	$7.44	4	$29.77
1/8" Clear Acrylic Sheet, 12"x24"	McMaster-Carr	$16.70	0.125	$2.09	4	$8.35
1"x1" Solid Acrylic Rod 4ft	McMaster-Carr	$25.64	0.67	$17.18	4	$68.72
MG996R Servo Motor	Amazon	$5.00	4	$19.99	4	$79.96
SparkFun RGB LED Breakout WS2812B	SparkFun	$3.33	4	$13.32	4	$53.28
3D Printer Model Material (Stratasys)	N/A	$250.00	0.33	$82.50	4	$330.00
3D Printer Soluble Support Material (Stratasys)	N/A	$200.00	0.2	$40.00	4	$160.00
6-32 Hex Nuts	McMaster-Carr	$0.01	20	$0.26	4	$1.02
6-32 Washers	McMaster-Carr	$0.01	4	$0.05	4	$0.19
6-32 Bolts, 1/4"	McMaster-Carr	$0.05	24	$1.09	4	$4.37
6-32 Bolts, 3/8"	McMaster-Carr	$0.04	16	$0.72	4	$2.87
6-32 Bolts, 1/2"	McMaster-Carr	$0.05	4	$0.21	4	$0.82
M3 Bolts, 3/8"	McMaster-Carr	$0.08	4	$0.30	4	$1.20
4-channel Relay Module	Amazon	$6.99	0.25	$1.75	4	$6.99
5A fuses	Amazon	$0.30	1.25	$0.37	4	$1.50
X-band motion detector	Parallax, Inc.	$33.99	0.25	$8.50	4	$33.99
5V, 20A Power Supply	Amazon	$18.99	0.25	$4.75	4	$18.99
Jumper Wires	Amazon	$0.07	36	$2.55	4	$10.19
1000 uF Capacitor	Amazon	$0.42	0.25	$0.10	4	$0.42
Perfboard	Amazon	$0.70	0.25	$0.17	4	$0.70
TOTAL COSTS				**$203.33**	**4**	**$813.33**
Total Costs, Excluding 3D Printed Material				**$80.83**		
Total Cost, Exc 3D, Per Acrylic Rod				**$20.21**		

Table 2. Bill of Materials for First Prototype (Absolute[1] Unit). All values are estimates.

Absolute Unit Costs - Prototype 1				
Item	*Distributor*	*Cost/Unit*	*Units/Absolute Unit*	*Cost/Absolute Unit*
1/4" Clear Acrylic Sheet, 12"x24"	McMaster-Carr	$29.77	0.25	$7.44
1/8" Clear Acrylic Sheet, 12"x24"	McMaster-Carr	$16.70	0	$0.00
1"x1" Solid Acrylic Rod 4ft	McMaster-Carr	$25.64	1	$25.64
MG996R Servo Motor	Amazon	$5.00	4	$19.99
SparkFun RGB LED Breakout WS2812B	SparkFun	$3.33	4	$13.32
3D Printer Model Material (Stratasys)	N/A	$250.00	0.5	$125.00
3D Printer Soluble Support Material (Stratasys)	N/A	$200.00	0.25	$50.00
6-32 Hex Nuts	McMaster-Carr	$0.01	32	$0.41
6-32 Washers	McMaster-Carr	$0.01	12	$0.14
6-32 Bolts, 1-1/4"	McMaster-Carr	$0.22	4	$0.89
6-32 Bolts, 3/8"	McMaster-Carr	$0.04	0	$0.00
6-32 Bolts, 1/2"	McMaster-Carr	$0.05	28	$1.44
M3 Bolts, 3/8"	McMaster-Carr	$0.08	4	$0.30
3/4" PVC L-Channel, 0.08" Thick	McMaster-Carr	$8.21	1	$8.21
5- Min Quik-Cure Epoxy	Amazon	$8.76	0.25	$2.19
4-channel Relay Module	Amazon	$6.99	0.25	$1.75
5A fuses	Amazon	$0.30	1.25	$0.37
X-band motion detector	Parallax, Inc.	$33.99	0.25	$8.50
5V, 20A Power Supply	Amazon	$18.99	0.25	$4.75
Jumper Wires	Amazon	$0.07	36	$2.55
1000 uF Capacitor	Amazon	$0.42	0.25	$0.10
Perfboard	Amazon	$0.70	0.25	$0.17
TOTAL COSTS				**$273.17**
Total Costs, Excluding 3D Printed Material				**$98.17**
Total Cost, Exc 3D, Per Acrylic Rod				**$24.54**