INTRODUCTION

Overview

LuCelegans is a 6-foot long interactive art installation that represents the nervous system of the organism *Caenorhabditis elegans.* The nervous system of *C. elegans* has been studied extensively, making it a very useful research and education tool for neuroscience and biology. The installation represents the worm's neuronal circuits that are sparked by various triggers such as smell, touch, and heat. It also includes video animations and a sonic component to create a more immersive experience for viewers. The name LuCelegans comes from the latin word for light, luce, and the name of the organism, *C. elegans.*

How the Model is Built

The model is built with various materials and many fabrication techniques are used to most accurately replicate the look of the worm. For example, frosted vinyl sheets represent the transparent cuticle ("skin") of the worm. They are attached with Velcro on 13 rings made of laser-cut acrylic, designed after electron micrographs of *C. elegans'* body cross sections. Acrylic parts are widely used throughout the model because the material is clear, imitating the transparency of the organism. PVC pipes and 3D-printed joints hold the rings in place. Specially designed locks are required to mount the 3D printed nose and tail on the 1st and 13th acrylic rings, respectively. The tail and head of the worm will be 3D printed in clear resin, maintaining the transparent look of the organism. The neuronal circuits are represented by red, blue, green, and yellow EL wires, color coding the function of each neuron. The complete model will feature representations of all types of *C. elegans* neurons; however, the number of neurons will be reduced to prevent cluttering. PVD mechanosensory neurons have a unique shape that has been addressed by laser-cutting clear acrylic sheets into a cactus-like shape. EL wires are then mounted on the acrylic template to represent nuerons.



Figure 1: LuCelegans Model in Progress

How the Model Works

The viewer will use radio frequency identification (RFID) cards to trigger chemosensory neurons equipped with RFID readers, conductive paper to activate mechanosensory neurons, and thermosensors to simulate thermosensitive neurons. Electrical components, like RFID readers, are hidden in the hollow 3D-printed head of the worm. The communication between sensors and circuits is facilitated by Arduinos. Video animations made with Blender feature each of the neuronal circuits that will be activated by the viewer (Figure 2). Through Raspberry Pi and Python code the correct video will be selected, and the animation will be displayed on a monitor next to the installation. A sound designed to accompany the animation will also play, creating a more immersive installation.

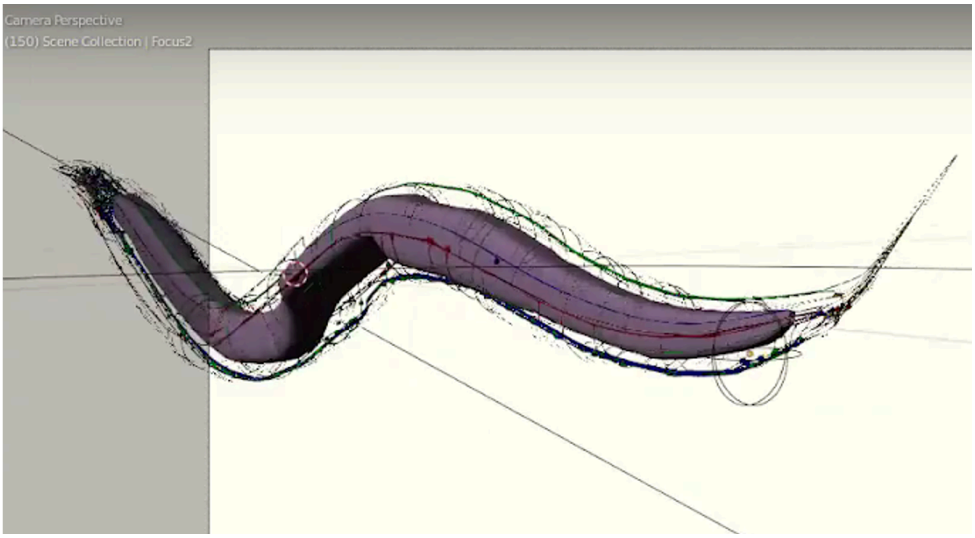

Figure 2: Blender Animation

Scope and Goal

Overall, the scope of LuCelegans is to interest the public in research, biology and the nervous system, and teach people of all ages about the use of model organisms like *C. elegans* in neuroscience research. This will be achieved by reaching the goal of having a fully working installation exhibited in various museums across the United States, starting with the University of Michigan Museum of Natural History.

METHODS

Developing a model to accurately depict *C. elegans* involves many different areas of expertise, which can be split into three main categories: building and fabrication, sensors and circuits, and sonics and audio. While the work done in these categories relates, there are also distinct challenges and goals associated with each subteam. Additionally, as the model progresses the work that must be completed changes. The methods for advancing the model that are outlined in this report correspond to the fourth phase of the model, which spans the year 2023.

Building and Fabrication

The building and fabrication subteam focuses on the design and construction of the model. There are a wide variety of fabrication methods used, which include but are not limited to 3d-printing with PLA and resin, laser-cutting, gluing, drilling, and velcroing. The following section of the report details the techniques that were used to develop the construction of the model in 2023.

Joints and PVC Pipes

Previous iterations of the model used wooden pipes with angled slots cut in the top to secure the acrylic rings representing *C. elegans'* cross section. However, there are electronics and wires that must be strung from the base of the model up to the acrylic templates of neurons, so it was determined that a hollow pipe in which wires could be strung through would be necessary. The team elected to use PVC pipes with holes drilled into the bottom of the pipe for inserting and stringing wires (Figure 3). Pipes were cut to the appropriate length and painted black.



Figure 3: PVC Pipe with Wire Access Hole

After switching to PVC pipes as support, there was no longer a mechanism to hold acrylic rings at an angle, which is essential to represent the natural curvature of the worm's body. The former wooden pole supports had slots cut into the top for the acrylic rings to rest in. Therefore, for the PVC pipes, joints connecting the PVC pipes and rings had to be designed and added to the model (Figure 4). 13 pairs of joints are used to hold each ring at a unique angle, and they are 3d-printed in black PLA. Initially, the joints were printed with a low infill density of 20%, but as they held the weight of the rings some joints began to break. Joints are now printed with an infill density of at least 50% to strengthen the part and its ability to support the weight of the rings and other pieces of the model.



Figure 4: 3d-printed Joint

Acrylic Stems and Beams

Another important aspect of the model that was worked on were the beams, which connect the acrylic rings together, and the stems that connect neurons to the beams. Each beam includes a slot for a stem that may face upward or downward. Due to the angle and spacing of the acrylic rings, the location of slots and length of the beams vary. Laser cutting acrylic sheets was the technique used to create beams and stems. All 24 beams and stems are done being laser cut, along with extras in case of malfunctions.

A challenge that occurred in phase four of LuCelegans was connecting the beams, stems, and neurons together. In the past, hot glue had been used, but it quickly became messy and did not allow for parts to be undone then put back together. Alternatively, the team decided to use clear elastics as a joining mechanism for acrylic parts. In addition to using elastics to connect beams, stems, and neurons, elastics are also used to secure EL wires to the acrylic PVD templates (Figure 5).

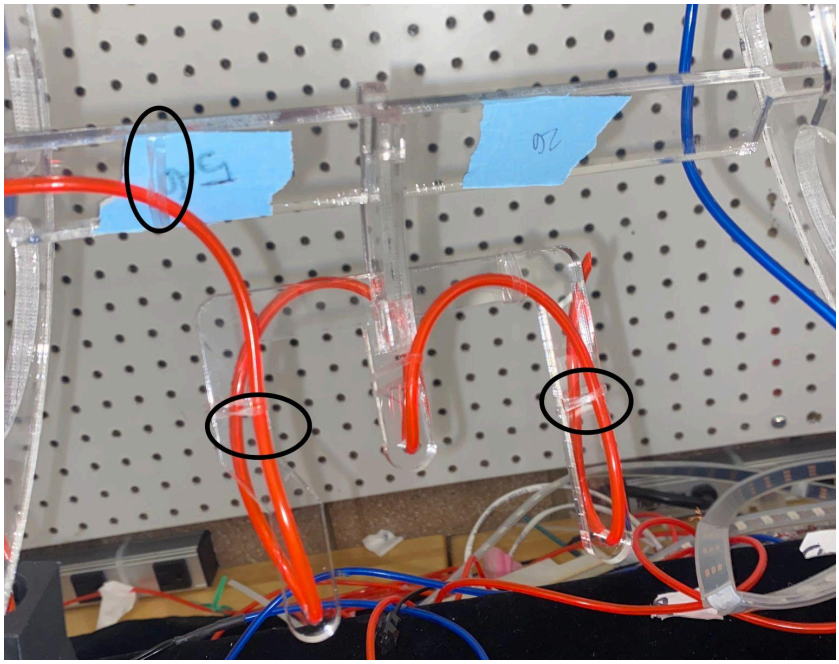

Figure 5: Elastics Securing EL Wire to PVD Template

Tail

Designing the tail which is attached to the 13th ring of the model was a large challenge faced during the developments made in 2023. The tail of the worm is to be 3d-printed in resin, maintaining the installation's transparent look. One issue the team encountered was creating a mechanism to attach the various parts of the tail together. Due to the size restrictions of resin 3d-printers, the entire tail cannot be printed in one piece. Therefore, the design had to be split into multiple pieces which are connected after printing. Initially, a locking mechanism that included slots for bolts was used. However, this proved complicated to print and was not creating the desired results when test printed with PLA. Eventually, it was decided to simply print the pieces of the tail without adding any special design, and connect them using epoxy glue. During phase four an entire tail prototype was not created, but a scaled down version was printed with resin and seemed to stay together well with epoxy glue.

Base

The wooden base of the model holds electronics needed to simulate *C. elegans'* neuronal circuits. EL wires are located in the base and strung through the PVC pipes to their respective locations on the installation. In previous iterations of LuCelegans, the base was composed of four solid wooden boxes. The phase four team found that it was incredibly difficult to access the electronics not stored directly on either end of the base, so access holes were cut along the side of the base to allow for easier manipulation of wires (Figure 6).



Figure 6: Access Door in Base with Blue EL Wires

Sensors and Circuits

The sensors and circuits subteam works on the electronics needed to represent neuronal reactions in *C. elegans.* EL wires represent key neurons, and Arduinos are used for communication between sensors and circuits. Raspberry pi and python code selects blender animations that show a more detailed view of the simulated neurons, as well as sound to create a more immersive experience for visitors of the installation.

Soldering

Soldering work is a large part of creating the model, because every neuron is represented with an EL wire that must be attached to a main wire in the base of the model. Red wires represent PVD/mechanosensory neurons, blue wires represent motor neurons, green wires represent interneurons, and yellow wires represent chemosensory neurons. In the model PVD and motor neurons are simulated across all 13 acrylic rings, so 13 EL wires had to be connected to one power source. This proved to be a challenge because connecting all 13 EL wires to one main wire was overloading the inverter and preventing the wires from lighting up. Previously, branches of white wires stemmed from the main wire before connecting EL wires, but the team decided to remove these branches in order to reduce the amount of voltage in the main wire. It was also decided to use a stronger inverter in hopes of being able to light 13 wires with the power supplied. After making these two changes, 13 EL wires lit at once (Figure 7). This was a large progress step made during the phase four team because soldering the wires is essential to completing the model.



Figure 7: EL Wires Representing Motor Nuerons

After the soldering of PVD and motor neurons was complete, issues did arise with transferring the wires to the model. EL wires are very fragile and as they were strung through the base and into the PVC pipes, some of the soldered connections were breaking. Luckily, the access holes in the base allowed for the wires to be repaired while still in the model.

Coding

A large portion of the work done in the phase four team was completing the raspberry pi code needed to select animations and audio clips. Previously seemingly impossible bugs were arising in the code, such as an inability to connect to wifi. Another issue that had to be debugged was a compatibility issue with the format of the blender animations and their ability to play on the monitor. This portion of the project was not one I worked on, but the team was able to resolve all

issues related to the code and have a working program by the end of 2023. The conductive touch paper sensors and RFID sensors are now able to read input and select the video and audio files associated with that neuronal reaction.

Sonics and Audio

The sonics and audio subteam composes original audio clips that correspond to various neurons lighting up. The purpose of these audio clips is to create a more interactive and immersive experience for people who view the model. During the fourth phase of LuCelegans, sonics and audio was not a component that needed to be prioritized. Therefore, the main task that was worked on for this subteam was developing an audio guide for spectators to use when interacting with the model. This audio guide is still under development, but an initial rough draft is complete.

CONCLUSION

Many important milestones for LuCelegans were achieved with the work of the phase four team during the year 2023. The work done on the sensors and circuits subteam pushed the project to its most advanced level so far. Displaying the complete model will interest the public about biology and neuroscience and allow people of all ages and backgrounds to interact with LuCelegans in a fun way.

Future Opportunities

In future phases of the project there are a few main tasks that must be completed before the installation's debut display. First, the Arduinos need to be connected to the soldered EL wires so the proper neurons light up in response to various sensors being triggered. Completing this step will be a large jump towards having a working prototype with all functionality that the final model will have. Additionally, more EL wires need to be added to represent additional neurons. Currently, only mechanosensory and motor neurons are represented. 3d-printing the tail with resin and designing and printing the head of the worm are two important tasks. Designing the head of the worm will be more complicated than the tail, because the head must hold RFID sensors for chemosensory neurons. The vinyl sheets that represent the cuticle skin must also be attached to the model via velcro attached to each acrylic cross section ring. Before displaying the installation in the University of Michigan Museum of Natural History, there are also many small tweaks to complete that will increase the aesthetic nature of LuCelegans.

ACKNOWLEDGEMENTS

The phase four team members that contributed to advancement of LuCelegans are Haley Bartimus, Sara Huang, Sean Li, Zheng Luo, Andres Rosas Chinea, and Christina Sheckler. All work was guided by the faculty advisor, Eleni Gourgou, of the mechanical engineering department.

Additionally, thanks go to ArtsEngine, UM College of Engineering, especially Deb Mexicotte, Amy Tackitt, Greg Wakefield, and John Granzow. Previous team members Richard Wall, Ray Yang, Taylor Gilbert, Millie Hernandez, Alex Reynolds, Indigo Knecht, Jaehong Min, Fee Cristoph, Manali Desai, Jiwen Chen, Amanda Taylor, Melinda Li are also thanked for their contributions. The project team is grateful to Linda Knox and Tom Brady, UM Duderstadt Center Ground Connect, to staff members at the Shapiro Library and the Duderstadt Fabrication lab. Finally, the project was supported by people at the OpenWorm Project, for sharing their Blender files on *C. elegans'* nervous system *in silico* models.