Humanoid Animatronic Learning Simulator for Medical Interactive Training (H.A.L. S.M.I.T.)

A Major Qualifying Project

Submitted to the Faculty of the Worcester Polytechnic Institute in fulfillment of the requirements for the degree in Bachelor of Science for

Mechanical Engineering
and Robotics Engineering

By

Daraius Boston (ME)
Dylan Hauer (ME)
Connor Lepage (ME)
Tristan Lepage (ME)
Ryan Shaw (ME/ECE)

Advised by

Prof. Pradeep Radhakrishnan (ME/RBE)
Prof. Kaveh Pahlavan (ECE/CS)

Copyright Notice

I. Abstract

The goal of this project was to design and develop an autonomous, modular, easily operable animatronic head to enhance realism in medical simulations. There exists a gap in the medical manikins field, on one end manikins that have limited use cases for lower cost, and on the other end manikins capable of a handful of complex simulations that are expensive. This project aims to create a low cost head and neck manikin capable of a plethora of complex simulations. The prototype from Cohen et al. was a continuation of an MQP, they focused on addressing the medical uses. This year's team continued where Cohen et al. left off. Redesigning CAD models and entire subsystems such as the neck. As well as, evaluating the electrical and software side of H.A.L. Ultimately, starting assembly of the head, adding user friendly UI, and testing subsystems.

II. Acknowledgements

The team would like to recognize individuals that helped the team through this process, and without whom this project could not have been completed. The team would like to thank Professor Pradeep Radhakrishnan for his advising and input that enabled this project to succeed and pushed the team members to reach their greatest potential. The team would also thank Dick et al. and Cohen et al. for their previous work on the animatronic and providing additional information and advice. We would like to recognize Barbara Fuhrman for purchasing materials from vendors not only for this project, but all Mechanical Engineering MQPs as well. The team would like to recognize Dr. Erica Stults for providing invaluable insight on 3D modeling during the skin design process. We would like to thank Ian Scott, Eliana Palumbo, and Sarah Brown for offering their time to talk with us, and provide valuable feedback about how training is done for EMS. Finally, the team would like to thank Peter Hefti for providing tools and lab equipment, as well as keeping the MQP lab organized and clean.

Table of Contents

Copyright Notice 2

I. Abstract 2

II. Acknowledgements 2

Table of Contents 3

List of Figures 7

List of Tables 11

Authorship 11

List of Abbreviation 15

Nomenclature 17

Executive Summary 18

Chapter 1: Introduction 18

Chapter 2: Existing Prototype 21
- 2.1 Rationale 22
- 2.2 Outcomes 22
  - 2.2.1 Neck Mechanism 22
  - 2.2.2 Eye Mechanism 23
  - 2.2.3 Jaw Mechanism 24
  - 2.2.4 Sensors and Electronics 25
- 2.3 Relevance to this MQP 26

Chapter 3: Background 27
- 3.1 Manikins in the medical field 27
- 3.2 Manufacturability 28
  - 3.2.1 Slide fits 29
  - 3.2.2 3D Printing 32

Chapter 4: Mission, Objectives and Requirements 34
- 4.1 Direction of the Project 34
- 4.2 Mission Statement and Objectives 35
- 4.3 Objective 1: Identify Areas of Improvement 36
  - 4.3.1 Areas of Improvement on Current Prototype 37
    - 4.3.1.1 Neck 38
    - 4.3.1.2 Jaw and Oral Cavity 39
    - 4.3.1.3 Lips 39

4.3.1.4 Eyes, Eyelids and Eyebrows 39
4.3.1.5 Lattice and Skin 39
4.3.1.6 Code Structure 40
4.4 Objective 2: Designing For Manufacturability 40
4.4.1 Snap/Slide fits 41
4.4.2 3D printing 41
4.5 Objective 3: Construct and organize 42
4.5.1 Assembly 42
4.5.2 Organization 43

Chapter 5: Base, Neck Enclosure, and Neck Mechanism 43
5.1 Methodology 44
5.1.1 Neck Enclosure 44
5.1.2 Neck Mechanism 44
5.2 Design and Implementation 46
5.2.1 Neck Enclosure 46
5.2.2 Neck Mechanism 48

Chapter 6: Oral Cavity, Jaw, and Lips 53
6.1 Methodology 53
6.1.1 Oral Cavity 54
6.1.2 Jaw 54
6.1.3 Lips 54
6.2 Design and Implementation 55
6.2.1 Oral Cavity 55
6.2.2 Jaw 59
6.2.3 Lips 59

Chapter 7: Lattice and Skin 61
7.1 Methodology 62
7.1.1 Lattice 62
7.1.2 Skin 66
7.2 Design and Implementation 70
7.2.1 Lattice 70
7.2.2 Skin 79

Chapter 8: Electronics and Code Structure 91
8.1 Peripherals and Implementation 92
8.1.1 Microcontroller 92
8.1.2 Power 93
8.1.3 Sensors 93
8.1.3.1 Camera 93
8.1.3.2 FSR 94

        8.1.4 Actuator 97
            8.1.4.1 Servos and Servo Drivers 97
            8.1.4.2 Solenoids 98
        8.1.5 UI 99

Chapter 9: Results **102**
    9.1 Manufacturability and Replicability 102
        9.1.1 Snap fits 102
    9.2 Mechanical Components 103
        9.2.1 Neck Mechanism 103
        9.2.2 Oral Cavity 103
        9.2.3 Jaw 104
        9.2.4 Lips 104
        9.2.5 Lattice 104
    9.3 Electronics and Coding Results 105
        9.3.1 Microcontroller 105
        9.3.2 Power 105
        9.3.3 Servos 105
        9.3.4 Solenoids 106
        9.3.5 Hearing and Speech 106
        9.3.6 UI and Touchscreen 106
        9.3.7 Code Structure 109
            9.3.7.1 Overall Architecture 109
            9.3.7.2 Stewart Platform Code 109

Chapter 10: Discussion and Future Work **113**
    10.1 Manufacturing and Assembly Time 113
    10.2 Base and Neck Enclosure 113
    10.3 Neck Mechanism 114
    10.4 Oral Cavity 114
    10.5 Jaw 119
    10.6 Lips 120
    10.7 Eyes 120
    10.8 Lattice/Skin 122
    10.9 Pulse 127
    10.10 Manufacturability 127
    10.11 Electronics and Code Structure 128
        10.11.1 Microprocessor 128
        10.11.2 Power 128
        10.11.3 Serovs 129

Chapter 11: Conclusion **129**
    11.1 Personal Reflection 129

Chapter 12: Broader Impacts Chapter 131
  1.1 Engineering Ethics 131
  1.2 Societal and global Impact 131
  1.3 Environmental Impact 131
  1.4 Codes and Standards 131
  1.5 Economic factors 132

References 132

Appendices 135
  Appendix A: Full Code and Demo Code 135
  Appendix B: Infographic for GUI 136
    Videos 138
  Appendix C: IRB Methodology 138
    Appendix C.1: Informed Consent 138
    Appendix C.2: Covid Supplement to Consent 140
    Appendix C.3: EMS Sample Scenario 142
    Appendix C.4: Electronics Specifications 142

List of Figures

Figure Number	Description	Page
1	***Prototype of animatronic head by Dick et al***	22
2	***CAD Model of Neck Mechanism by Cohen et al***	24
3	***CAD Model of the Eye Mechanism by Cohen et al***	25
4	***CAD Model of the Jaw Mechanism by Cohen et al***	26
5	***Accessibility difference between two parts***	29
6	***U-connector type snap-fit***	31
7	***Torsional snap-fit***	32
8	***Annular snap-fit***	33
9	***Neck Lattice CAD***	42
10	***Example of a Stewart platform***	46
11	***CAD Model of the Neck Enclosure by Cohen et al***	47
12	***CAD Model for Preliminary Neck enclosure***	48
13	***Rack and pinion based linear actuator, housing (left) and rack (right) CAD models***	50
14	***U clip (left) and Stewart platform assembly (right) CAD models***	50
15	***Concept of Sarrus linkage based linear actuator design***	51
16	***CAD redesign of Sarrus linkage based linear actuator***	52
17	***Design of sliding joint based linear actuator***	52
18	***Lead screw housing CAD design***	53
19	***Linkage based Stewart platform***	54
20	***CAD Model of the Lips by Cohen et al***	56
21	***Final CAD Design Jawbone and lower teeth Interaction***	57

22	***Preliminary Lower Teeth Redesign CAD model***	57
23	***Ramp Addition to Preliminary Design CAD model***	58
24	***CAD depicting Intersection of Lower Oral Cavity Interaction***	59
25	***Bottom Teeth Final Design CAD model***	59
26	***Comparison of Jawbone by Cohen et al (left) and our redesign (Right)***	60
27	***Avatar Animatronic***	61
28	***Preliminary Lip Redesign CAD model***	61
29	***Final Design for Lips Subsystem***	62
30	***Neck lattice to neck platform connectors utilized derived from the user manual by Cohen et al***	64
31	***Side head lattice to neck lattice connectors utilized derived from the user manual by Cohen et al***	65
32	***Crown lattice to side head lattice connectors utilized derived from the user manual by Cohen et al***	66
33	***Gutter style slide-fit, part a(left) and b(right)***	66
34	***Slide-fit testing block, consists of 0.75%, 0.5%, and 0.25%***	67
35	***Phone Case with TPU components***	68
36	***Demonstration of Multiple Infills in Cura***	69
37	***Main Infill Settings in Cura***	70
38	***Per object settings in Cura***	71
39	***Neck Slide fit design to remove four connectors***	72
40	***Neck to side-head slide fit design to remove four connectors***	73
41	***Neck Slide fit design utilizing gutter style slide-fits***	74
42	***Final neck slide fit design idea utilizing a trapezoidal puzzle piece like slide-fit***	74

43	***Crown to side-head lattice design idea utilizing a trapezoidal puzzle piece like slide-fit, utilized idea(left), scrapped idea(right)***	75
44	***Two halves to the neck lattice showcasing the removed connectors circled in red***	76
45	***Two halves to the neck lattice showcasing the new slide fit design and the removed tabs from the previous figure***	77
46	***Two halves to the side-head lattice showcasing the removed or non-utilized connectors circled in red***	78
47	***Two halves to the side-head lattice showcasing the new connectors and slide-fits circled in blue***	78
48	***The Designed Crown Lattice Showcasing The Removed Or Non-utilized Connectors Circled In Red***	79
49	***The Designed Two Halves Of The Crown Lattice Showcasing New Connectors And Slide-fits Circled In Blue***	80
50	***The Test Models in Cura***	81
51	***A 4mm Skin Test Print***	82
52	***Early Version of Skin Using Surface Modeling***	83
53	***Subdivided Lattice with planes***	84
54	***Sketches representing lattice***	85
55	***Sketch with offset***	85
56	***Loft Between two sketch planes***	86
57	***Hole being covered by skin***	87
58	***Neck Lattice with complete skin***	87
59	***Exterior and Interior of TPU test print at 0% infill***	88
60	***TPU lattice without skin printing***	89
61	***TPU skin test prints (Left 10%, Right 15% infill)***	90
62	***Silicone skin alongside TPU skin***	91

63	***Close-up of Lattice with Skin in Cura - Variable Infill***	92
64	***Completed Print of Lattice with Skin in TPU***	92
65	***Pinout Diagram***	93
66	***The Pixy2 Wiring Diagram by Cohen et al***	95
67	***Wiring Diagram for FSRs by Cohen et al***	96
68	***Microphone Wiring Diagram by Cohen et al***	97
69	***Speaker Wiring Diagram by Cohen et al***	98
70	***Example Wiring Of Daisy Chained Pwm Servo Drivers by Cohen et al***	99
71	***The Wiring Of The Pulse Subsystem by Cohen et al***	100
72	***The Nextion Touch Screen Wiring***	101
73	***Nextion Editor Event Panel***	101
74	***Example Of Button With Code To Call A Function***	102
75	***Screenshots of the Three Pages; Simulation(left), Manual (center), and Demo (Right)***	108
76	***Coordinate System Of The Stewart Platform***	111
77	***The Three Rotational Matrices And The Resultant Matrix***	112
78	***Servo parameters***	113
79	***Image Showing Spee and Wilson Curve***	117
80	***Mask Testing Results Image***	119
81	***Schlieren Photography Setup***	120
82	***Dielectric Elastomer Actuator***	122
83	***Iris Mechanisms***	123
84	***Cuboid Infill***	124
85	***Line Infill***	124
86	***Visible Layer Lines on TPU Test Print***	125

87	***Acetone Print before and after smoothing***	126
88	***Consumer Grade Acetone Vapor Bath***	126
89	***Commercially Available 3D Coating from Smooth-ON***	127

List of Tables

Table Number	Description	Page
1	3D printable filaments comparisons	34
2	Table of connectors used to attach the pieces of the lattice system	63
3	TPU Settings for Skin and Solid Sections	82
4	List of Servos; Names, Quantity, Voltage, Subsystem	98

Authorship

Chapter	**Primary Authors**	**Primary Editor**
Executive Summary	All	All
1	Daraius Boston, Connor Lepage	All
2	Daraius Boston, Tristan Lepage	All
2.1	Daraius Boston, Tristan Lepage	All
2.2	Daraius Boston, Tristan Lepage	All
2.2.1	Daraius Boston, Tristan Lepage	All
2.2.2	Daraius Boston, Tristan Lepage	All
2.2.3	Daraius Boston, Tristan Lepage	All
2.2.4	Ryan Shaw	All
2.3	Daraius Boston, Tristan Lepage	All
3	Connor Lepage	All
3.1	Connor Lepage	All
3.2	Connor Lepage	All
3.2.1	Connor Lepage	All
3.2.2	Daraius Boston, Tristan Lepage	All
4	Daraius Boston,Tristan Lepage, Dylan Hauer, Connor Lepage	All
4.1	Dylan Hauer	All
4.2	Dylan Hauer	All
4.3	Connor Lepage	All
4.3.1	Dylan Hauer	All
4.3.1.1	Tristan Lepage	All

4.3.1.2	Tristan Lepage	All
4.3.1.3	Tristan Lepage	All
4.3.1.4	Tristan Lepage	All
4.3.1.5	Daraius Boston,Tristan Lepage	All
4.3.1.6	Ryan Shaw, Tristan Lepage	All
4.4	Connor Lepage	All
4.4.1	Connor Lepage	All
4.4.2	Tristan Lepage	All
4.5	Connor Lepage	All
4.5.1	Tristan Lepage	All
4.5.2	Tristan Lepage	All
5	Tristan Lepage, Dylan Hauer	All
5.1	Tristan Lepage, Dylan Hauer	All
5.1.1	Tristan Lepage	All
5.1.2	Dylan Hauer	All
5.2	Tristan Lepage, Dylan Hauer	All
5.2.1	Tristan Lepage	All
5.2.2	Tristan Lepage, Dylan Hauer	All
6	Tristan Lepage	All
6.1	Tristan Lepage	All
6.1.1	Tristan Lepage	All
6.1.2	Tristan Lepage	All
6.1.3	Tristan Lepage	All
6.2.1	Tristan Lepage	All
6.2.2	Tristan Lepage	All

6.2.3	Tristan Lepage	All
7	Daraius Boston, Connor Lepage	All
7.1	Connor Lepage	All
7.1.1	Connor Lepage	All
7.1.2	Daraius Boston	All
7.2	Conor Lepage	All
7.2.1	Connor Lepage	All
7.2.2	Daraius Boston	All
8	Ryan Shaw	All
8.1	Ryan Shaw	All
8.1.1	Ryan Shaw	All
8.1.2	Ryan Shaw	All
8.1.3.1	Ryan Shaw	All
8.1.3.2	Ryan Shaw	All
8.1.3.3	Ryan Shaw	All
8.1.3.4	Ryan Shaw	All
8.1.4	Ryan Shaw	All
8.1.4.1	Ryan Shaw	All
8.1.4.2	Ryan Shaw	All
8.1.5	Ryan Shaw	All
9	Connor Lepage	All
9.1	Connor Lepage	All
9.1.1	Connor Lepage	All
9.2	Dylan Hauer	All
9.2.1	Dylan Hauer	All

9.2.2	Dylan Hauer, Tristan Lepage	All
9.2.3	Dylan Hauer	All
9.2.4	Dylan Hauer	All
9.2.5	Dylan Hauer	All
9.3.1	Ryan Shaw	All
9.3.2	Ryan Shaw	All
9.3.3	Ryan Shaw	All
9.3.4	Ryan Shaw	All
9.3.5	Ryan Shaw	All
9.3.6	Ryan Shaw	All
9.3.7.1	Ryan Shaw	All
9.3.7.2	Ryan Shaw	All
10.1	Tristan Lepage	All
10.2	Tristan Lepage	All
10.3	Ryan Shaw, Dylan Hauer	All
10.4	Tristan Lepage	All
10.5	Tristan Lepage	All
10.6	Tristan Lepage	All
10.7	Ryan Shaw	All
10.8	Daraius Boston	All
10.9	Ryan Shaw	All
10.10	Ryan Shaw	All
10.11	Ryan Shaw	All
10.11.1	Ryan Shaw	All
10.11.2	Ryan Shaw	All

10.11.3	Ryan Shaw	All
11.1	Daraius Boston, Tristan Lepage	All
12.1	Dylan Hauer, Connor Lepage	All
12.2	Daraius Boston	All
12.3	Connor Lepage	All
12.4	Tristan Lepage	All
12.5	Dylan Hauer	All

List of Abbreviation

Abbreviation	Description
AC	Alternating Current
ABS	Acrylonitrile Butadiene Styrene
AO	Analog Output
BPM	Beats Per Minute
CAD	Computer Aided Design
ROM	Range of Motion
CPR	Cardiopulmonary Resuscitation
DC	Direct Current
DAC	Digital-to-Analog Converter
DO	Digital Output
DOF	Degrees of Freedom
DIY	Do it yourself - partianing to easily accessible tools and processes
EMS	Emergency Medical Services
EMT	Emergency Medical Technician
FSR	Force Sensitive Resistor
GND	Ground
ISR	Interrupt Service Routine
IQP	Interactive Qualifying Project
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MQP	Major Qualifying Project
PLA	Polylactic Acid

PETG	Polyethylene terephthalate
I^2C	I-Squared-C
SDA	Serial Data
SCL	Serial Clock
TPU	Thermoplastic Polyurethane
TPE	Thermoplastic elastomers
UI	User Interface
VCC	Voltage Common Collector
WPI	Worcester Polytechnic Institute

Nomenclature

Nomenclature	Description	Additional Notes
V	volt	Used for electrical analysis
A	ampere	Used for electrical analysis
Ω	ohm	Used for electrical analysis
“	inch	Used for length
N	newton	Used for force calculations
dB	decibel	Used for sound test
m	meter	Used for length and dimensions
Hz	hertz	Used for frequency
M#	millimeter Screw Size	Used for screw thread height
°	degree	Used for angles
mm	Millimeter	Used depicting lengths
kg-cm	kilogram-centimeter	Used for torque
mm^3	Cubic Millimeter	Used in volume analysis

Executive Summary

For a summary of our project, please visit our page on the virtual showcase by searching our names in the following link. On this page you will find a video that summarizes our work as well as slides which give more information.

https://drive.google.com/file/d/1UudfeOG26KFhuOyQtxq2_Rw1loETZO3f/view?usp=sharing

Chapter 1: Introduction

Patient simulators are tools used by medical professionals and students to mimic human antimony or function [1]. They are commonly found in educational settings as well as in dedicated simulation centers. Simulation allows both experienced professionals and students experience in situations that a healthy human volunteer could not demonstrate. Patient simulators vary from highly realistic models all the way down to simplified representations of anatomy. Medical simulation is measured by fidelity on a scale of low to high. Fidelity measures how completely a tool replicates human physiological functions. Lower fidelity machines are good for training a specific task. An example of an extremely low fidelity simulation tool is a suture practice kit [2], which simulates wounds in human skin with a single piece of silicone. Other examples of low fidelity simulators include manikins like CPR dummies and model urinary tracts for catheter insertion training [3]. These lower fidelity simulators are typically static and cost a mere fraction of the higher fidelity manikins.

Mid-fidelity manikins are similar to lower fidelity manikins in terms of how they look; however begin to incorporate electronics that mimic physiological functions, such as breathing and cardiac function. Mid-fidelity manikins are mainly used in educational settings where students can practice diagnosis and decision making based on vital signs. This prepares the students for work with actual patients, allowing for more accurate and quick diagnosis [3].

High fidelity manikins, typically costing well over $20,000 [4], are usually full anatomical models of humans, able to mimik most of the physiological functions that humans go through [3]. They can mimic breathing, speech, the sounds of organs, and even the process of giving birth. Having experience in these scenarios prior to meeting the patient is extremely valuable to the medical community. This has led to a growing demand for medical simulation tools.

The initial creation of this prototype by Dick et al focused on designing the systems and creating a working head. The next group consisting of Cohen et al worked to change the direction of the project towards medical applications. With this change came many improvements to the head in order to adapt it towards medical simulations while also the removal of unneeded features. Many issues arose with last year's MQP as with the Covid-19 pandemic many parts did not get printed and CAD files were in disarray. Testing also showed issues with actuation of the jaw and neck mechanisms when included in a completed assembly of the head.

With this in mind we intend to assess areas of improvement as well as define any ways we can improve manufacturability of our device. The main aspects that we will focus on are mechanical improvements, structural and material modifications, and improvements in manufacturability. Once these areas of improvement were identified and requirements for each area were developed, they were designed, implemented and tested.

The following report will be organized into various chapters which will discuss the different aspects of our project or regarding design changes that occurred on different systems in our animatronic head. Chapter 2 provides some background on the previous years MQP in which our project continues off of. Chapter 3 will provide needed background regarding manikins in the medical field and manufacturability, two foundational concepts that set the base for our project. Next Chapter 4 will describe our direction of the project as well as our three main objectives. This chapter will also provide information on the different areas of improvement we had defined and a general description on what our intent was regarding redesign. Chapter 5 will begin our sections that dive into the different systems that we worked on and our methodology when it comes to our redesign and implementation. More specifically chapter 5 will focus on changes we made to the base, neck enclosure, and neck mechanism focusing on the design and implementation of a Stewart platform. Chapter 6 will continue on this same effort and provide information on the changes made to the oral cavity, jaw, and lips. Chapter 7 will focus on all of the changes we made to both the lattice and skin subsystems focusing on our designs for snap fits and a new skin creation method using different infill percentages on the inside and outside layers of our lattice pieces. Next, Chapter 8 focuses on the changes made to our electronics and coding emphasizing overall code redesign and the implementation of an LCD screen. Chapter 9 is where we describe the results of our redesign attempts and how objectives were met emphasizing the work we did improving manufacturability. Chapter 10 describes potential areas for future work breaking down what improvements can be made on individual systems as well as how manufacturability can be improved. Lastly chapter 11 is our conclusion describing a personal reflection on how our classes at WPI assisted us in completing this project. Following this are our references and appendices

Chapter 2: Existing Prototype

An initial prototype was created by Dick et al. [5] which was improved and adapted to medical training by Cohen et al. [6]. During these time periods components of the design were built, tested, and improved upon. Below, in figure 1, is the most complete assembly of the head by Dick et al.

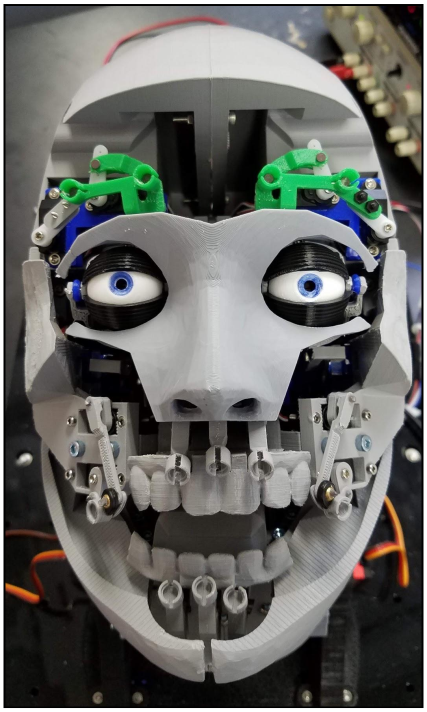


Figure 1: Prototype of animatronic head by Dick et al

The head inherited by our group was improved upon from this version; however an assembly had not been completed due to the Covid-19 Pandemic. The system needed a lot of work before we could begin our assembly and testing. By using recommendations from last year along with our objectives created we began research into potential redesign additions.

2.1 Rationale

The Animatronic Head project was started to further the development of a lower cost medical animatronic to allow for more access to medical training. Previous years cited high costs as one of the main contributing factors to the inaccessibility of animatronics. To combat this, 3D printing was chosen as a main manufacturing technique, due to its comparatively low cost. This project was started as a feasibility study to determine the viability and usefulness of low cost medical training animatronics.

2.2 Outcomes

Showcased below is the outcomes and achievements of last year’s MQP team. This includes changes made to the neck, eye, jaw, sensors, and electronics. This section then goes on to describe the importance of this and its relevance to this year's MQP.

2.2.1 Neck Mechanism

Last year's MQP team [6] assembled and completed tests of many of the Head Subsystems. These include testing of the neck, the eyes and the jaw. The neck mechanism shown in figure 2 below was assembled and tested. This neck was made of a two bar linkage with three servos required for actuation. This design contained three DOF and was capable of ±40°about the X axis ±45° about the Y axis and 35° left or right about the Z-axis. It is important to note that the neck the previous group had developed was only tested as a subsystem capable of generating approximately 15kg-cm. Comparing these torque capabilities it is obvious that there would be issues actuating the neck with the head fully assembled especially if weight is added through design modifications.

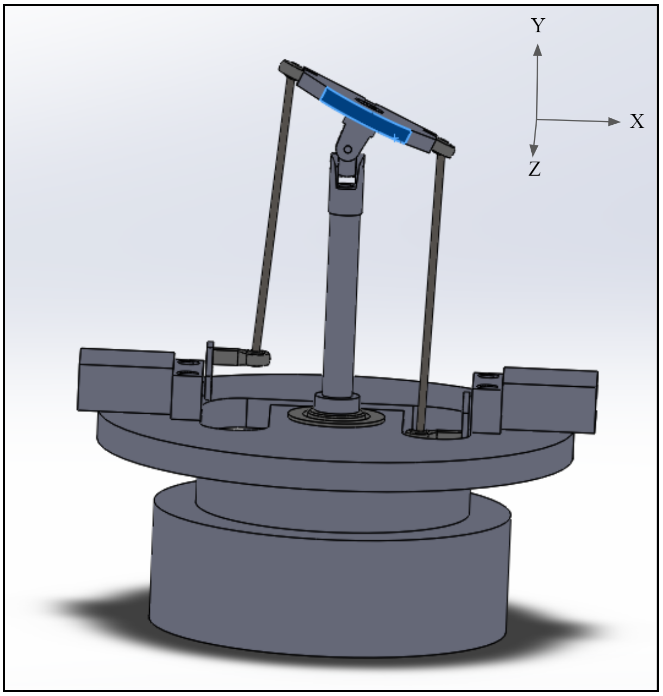


Figure 2: CAD Model of Neck Mechanism by Cohen et al

2.2.2 Eye Mechanism

A redesign of the Eye mechanism was also completed but was never printed and tested. This took steps towards compatibility by increasing the volume from 107,900mm^3 to 129,054mm^3. Figure 3 shows the eye assembly as the 2019-20 team designed. Unfortunately, many issues were discovered with the eye assembly's CAD model. Multiple part files were missing and the updated version of some parts were never saved. This is believed to be due to the start of the Covid-19 Pandemic towards the conclusion of their project.

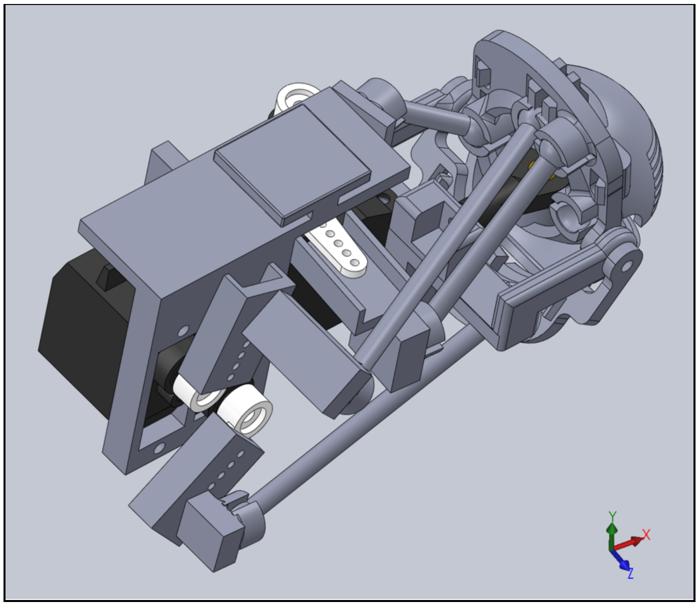


Figure 3: CAD Model of the Eye Mechanism by Cohen et al

2.2.3 Jaw Mechanism

The Jaw mechanism inherited by our group was improved upon from the 2018 [5] version; however due to the same reasons as the Eye, many parts needed serious changes or a complete redesign. Luckily with the Jaw, previous years had manufactured test prints that we were able to use as a base for our design. This subsystem was created using a 6 bar linkage and 4 servos, two for opening and closing the jaw and two for jaw thrusting maneuvers. Figure 4 shows the inherited cad for the Jaw mechanism. This subsystem needed significant changes as it had been assembled using glue and the jaw was only able to open to 30mm at a 30° hinge angle. This was roughly 52% of its required opening which was estimated to be 57.2mm Due to restrictions caused by the lips the jaw was unable to actuate with the lips attached even with a force of 3.6kg-cm being supplied.

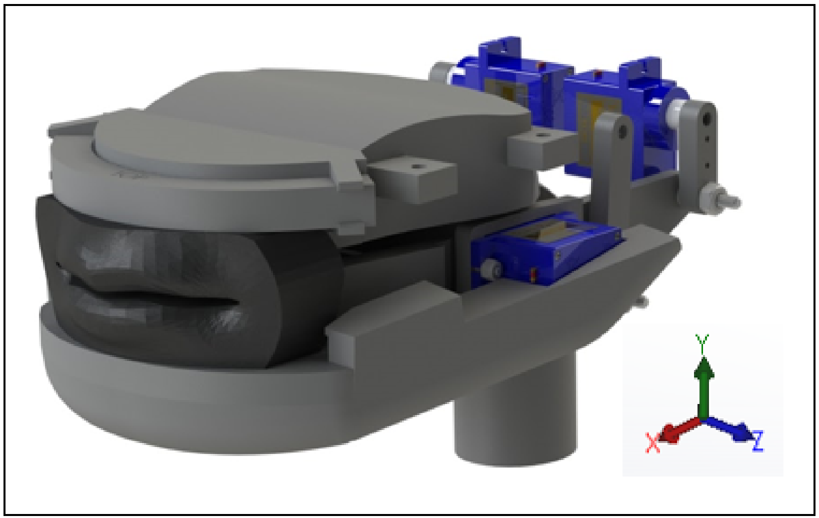


Figure 4: CAD Model of the Jaw Mechanism by Cohen et al

2.2.4 Sensors and Electronics

From the Dick et al. iteration to Cohen et al. iteration, the electronics currently includes; amplifier and speaker, microphone, 3 different servo types and servo driver board, LCD screen and keyboard, FSRs, camera, and solenoids. These components have been put through various testing, many of the systems have been tested as stand alone systems and not fully integrated into the head.

The microphone works essentially as a switch and plays a pre-programmed response giving its limited use cases. The LCD screen was noted as lacking ability to communicate enough information to the user. The FSRs are installed on the lattice in such a way that they are twisted which gives off a reading, this needs to be taken into account in the code. The Camera has a well documented testing and evidence of working eye tracking code. The solenoids and the corresponding code is fully flushed out and tested.

The code was developed without the peripherals due to Covid-19 and therefore untested, this is a major evaluation that was conducted. Several issues were discovered, such as deallocated memory in the UI functions as well as polling architecture.

2.3 Relevance to this MQP

Figures 2, 3 and 4 show that we inherited a large number of incomplete systems. As it stood, the prototype produced by the 2019-20 team was unusable for medical simulation and training. This is due in large part to the neck mechanism not being strong enough as well as the abundance of missing CAD files. There was, however, a large collection of disorganized files and existing prototypes. Given this knowledge and these items, the 2019-20 project served as an excellent jumping point for improvement and eventual implementation for our team.

Chapter 3: Background

Showcased below is the background required to understand the project as a whole. This is broken up into manikins in the medical field, sensors and programming in animatronics, and manufacturability as a whole.

3.1 Manikins in the medical field

Manikins are used in various applications throughout the medical field . The main use they serve is simulating health complications as running the same training scenarios with a human volunteer would not yield the same experience or simulate the same health problems. As such, some training is done best through a manikin or an animatronic.

One of the more prevalent training manikins are CPR manikins. These are manikins used to teach chest compressions when learning CPR by making a clicking sound when compressions reach a certain depth [7]. A manikin is required for training as chest compressions could harm a person if they're not in a life threatening position.

From our meeting with WPI EMS, a lot of EMT training is hard or impossible to practice on another human for a few reasons. A procedure may be invasive and could injure or make the person uncomfortable. Additionally, a procedure could be impossible to practice on a normal healthy human. An invasive procedure could be defined as inserting anything into one's body during a medical procedure. An example of this is a jaw thrust maneuver, which involves opening a patient's airway to deliver oxygen [8]. Another example is nasopharyngeal and oropharyngeal tube insertion, which involves putting a small tube through the nose and into the mouth [https://www.ambulance.qld.gov.au/docs/clinical/cpp/CPP_Nasopharyngeal%20airway%20insert ion.pdf]. These procedures are extremely uncomfortable and sometimes painful to undergo. So, use of a specialized manikin would give medical personnel the experience they need without bringing harm to human volunteers.

Medical situations that can not be simulated with a healthy human are generally in the realm of health complications where the subject would be put at risk to simulate the issue. Examples of this could be poor pupil dilation or irregular heart rates [9].

3.2 Manufacturability

Manufacturability is the ease at which something can be built or manufactured. This is an important engineering principle, especially in the case of a do-it-yourself animatronic.

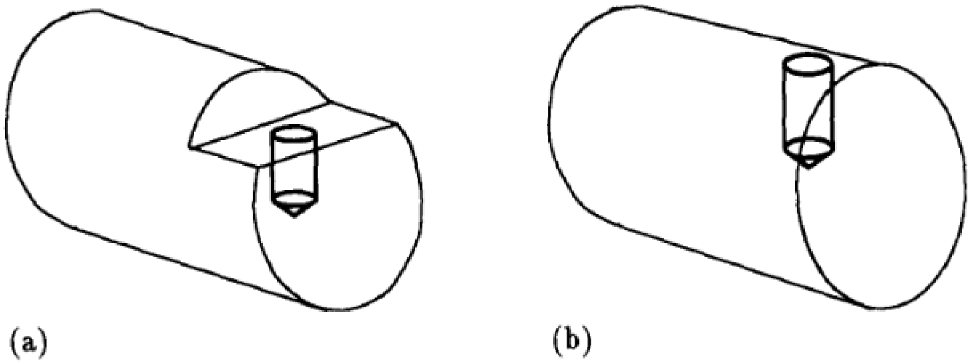


Figure 5: Accessibility difference between two parts, reproduced as is from [10]

Shown in Figure 5 is an example taken from *Guptaa and Nau [10]* . This example showcases object “a” that is designed for manufacturability well, and object “b” which is designed poorly. This is based upon the manufacturability principle of accessibility with object “a” being much more accessible due to a flat surface [11]. Another great example of this accessibility principle is also showcased through this figure. The fillet at the bottom of the hole would allow a screw to easily be inserted, as opposed to a flat surface in which it would have trouble finding the part it is supposed to screw into. This is involved in our project through the use of mainly slide-fits which are a form of torsional snap-fit.

3.2.1 Slide fits

The main premise is that snap-fit joints are comprised of "a protruding part of one component, e.g., a hook, stud or bead that is deflected briefly during the joining operation and catches in a depression"[10]

To start explaining this, you must assume the process of elastic deformation must be active. Elastic deformation is the first step before a transition to plastic behavior and is when the material goes back to its original form without undergoing yielding to change its shape permanently. This is showcased through this article on elastic deformation well.[12] This basically means that a piece of one part is bent through a perfect elastic deformation so that after the protruding part passes the other part it then depresses back to a normal position so that the two parts join. This is expressed nicely below from figure 6 of this article from *Bayer Material Science [10]*.

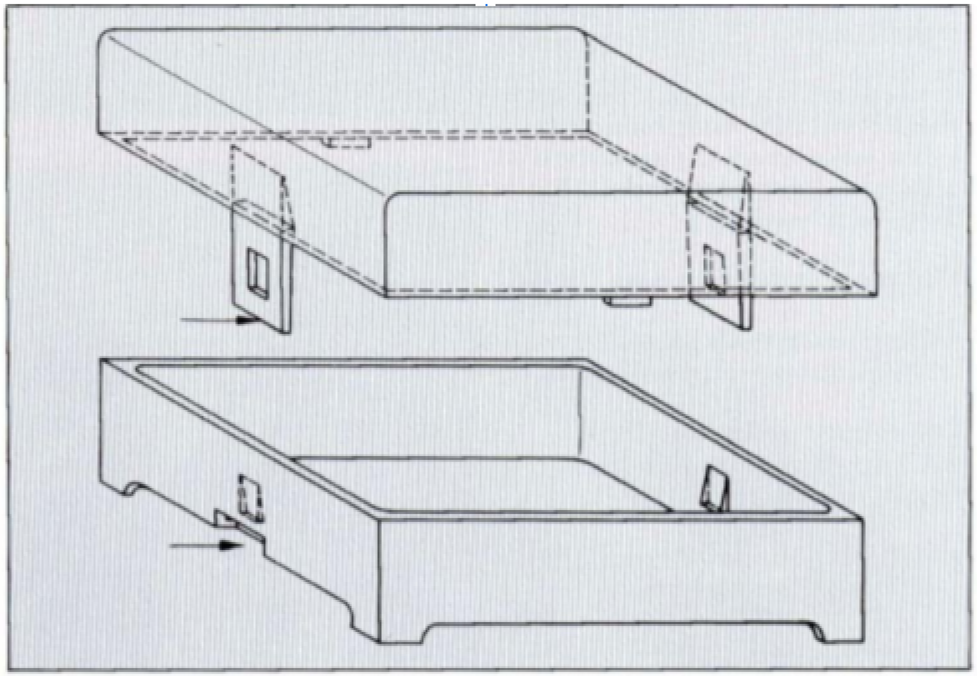


Figure 6: U-connector type snap-fit, reproduced as is from [10]

The next important point of this article is its breakdown into specific and important types of snap-fits. The first type listed are cantilever snap joints. The great part of this type is that they are separable but also hold firmly. This type is the same as shown in figure 6 from *Bayer Material Science [10]*. The next type is a Torsional snap-fit. This type of fit involves the use of a "deflection force that is given largely by torsion that its shaft permits an easy opening of the cover under a force P"[10]. An example of this is shown below:

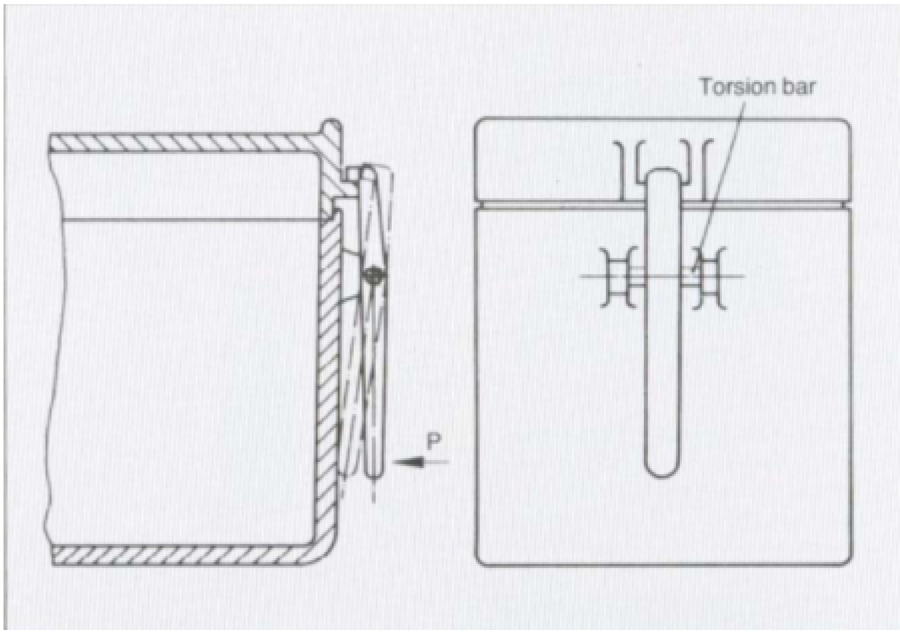


Figure 7: Torsional snap-fit, reproduced as is from [10]

The most important type according to the article is an annular snap-fit. This type is held together by a bunch of small undercuts that in turn give this type some really great strength. This is shown below in figure 8 from *Bayer Material Science [10]* which showcases a lamp housing.

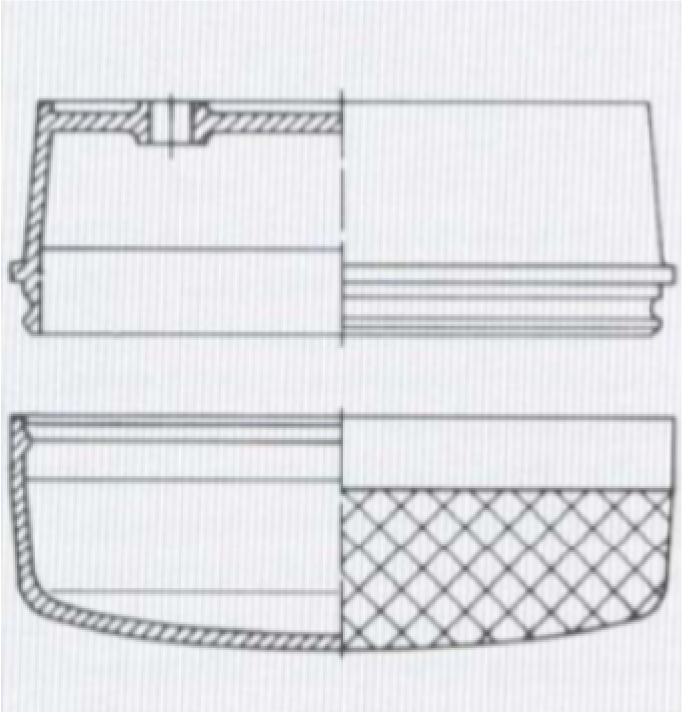


Figure 8: Annular snap-fit, reproduced as is from [10]

3.2.2 3D Printing

3D printing is a form of additive manufacturing that utilizes melted polymers to create parts. 3D printing is one of the best choices when trying to increase the manufacturability of a complex part. This is due to a variety of reasons but the main one being that acquiring a 3D printer is much simpler and much more inexpensive when compared to tooling required to create parts through other techniques such as machining. 3D printing also enables the creation of complex parts by allowing support structures and a variety of ways to change material properties such as changing infill percentage. This method of manufacturing ensures that most individuals, if given the CAD files and assembly procedure, would be able to create an exact copy of our design. This also enables the ability to easily change and prototype specific parts. By simply adjusting a CAD model to fit the needs of the user or customer, one would be able to easily print out new parts to install into the animatronic head. This makes adjustments to different training purposes simple and easy. This method is also much more cost effective than traditional manufacturing processes such as injection molding or machining. For one, this method allows for quick production by being faster than traditional processes but also, as stated above, enables much faster designing through the use of CAD. This is compounded when adding on the fact that most times operators are not required to produce a good print and can get on with other tasks while the printer does the work [13]. This method is also much more cost effective. This is because the materials needed to 3D print are cheaper and do not need much space to store a large stock of materials except if bulk part production is necessary. Overall, by making production cheaper and design faster, 3D printing has many obvious advantages that aid in manufacturability. 3D printing also has a wide range of materials it can work with; PLA, ABS, TPU, TPE and PETG. These materials are useful in different ways and for different applications. Table 1 shows information and the material properties of these materials.

Table 1: 3D printable filaments comparisons

Material	**Tensile Strength (MPa)**	**Density (g/cm^3)**	**Print Temps (°C)**	**Max Service Temp (°C)**	**Flexible**
PLA	65	1.24	190-220	52	No
ABS	40	1.04	220-250	98	No
PETG	53	1.23	230-250	73	No
TPU	40-85	1.06-1.14	220-270	80-95	Yes
TPE	26-43	1.19-1.23	225-245	60-74	Yes

Chapter 4: Mission, Objectives and Requirements

This chapter outlines the decision process we took to determine the direction of the project and defines the mission and objectives. The requirements for this project are listed in depth below.

4.1 Direction of the Project

The previous year's team decided to take the project in the direction of EMT training. Due to difficulties regarding COVID-19, our team was not left with a complete assembly of the head. As a result, the beginning of our project was largely focused on putting together the puzzle pieces so to speak.

Our project was far from being solely centered around organization, though. Our main concern was making improvements to last year's model on a few fronts. Namely; improving upon the skin lattice, the neck mechanism, the assembly process, rewriting the code, and improving organization of the digital models.

In regards to the skin lattice, the original model had the skin and structural pieces as different parts, electing to make the skin out of silicone. When changing this, we decided to integrate the skin into the structural segment, making it one piece to print.

The neck mechanism was too weak to support the head in its current state and, as a result, we felt it was best to go for a new design. Stewart platforms seemed like the best choice as they are stronger but also allow the neck six DOF, a great improvement from the original design's three.

The assembly process was another concern of ours. The implementation of snap and slide fits combined with a reduction of hardware was a must. This meant it would be quicker and easier for consumers to assemble.

The code to control a fully operational head was pushed to the Github but untested. A full wiring of the electronics and compiling the code was needed to ensure functionality. Improving organization of our digital models was crucial, not only for the consumer, but also for our own sake. The improved organization provided easy access to CADfiles for the sake of redesigning or reprinting. It also supplied us with a complete inventory of parts as some files were missing in the beginning of our project.

4.2 Mission Statement and Objectives

Our purpose while working on this project was to improve upon the design of an animatronic head designed for use in EMT training while maintaining the ideas of being both modular and inexpensive. To accomplish this, we wanted to improve the realism of the head as well as make it easier to assemble and use.

Improvements in realism were accomplished in two ways. One was making improvements to the neck design. Improving its stability and degrees of freedom would allow the neck to move much more realistically. Improving the feeling of the skin lattice was another way we elected to accomplish this. By softening the outer side of the neck and head lattice, the surface would be more soft to the touch and therefore more lifelike.

Ease of assembly was a big objective of ours from the start. In the beginning of our project, the head lattice was held together exclusively with hardware, much of which was hard to reach by hand or with tools. Reduction of hardware and addition of snap fits and slide fits would help improve our user experience during assembly.

Lastly was to test the software and to make changes as necessary. This was mainly done by evaluating the functions with the timer structure and the overall polling architecture as well as programming the new neck subsystem and UI system.

4.3 Objective 1: Identify Areas of Improvement

First, we wanted to see how the project could be improved in terms of medical testing and EMT/EMS training. This was done through research into aspects like the Glasgow coma scale as well as the surveying of WPI's EMS members to get their opinion on the features required for their training purposes.

Next, we improved on a number of different subsystems within the head. We started off with the creation of a Stewart platform to replace the previous neck design. The old neck could not sufficiently perform the required tasks of supporting the weight of the head while in motion. To solve this we built a Stewart platform that can support the weight of the head as well as perform more life-like movements. We also redesigned the neck housing as the previous years was blocky and made of wood, making it not easily replicable.

The oral cavity is the next subsystem we completely redesigned. The old jaw could not open mainly because of the lips being too rigid. We researched problems regarding this and created preliminary designs for similar style lips to that shown in Disney's *Avatar* animatronics where it is created in segments rather than one solid piece. We have also created CAD models for this potential design and drew out potential implementations of a waterproof oral cavity for possible dental and swallowing applications. We opted for a simpler solution of designing the current lips into two separate pieces due to time constraints.

Following that, we also developed the eyes further. The last group already had a preliminary design for a new eye subsystem. We then went about building it to discover multiple issues with the linkages not being long enough or not fitting right. This led to a partial redesign in terms of lengths, We are still encountering some issues regarding the strength of the material that needs to be researched as some connections are as small as 2mm.

Next was a complete redesign of the lattice and skin subsystems. As for the lattice we have worked on implementing designs we created in terms of conceptual, ready to print, CAD objects. These are fully completed and are being implemented in a build of the head. As for the skin, we created a procedure to implement a partial infill percentage on the outside layer of the lattice. This will produce a skin-like feel while still allowing the lattice to be the rigid, matrix like structure that holds the head together.

4.3.1 Areas of Improvement on Current Prototype

The existing prototype was not something we could begin working with in its current state. When we began our project, it was nothing more than a mixture of different iterations of parts, some partly assembled, some not at all. On a positive note, many of the subassemblies were together. This made for much easier analysis and modification of the parts.

Many pieces of the lattice had sections cut out of them, which was evident of filing or in some cases burning away material. We imagine this was due to fitment issues or made it easier to route the wiring in its current state.

While disassembling the head lattice there were a few glaring problems. One was a mix of both SAE and Metric hardware. Another issue was that much of the hardware was incredibly hard to access by hand and nearly impossible with a tool. This made the disassembly process difficult so we could only imagine what it was like to put together. But, the disassembly did lead to a point we wanted to address, manufacturability. Reducing the amount of hardware along with eliminating the mix of both SAE and Metric hardware was a must. This led to our decision to implement snap fits wherever possible in the current design.

The current design of the neck was unstable. The platform on which the head would be attached seemed to constantly sag forward. The universal joint in the central beam as well as the two arms connected to servo motors seemed unable to support the weight. Clearancing issues around those same servo motors were also evident from the many filing marks made to allow the servo motors full range of motion.

The current organization of many of the CAD files was also poor. Digital versions of the parts were fickle to find. After going through the parts with a corresponding list of every part, we found that some of the part files were nonexistent and needed to be remodeled entirely.

4.3.1.1 Neck

The neck was one of the primary focuses of this project in terms of mechanical subsystems. Last year's team made great improvements by increasing the DOF possible and designing a neck capable of human-like movements. One issue is that with the current design only having two servos preliminary testing showed the neck would be too weak to hold and move the head especially if any weight was added in our redesign. Due to this we went with a Stewart platform based design that would have six servos therefore adding the strength we needed to move the neck when the head was fully assembled. This addition of four servos also enabled six degrees of freedom allowing much more lifelike motion.

4.3.1.2 Jaw and Oral Cavity

With the vast improvement made by last year's team in these subsystems slight adjustments were needed to correct inconsistencies when fully assembled. The main issue that was improved was the manufacturability by removing the need for adhesives during assembly. To do this we added hardware and corresponding features to the part.

4.3.1.3 Lips

While not that large of a focus, the lips needed to be redesigned so as to not restrict the motion of the jaw. With preliminary testing, it was found that even with TPE lips the jaw was not strong enough to work against the force added by the lips. To remedy this we took on a complete redesign of the lips to work synergistically with the current jaw mechanism.

4.3.1.4 Eyes, Eyelids and Eyebrows

The eyes were mostly complete when we inherited the project. There were a few issues with range of motion for some of the linkages as well as some missing cad files. To remedy this we decided to focus on reworking the cad assembly to remedy the linkage issues and replace all of the missing models. Specifically we had to redo the length of many of the linkages and replace the eyeball.

4.3.1.5 Lattice and Skin

The lattice and skin were the primary focuses of overall redesign. Last year's team had used a silicon skin that was molded and attached over the top of the lattice using magnets. This was not lifelike and did not aid in the manufacturability of our design. We decided to, instead of making these two different parts, combine the skin like feel with the lattice pieces by incorporating two different infill percentages between the outer and inner portion of the lattice when printing.

4.3.1.6 Code Structure

The code structure was upgraded by the previous group in terms of organization and the use of a timer based system for individual subsystems. However, with covid-19, the code was left untested. A full wiring and debugging had to be done. The replacement of the "delay()" function with "mills()" was beneficial to the function of the subsystems. However, the polling architecture can be improved with interrupt architecture. This would allow for smoother and more accurate simulation movements and sensor readings. With suggestions from the previous years group, the UI peripherals would be upgraded to a touch screen.

4.4 Objective 2: Designing For Manufacturability

Designing for manufacturability was one of the most important and extensive objectives within our project. As soon as we saw the animatronic we knew it was crucial to be able to replicate it. This was not able to be done in the current state we received it and with numerous amounts of connectors, the building of the head was confusing and could lead to a loss of replicability. On top of that, not all CAD files were available. As an example, if this head was to be sent to a local community college so they could build and use it, or if it was made open source, a lot would be missing.

The first thing our team did was contact last year's team and gather all of the CAD part files for the Animatronic as well as recreating any that were lost. We also converted and unified all of the units to metric. This allows all of the pieces to be printed and easily understood.

Next, we focused a lot on the use of snap-fits, this is a type of connector that can be built into a part and will allow a strong connection without the need for extra materials. We implemented this into the entire lattice structure, removing the need for a soldering iron, 8 screw inserts, and 12 connectors. This will make assembly faster and less confusing.

4.4.1 Snap/Slide fits

The connection type that we mainly used was that of a slide-fit. This is a form of a torsional snap-fit in which we used a trapezoidal, puzzle piece like connector. This consists of a plus and a minus portion and is showcased in Figure 9.

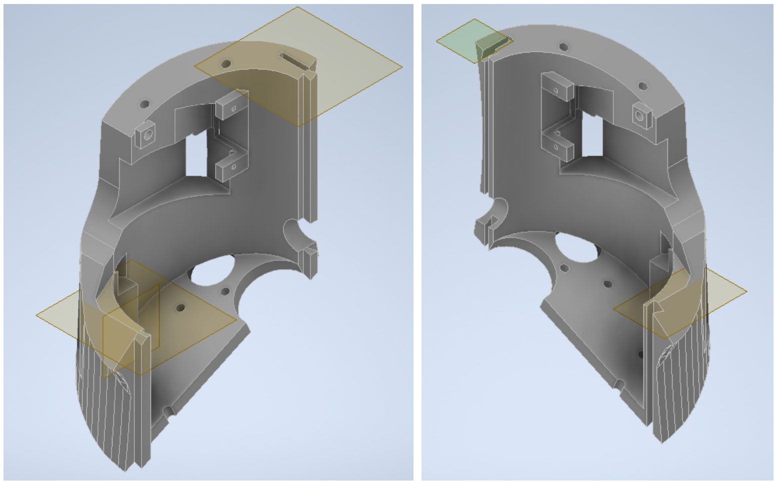


Figure 9: Neck Lattice CAD

This simple change will create a much more manufacturable animatronic head with the main benefit being a reduction in time for this section to be built.

4.4.2 3D printing

Due to the do-it-yourself and low cost nature of the project, 3D printing was the technique that we wanted to use for the majority of our manufacturing. This is due to the low cost and availability of the technology for both the tools as well as the filaments and materials. Previous years designed the majority of the head to be manufactured using 3D printing in PLA. We hoped to convert even more of the head to 3D printable parts as well as utilize a more diverse range of 3D printed materials.

4.5 Objective 3: Construct and organize

For the third objective we mainly wanted a way to create a more organized project as a whole, and to assemble the entire head. One of the first things we did in this project is implement a CAD database. This was partially for our group so we could get organized, but also for future groups so that they do not experience a disorganized handoff of the project. What we did is fix all of the broken parts and assemblies and have part files available for every piece of the head. This was then uploaded to github for future groups' easy access .

Next was the assembly of the head. As of right now we have multiple complete subsystems built. This includes the eyebrow and oral cavity with the eye subsystem being close to fully built. We want to implement the new neck into this build so we have the base clear and ready to start with the Stewart Platform.

4.5.1 Assembly

One of our main objectives was to pick up where last year's team left off and assemble the entire animatronic head. This included the need to print out all unprinted designs as well as printing out and implementing any new designs we come up with. This was a large objective of ours, the main reason being the head was not assembled and only subsystems were tested. We also wanted to get everything constructed so we could have EMS personnel adequately assess the achievements and shortcomings of our completed animatronic head. This would provide us with useful information especially regarding the next steps and which systems need more development to be used for training purposes.

4.5.2 Organization

To aid in organization we had two smaller objectives in mind. The first is to create a CAD database in order to ensure all current CAD files are held in one place, are easy to access, and are all correct. The second is to ensure all printed and assembled parts are packed up properly and neatly for an easy hand off to the next team. In order to accomplish the first smaller objective we needed to ensure a unification of all units to metric as well as create any files or assemblies that were broken or missing. We are also going to make it a priority to gather all needed parts and store them neatly in organized boxes to hand off to the next team. This objective is of utmost importance as it really slowed down our progress when beginning the project due to a lack of available CAD files and parts. By ensuring a working CAD database and organized parts we hope to enable a quick transition into improving the animatronic head for the next team.

Chapter 5: Base, Neck Enclosure, and Neck Mechanism

This chapter details the base, neck enclosure, and Neck mechanisms progress that was made and what research led us to these design decisions. This chapter outlines the specifics of redesign regarding the neck enclosure and the neck mechanism focusing on our implementation of a Stewart platform.

5.1 Methodology

5.1.1 Neck Enclosure

With the new design for the neck mechanism being a Stewart platform, as depicted in the following section, a new neck enclosure needed to be designed to encompass the new shape and dimensions. The first thing we thought of was to make sure it would be 3D printed instead of the current wooden enclosure. We also wanted to use the idea of split infill percentages in order to create a skin like feel that was not present in the previous iteration of the neck enclosure. Lastly this was designed with manufacturability in mind by using slide fits and limited fasteners in order to make the subsystem easier to assemble.

5.1.2 Neck Mechanism

The previous group's design for the neck mechanism involved a universal joint and three servo motors. Two motors drove the head in different directions so it could tilt while one rotated the assembly. Altogether, this allowed the head 3 DOF, tilting left to right, up and down, and being able to shake its head back and forth. The previous group never actually got the mechanism in a state where it was moving, and on top of that we believed it would not be able to support the weight of the head.

When modifying the neck mechanism, we wanted to accomplish two things. One, increase the DOF. Two, build a more structurally sound neck mechanism. We believed the best way to accomplish both of these tasks was to build a Stewart platform.

Figure 10: Example of a Stewart platform, reproduced as is from [14]

A Stewart platform, as seen in Figure 10, is essentially a platform supported by six legs. These legs are usually in the form of linear actuators, meaning each leg can increase or decrease its length. Each leg has universal joints attached at either end. These universal joints are what connect the linear actuators to the base or the platform. As the legs actuate, the platform has the ability to move.

Because each leg is its own mechanism, Stewart platforms have 6 DOF; X, Y, Z, roll, pitch, and yaw. For our purposes, this allows the head to have more realism and fluidity in its motion. Another benefit of the Stewart platforms utilization of 6 legs is that the head will be evenly supported throughout the mechanism and the weight of the head will no longer be a concern.

5.2 Design and Implementation

5.2.1 Neck Enclosure

Going into the design for the neck mechanism we can see that the previous design takes on an obscure shape which is a somewhat unrealistic representation of the human shoulders as the enclosure is meant to be. Figure 11 shows the previous design which was constructed out of wood that was cut into the correct shapes in order to speed up construction time due to a time crunch.

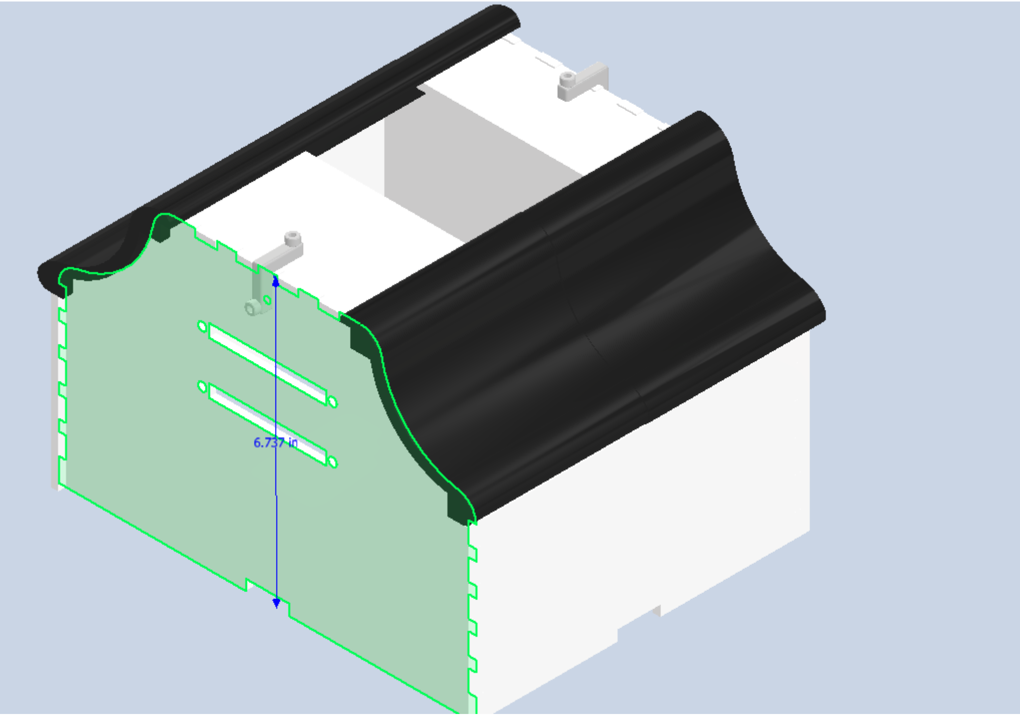


Figure 11: CAD Model of the Neck Enclosure by Cohen et al

We made it a priority to spend a lot of time designing so we would have adequate time printing. This way we wouldn't be rushed to create a design not up to the caliber of the rest of the animatronic head. Our design is completely 3D printed parts with an entirely different shape, the preliminary design is as follows.

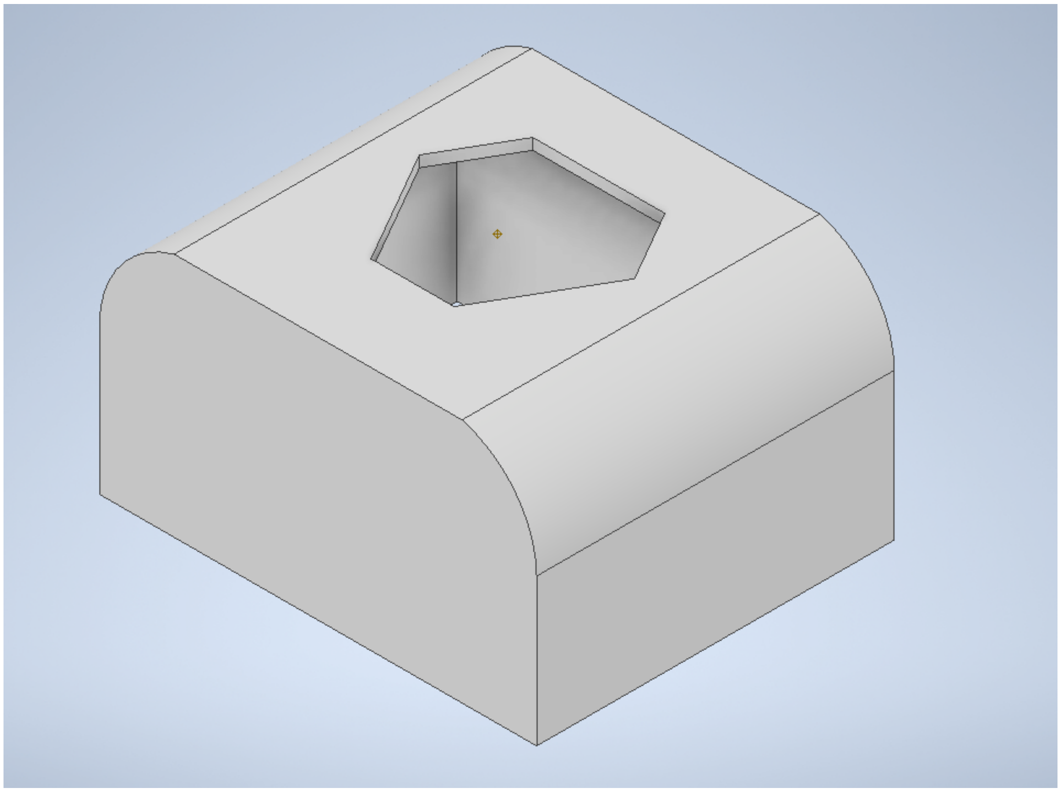


Figure 12: CAD Model for Preliminary Neck enclosure

As shown in figure 12, the shaping of the shoulder caps shown in black in the first image have been shaped to appear more natural when looking at the silhouette of the animatronic head and the cutout where the top of the neck mechanism will protrude was reshaped to be synergistic with the new neck mechanism. We also designed this structure to be easily assembled and disassembled by getting rid of hardware that would be used and replacing it with snapfits. These snapfits allow for ease of access to the neck mechanism and wiring by means of ease of removal. Also by changing the aperture shape at the top we allow for all ranges of motion of our new neck mechanism while the original enclosure would definitely limit the movement of our new mechanism. This is also designed to allow the application of our new skin design where the outer

3 mm would be adjusted to a different infill percentage and printed from TPU in order to give a tender skin-like feel when touched.

5.2.2 Neck Mechanism

When designing our stewart platform we went through a number of different ideas for how we were going to move our legs.

The first method we chose was implementation of linear actuators. Linear actuators are commonplace in stewart platforms of both small and large scale implementations. The benefits of using a linear actuator are that they can be extremely strong, therefore strong enough to support the weight of the neck, many come pre-assembled and ready to hook up to an arduino, and there are already many examples of linear actuators being implemented in stewart platforms.

The main downsides to using a linear actuator in our stewart platform were speed and cost effectiveness. Using small scale and somewhat economic linear actuators meant that the actual speed of actuation suffered. This would result in our head moving somewhat sluggish and therefore not as realistically as we would like. The other downside is cost. Even hobbyist level linear actuators tended to run about $100 per actuator. Needing six to create a stewart platform would in a sense fail our goal of remaining cost effective.

Our group decided we needed to go a different route with moving our stewart platform, but we still wanted to use linear actuators. So, the thought came to mind of making our own. We began researching a variety of different linear actuator designs. We designed different linear actuators using both linkages and rack and pinion formats.

The first design we came up with was a rack and pinion design. In figure 12 you can see the different 3D printed parts that would make up this design:

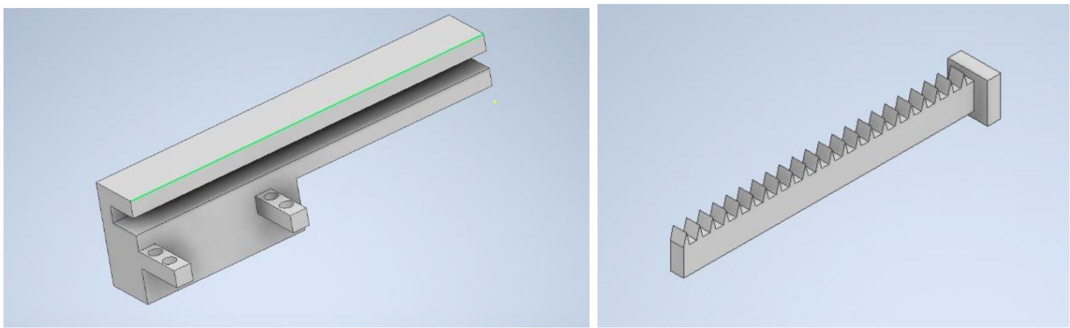


Figure 13: Rack and pinion based linear actuator, housing (left) and rack (right) CAD models

Because of the use of 3D printed parts, this process would be both cost effective and modular. As shown CAD modeling was used to come up with a design for a housing and rack for this first linear actuator design. The housing has holes to attach to a servo motor and a channel to allow the guiding of the rack through it. This design would use a 360-degree servo motor or stepper motor attached to a pinion in order to actuate the rack which would in turn move the specified actuator in the Stewart platform. This design also contains u clips on both the top of the rack and bottom of the housing to provide additional movement required when designing a Stewart platform with 6 linear actuators. Figure 14 shows the U clip design and Stewart platform orientation (missing the top platform to provide visibility)

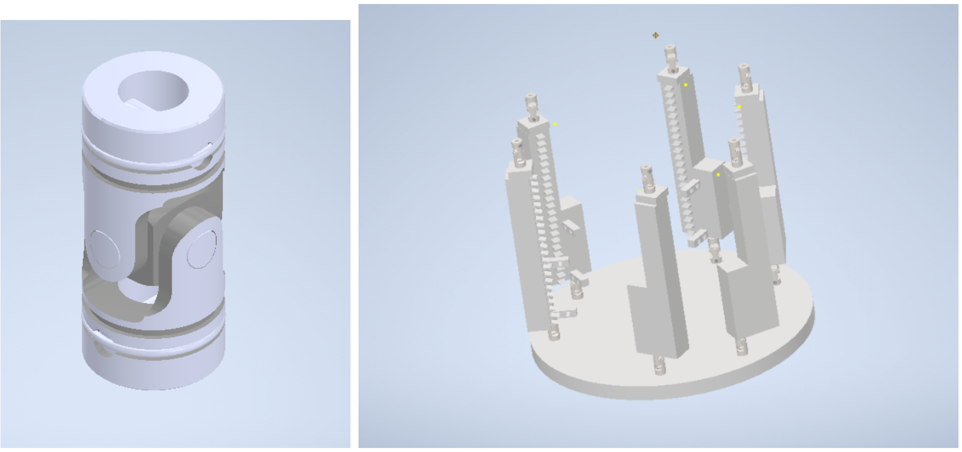


Figure 14: U clip (left) and Stewart platform assembly (right) CAD models

But, there were constraints. One was that the servo motors would need to be able to move 360 degrees and still be strong enough to support the head. This constraint increased the cost of servo motors we would need to purchase. The second issue is that with a rack and pinion, movement may have been a lot slower and therefore less lifelike. So, we decided against it.

The next linear actuator design we explored utilized a lead screw and threaded rod to provide actuation to two arms and was based on the Sarrus linkage.

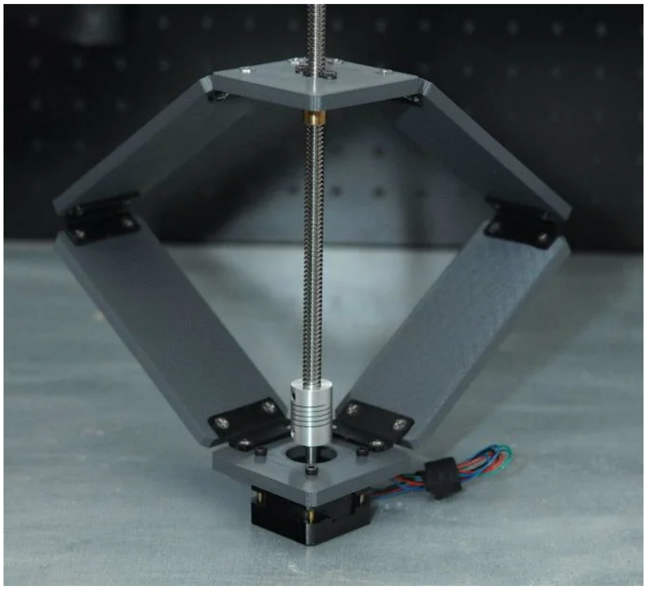


Figure 15: Concept of Sarrus linkage based linear actuator design, reproduced as is from [15]

As shown this design utilizes 3 hinge joints on each “arm” to allow for actuation when the uppermost platform is moved up and down through clockwise and counterclockwise motion of the attached stepper motor. This motor is attached to a shaft coupling which connects it to the threaded rod necessary for actuation. This design looked promising as it provided a majority of easily printable parts but ultimately was decided against due to its complexity and potential range of motion issues resulting from six of these being involved in a Stewart platform. Due to this we made an adaption to this design to solve the range of motion issue.

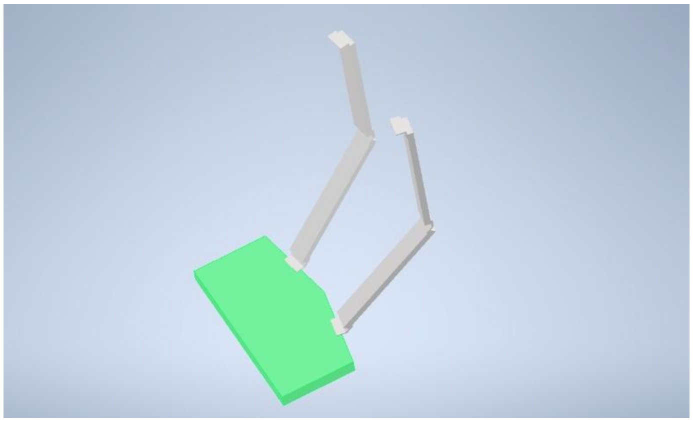


Figure 16: CAD redesign of Sarrus linkage based linear actuator

With this change to the shape of the base plate the arms would be positioned outwards to prevent collision of any of the arms that would restrict range of motion. While this solved our initial problem with the design it created a new problem where the neck enclosure would have to increase significantly in size to encompass these arms protruding outwards. Another potential design utilized a sliding joint connected to a two-bar linkage mounted on a driving shaft as shown in the following image:

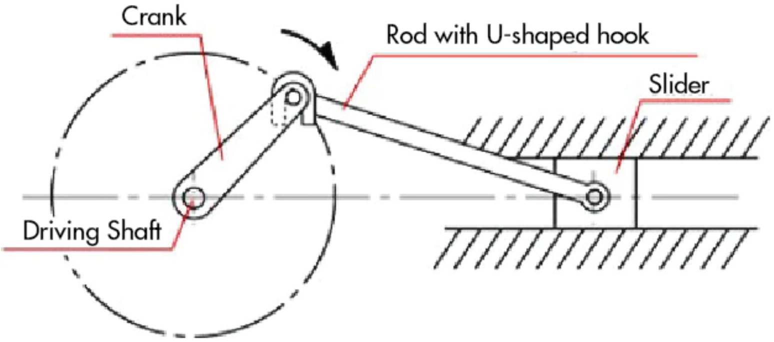


Figure 17: Design of sliding joint based linear actuator, reproduced as is from [16]

The main benefit of this design was that a 180-degree servo could be used for this actuation and all of the parts could be 3D printed. This was abandoned for a simpler design using the same lead screw idea as before but, instead of utilizing the Sarrus linkage, utilizing a housing with threaded holes for actuation. A potential design for such a housing is shown in Figure 18.

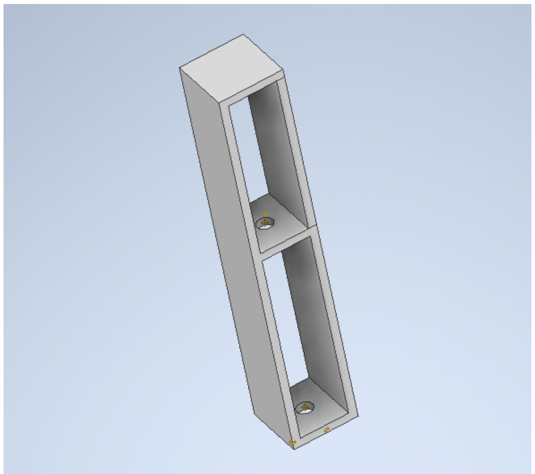


Figure 18: Lead screw housing CAD design

As stated, this would use a stepper motor or 360-degree servo to move a lead screw clockwise and counterclockwise to move this housing along the lead screw.

Ultimately, we found a much simpler design utilizing a two-bar linkage created by attaching the arm of a servo motor to a metal rod with ball joints on both ends as shown in Figure 19.

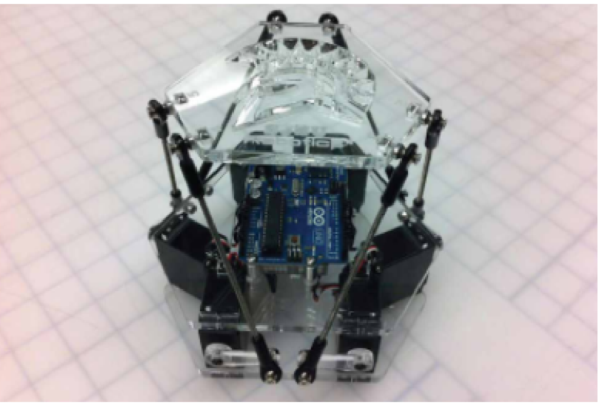


Figure 19: Linkage based Stewart platform, reproduced as is from [17]

This design is similar to one that utilizes linear actuators in practice. However, rather than the legs changing their length, they are simply moved up and down by the servo motor’s arm. Additionally, the universal joints are replaced with rod ends which utilize a small ball joint. The design uses 3 layers, a base which contains the servo motors press fit in and a breadboard for the wiring. The next layer, placed on top of the servo motors and press fit in, acts as a place to mount the microcontroller that controls the servo motors. The last layer is held up with six threaded rods with rod ends at each end, allowing the top platform, which will support the head, six DOF.

Chapter 6: Oral Cavity, Jaw, and Lips

6.1 Methodology

This chapter showcases the design and implementation of the Oral Cavity, Jaw and Lips. This includes the modifications made to these three sections, their justifications as well as their manufacturing and assembly.

6.1.1 Oral Cavity

When it came to our goals for the oral cavity there were a lot of areas that needed improvement. The previous year's design was assembled using super glue to attach both the lower jawbone to the lower teeth portion as well as to attach the trachea. Our goal was to remove any need for glue and instead use snapfits or easy to install hardware. We also wanted to take steps towards waterproofing the oral cavity to help applications requiring the use of liquids such as swallowing and dental simulations. There were also issues with the lower teeth portion regarding the intersection of material that needed to be adjusted.

6.1.2 Jaw

As stated above last year's design for the jawbone was not synergistic with the lower teeth portion in the sense that glue was needed to attach the two. To remedy this we set a goal to use a better form of attachment while also making efforts to make the overall system waterproof and realistic.

6.1.3 Lips

The previous years design was not capable of opening and closing the jaw primarily due to the current lip design. Last year's lip design utilized one solid piece that was to be printed using TPU to allow for movement and overall synergy with the jaws movements as shown below:

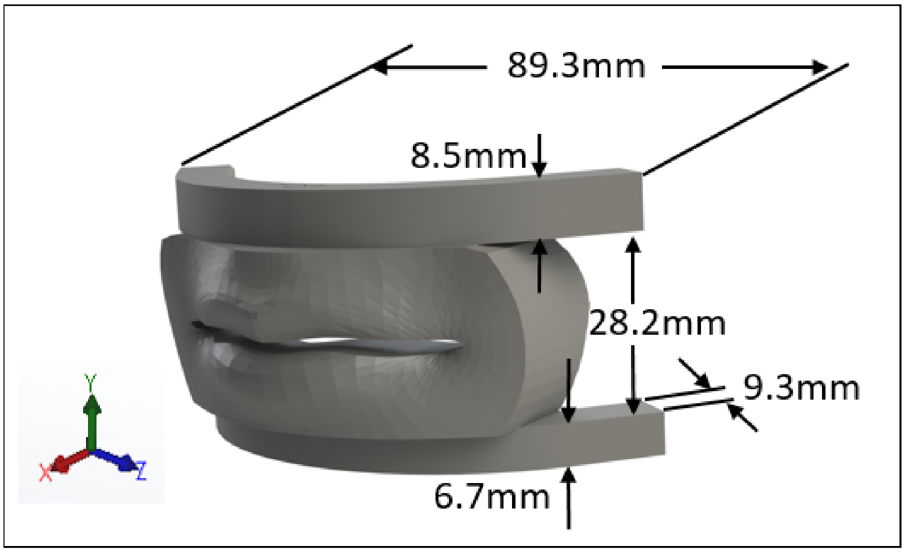


Figure 20: CAD Model of the Lips by Cohen et al

This was far from the case with the lips being far too rigid to allow for actuation of the jaw. Due to this we had to do one of two things, redesign the lips to work with the jaw better or increase the strength of the jaw to work with the current lip design. The latter of which was decided against as it was determined that if the jaw strength was increased to work with the lips over time the lips would wear down and after sufficient wear ultimately would fail.

6.2 Design and Implementation

6.2.1 Oral Cavity

When redesigning this subsystem we wanted to keep our research objective of manufacturability in the forefront of our minds. Due to this we decided to remove the need for glue by incorporating two M4 x 0.7mm thread, 20mm long and two Steel Hex Nuts M4 x 0.7mm thread (3.2mm Height) to hold the jawbone and lower teeth together shown below:

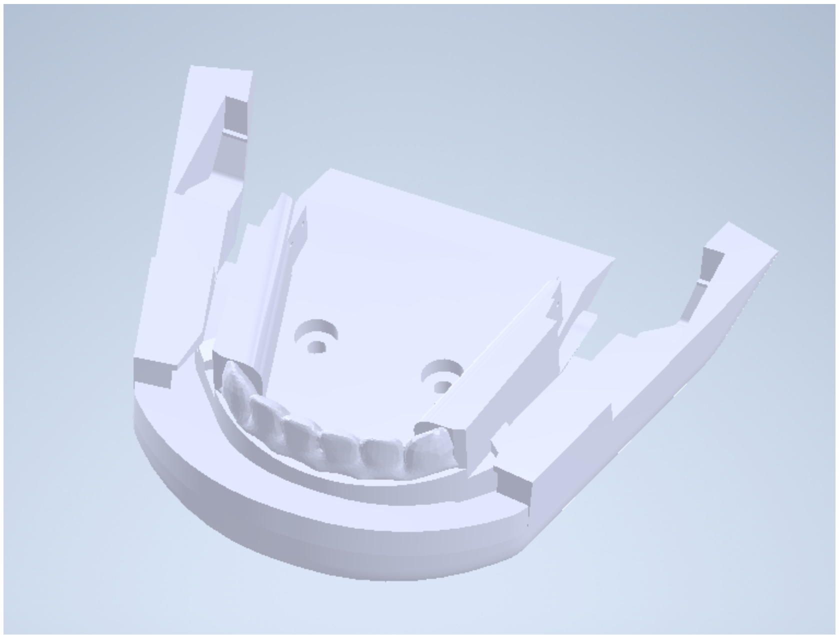


Figure 21: Final CAD Design Jawbone and lower teeth Interaction

The initial design was a lot different from the above image in the sense that the preliminary design was just aimed at creating features for the lower teeth to allow for the attachment to the jawbone.

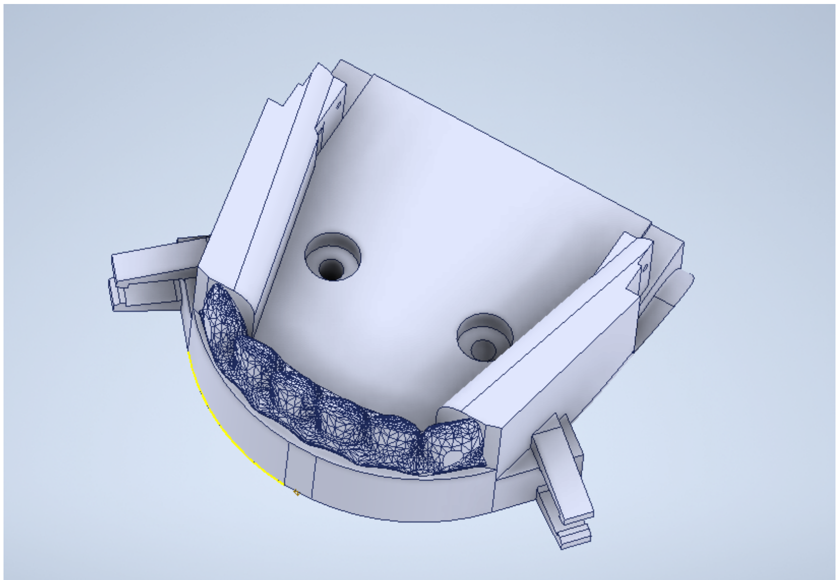


Figure 22: Preliminary Lower Teeth Redesign CAD model

This design utilized two counterbored holes and the hardware previously mentioned to attach to the jawbone. This was designed with future applications in mind where with the counterbored holes the hex nuts would sit flush with the top face and thus would not interfere with any additions. One main problem with this design was that with the installation of the trachea there would still be a large hole between these two pieces and thus training such as oropharyngeal tube insertion would not be possible as the tube would not be fed down the trachea as it would on a real human. To remedy this situation we designed a ramp to be included on the back of the lower teeth part in order to feed the aforementioned tube directly into the trachea making training possible and our model more realistic.

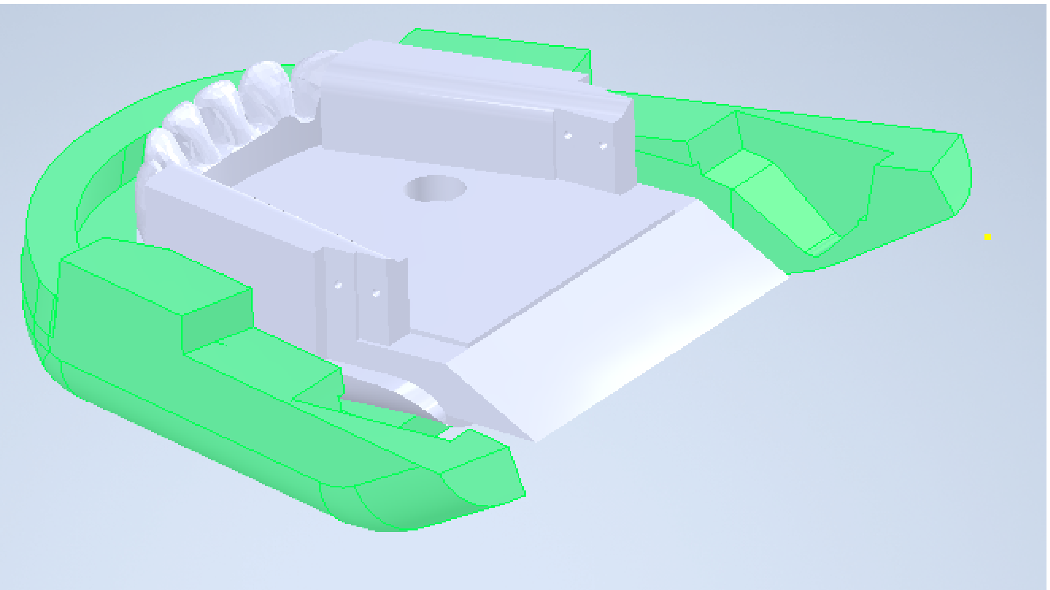


Figure 23: Ramp Addition to Preliminary Design CAD model

After more research and prototyping these two parts, a large problem with their interaction that had gone unnoticed by last year's team was made obvious and needed adjustment. This issue came from the fact that the clips required to attach the lips were designed to intersect with the lower jawbone as shown in the following picture:

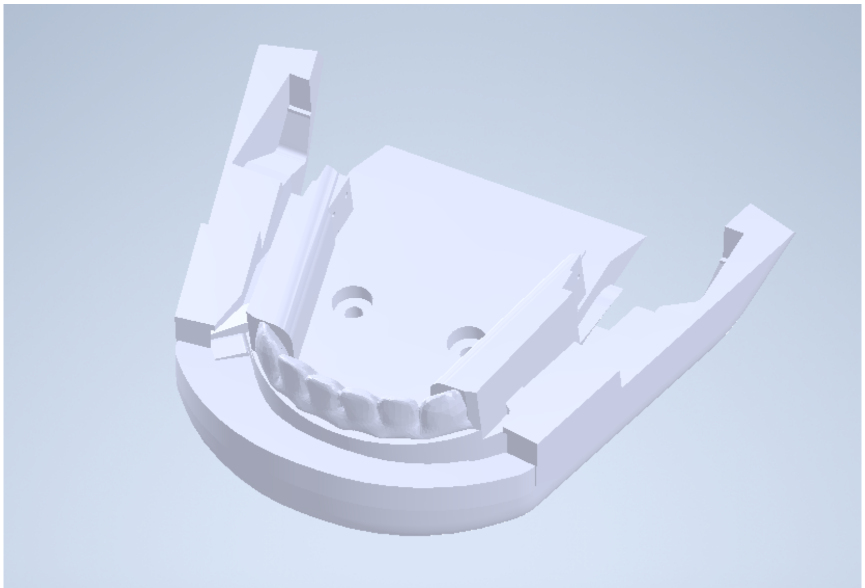


Figure 24: CAD depicting Intersection of Lower Oral Cavity Interaction

As can be seen these clips directly impact the jawbone piece and thus in reality would not fit together and it would be even harder to install the lips. After further testing it was found the clips were not needed to hold the lips in place as the channel between the two parts did a good job of holding the lips in place. Thus we simply removed the clips from the bottom teeth part and completed the design as shown below

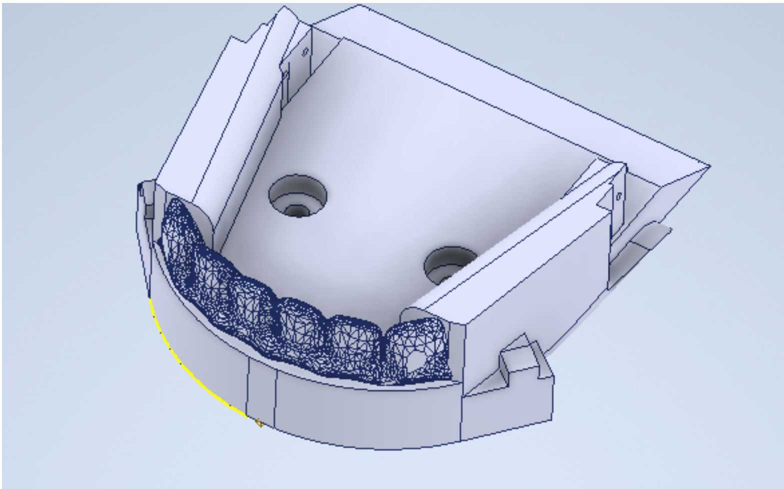


Figure 25: Bottom Teeth Final Design CAD model

6.2.2 Jaw

As previously discussed this piece attaches directly to the underside of the bottom teeth part. This design process was much simpler in the sense that there was only one revision to last year's design. With the installation of hardware to attach the two the previous years design needed an extension of the lower platform to create an area for interaction. A comparison of these two parts is shown below:

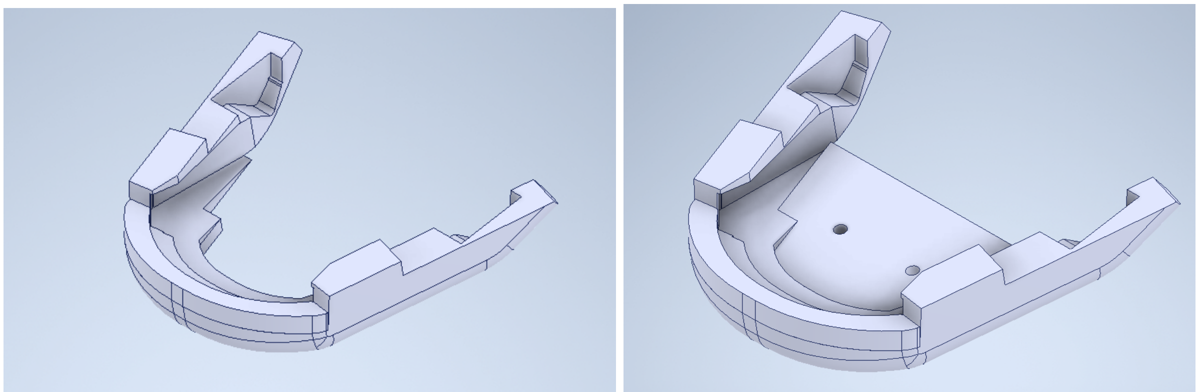


Figure 26: Comparison of Jawbone by Cohen et al (left) and our redesign (Right)

By extending this platform we enabled the attachment to the bottom teeth through two counterbored holes.

6.2.3 Lips

As described in our methodology chapter on the lips the main problem was with their interaction with the movements of the jaw. With our decision to redesign the lips instead of changing the specifications of the jaw we began by looking for inspiration. Our main inspiration for a potential lip redesign strategy came with finding an article depicting the highly advanced animatronics used in Disney's Avatar rides [18]. The lip design specifically, as shown below, was extraordinarily advanced and allowed for extensive movements to replicate facial expressions.

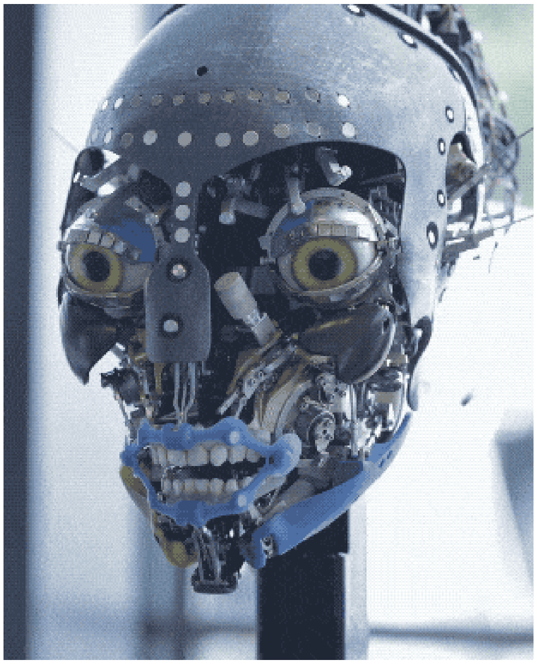


Figure 27: Avatar Animatronic, reproduced as is from [18]

As we did not have a focus on entertainment all of these motions for gestures were not important and in turn were not required. We did take the idea of making the lips two pieces that would rotate on a hinge attached to the upper portions of the oral cavity with a preliminary design shown below:

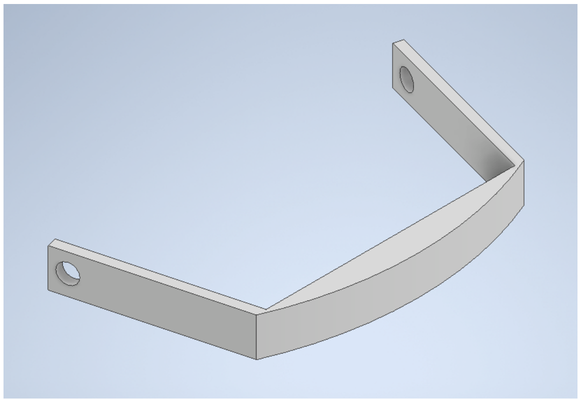


Figure 28: Preliminary Lip Redesign CAD model

As this redesign added unneeded complexity where the only requirement of the lips was to appear realistic we decided to scrap the idea and instead solve our problem by splitting the current lips into two separate parts so as to not restrict the motion of the jaw.

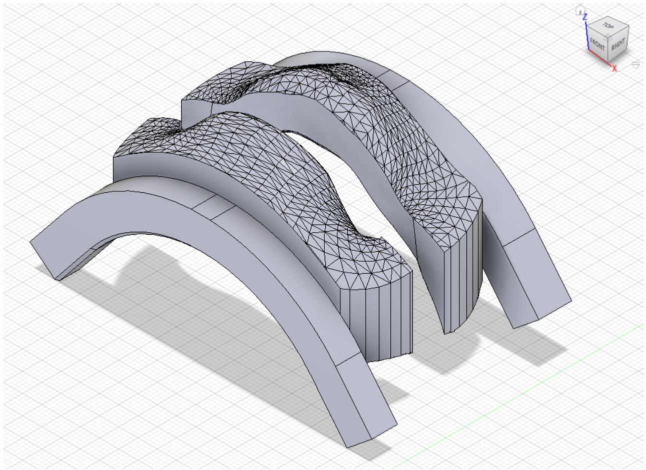


Figure 29: Final Design for Lips Subsystem

The material would also be changed from TPE as the softness of the lips was not necessary and added to the complexity and printing time of the part.

Chapter 7: Lattice and Skin

This chapter showcases the design and implementation of the lattice and skin. This includes a snap-fit design for all three sections of the lattice, the lower, middle, and crown. The skin was also designed in 3d printable materials and utilized a partial infill to replicate a skin-like feel. The lattice underwent a huge redesign in terms of manufacturability, and ease of replicability. And the skin lattice went through a complete redesign as well, consisting of infill changes, and material trials. These changes are showcased in the detailed methodology written below.

7.1 Methodology

7.1.1 Lattice

One of the biggest sections of our project was a redesign of the lattice and skin subsections. Prior to this redesign, the lattice was a large system which utilized the following connectors to connect its parts listed in the table 2 below.

Table 2: Table of connectors used to attach the pieces of the lattice system

Lattice Connectors Used			
Piece	***Type***	***Amount Used***	***Where***
Neck Lattice	4-40 ¾” Button Head Hex Drive Screws link	10	Figure 30
Neck Lattice	4-40 Nylon Insert Lock Nuts link	10	Figure 30
Side Head Lattice	4-40 ¾” Button Head Hex Drive Screws	4	Figure 31

	link		
Side Head Lattice	4-40 0.188” Brass Screw-to-Expand Inserts link	4	Figure 31
Crown Lattice	4-40 0.188” Brass Screw-to-Expand Inserts link	4	Figure 32
Crown Lattice	4-40 ¾” Button Head Hex Drive Screws link	4	Figure 32

Showcased in figure 30 below is the neck lattice parts and their connection to the neck platform. The circled fasteners are the ones utilized in the connection of these three pieces. This consists of a total of 10 4-40 ¾” button head hex drive screws, and the correlating 4-40 nylon insert lock nuts.

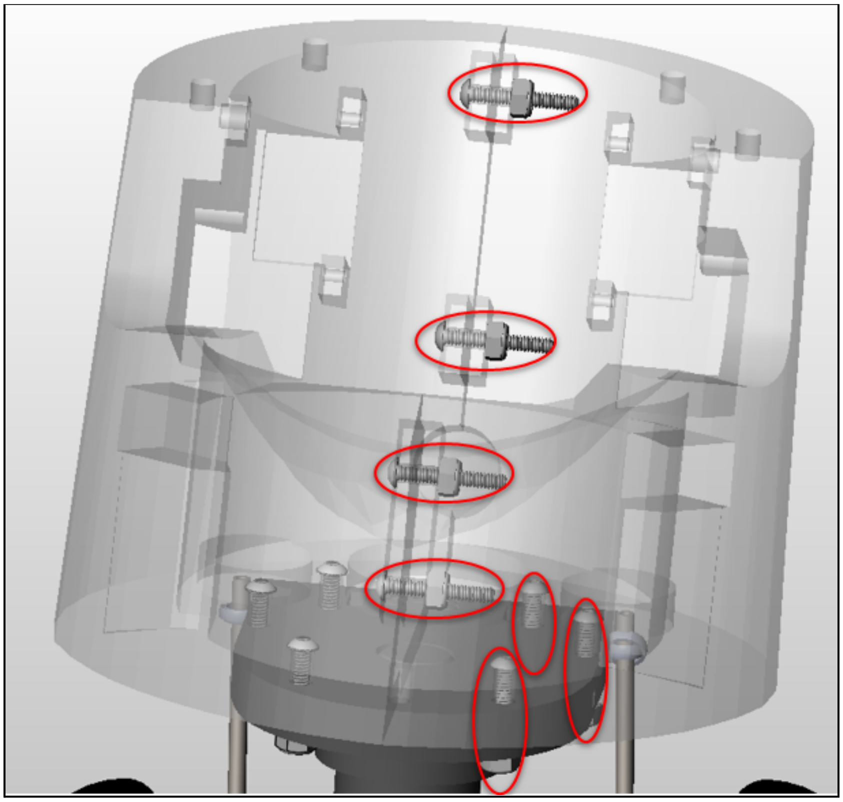


Figure 30: Neck lattice to neck platform connectors utilized derived from the user manual by Cohen et al

Next showcased in figure 31 below is the side head lattice parts and their connection to the neck lattice. The circled fasteners are the ones utilized in the connection of these three pieces. This consists of a total of 4 4-40 ¾" button head hex drive screws, and the correlating 4-40 0.188" brass screw-to-expand inserts that are present underneath.

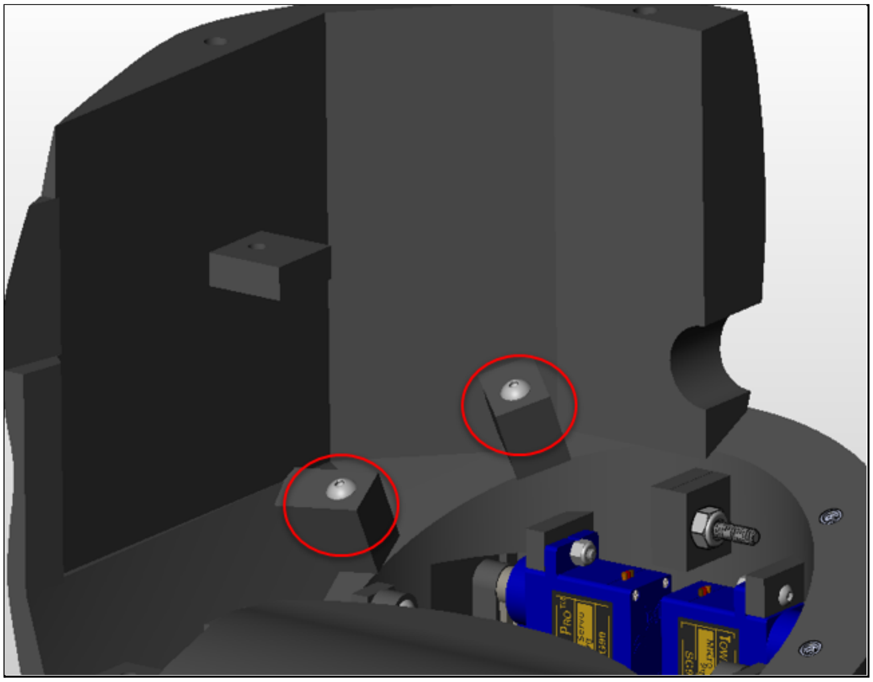


Figure 31: Side head lattice to neck lattice connectors utilized derived from the user manual by Cohen et al

Lastly, showcased in figure 32 below is the crown lattice parts and their connection to the side head lattice. The circled fasteners are the ones utilized in the connection of these three pieces. This consists of a total of 4 4-40 ¾" button head hex drive screws, and the correlating 4-40 0.188" brass screw-to-expand inserts that are present underneath.

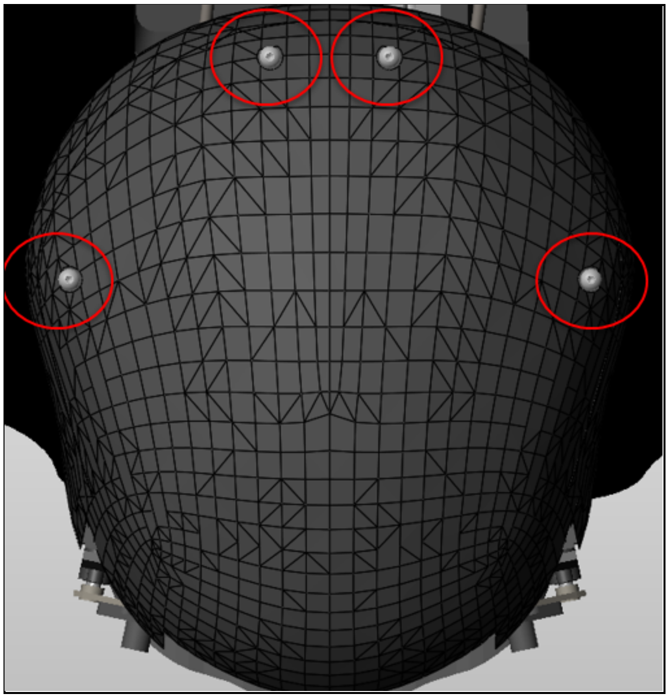


Figure 32: Crown lattice to side head lattice connectors utilized derived from the user manual by Cohen et al

In an attempt to remove the need for connectors in accordance with objective 2 of designing for manufacturability, we introduced slide-fits. This task involved a large amount of testing through trial and error. We ended up doing a puzzle type slide-fit after trying a gutter style slide-fit as shown in figure 33 below.

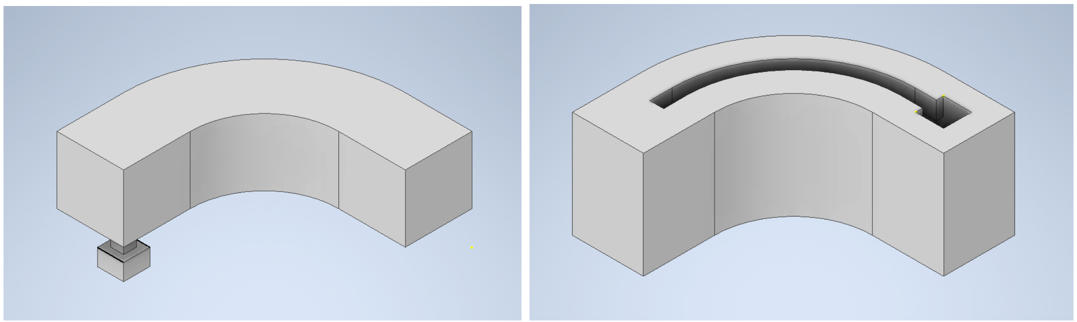


Figure 33: Gutter style slide-fit, part a(left) and b(right)

The large amount of trials is due to the fact that tolerancing between the plus and minus sides of the slide-fits needs to be high, but not so high as to limit mobility of the connection. We solved this tolerancing issue through the use of various slide-fit test prints. This was done through interval tests of different offsets between the two pieces, starting at 1%, 3%, and 5% then narrowing down between those intervals. The percentages refer to the difference in size between the two pieces. For example a 10% difference between two 10mm blocks would be a 9mm block and a 10mm block. A screenshot of the CAD model as well as the test print are shown in Figure 34 below. We inferred from the first test print that the tolerance difference needed to be below 1% difference, this then resulted in the test print shown in the figure below. The 0.75% difference was the best in terms of tolerancing between the two sides, meaning it is tight enough to hold it in place but not too tight as to get stuck.

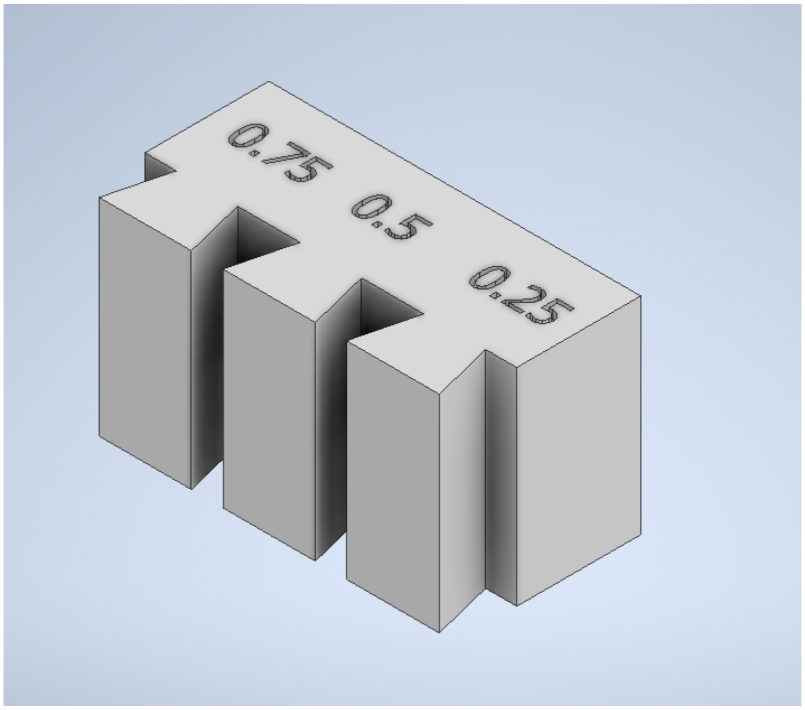


Figure 34: Slide-fit testing block, consists of 0.75%, 0.5%, and 0.25%

7.1.2 Skin

We inherited a silicone skin that had to be manufactured using 3D printed molds as well as chemicals to create a silicone shell. This not only added manufacturing processes and tools, but also required fasteners to attach the skin to the existing PLA lattice. We wanted to simulate the texture and softness of skin on our model without adding much complexity or cost to the project. We theorized that by using flexible plastics, we could 3D print an outer skin layer simultaneously that is directly joined to the rigid lattice.

The first step to creating a lattice that printed with both skin and solid sections was to pick an appropriate material. To assure the skin was soft, we looked at Thermoplastic Polyurethane (TPU) and Thermoplastic Elastomers (TPE). These are fused deposition modeling (FDM) 3D printable materials that are known for their elasticity and transparency [19]. Additionally, this class of plastic can also be made ridgid. It has historically been used in the automotive industry for a range of components, from soft belts to harder dashboards and exterior detailing. TPU is also used in many other industries as shown in figure 35.

Figure 35: Phone Case with TPU components

We did some initial testing with both materials and, after assessing the availability of materials, we decided to use TPU. TPU was far easier to procure due to supply chain issues, which were impacted by COVID. However, it is important to note that depending on the specifics of the TPE/TPU choice, both materials could work for the skin/lattice application as the material properties of both meet the needs of the project.

After selecting the material, we picked a software that allowed printing different models with different infills to produce G-Code. We predicted that we would need a much lower infill for the skin and a much higher infill to create a rigid lattice using TPU. This is due to the understanding that the thicker a portion material is, the less it is able to bend. We hoped that TPU would be rigid enough to support itself at the thickness found in the head lattice. After some research, we selected Cura by Ultimaker [20]. Cura has a feature called "*per object settings*" through which different models can be loaded in and have different print settings that override the settings of the overall print. For example, a cube can be imported into a model and placed inside a larger cylinder, which is at 70% infill. If the "per object settings" are accessed for the smaller cube and the infill is set to 20%, this will override the 70% infill and print that section of the cylinder at 20% infill (see Figure 36).

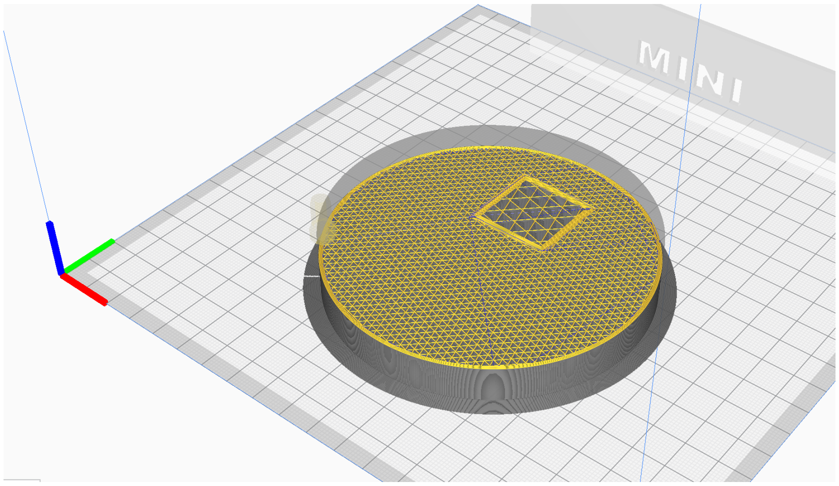
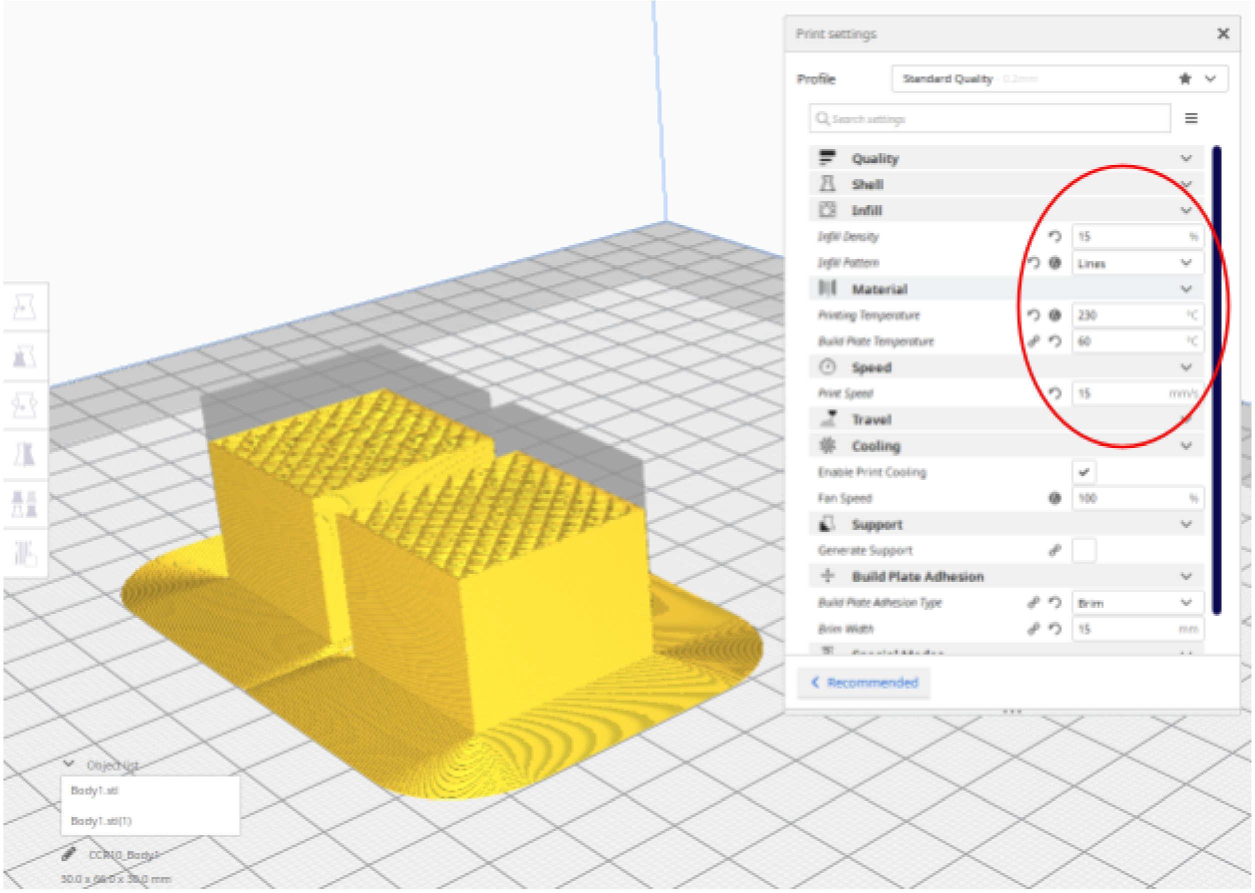


Figure 36: Demonstration of Multiple Infills in Cura

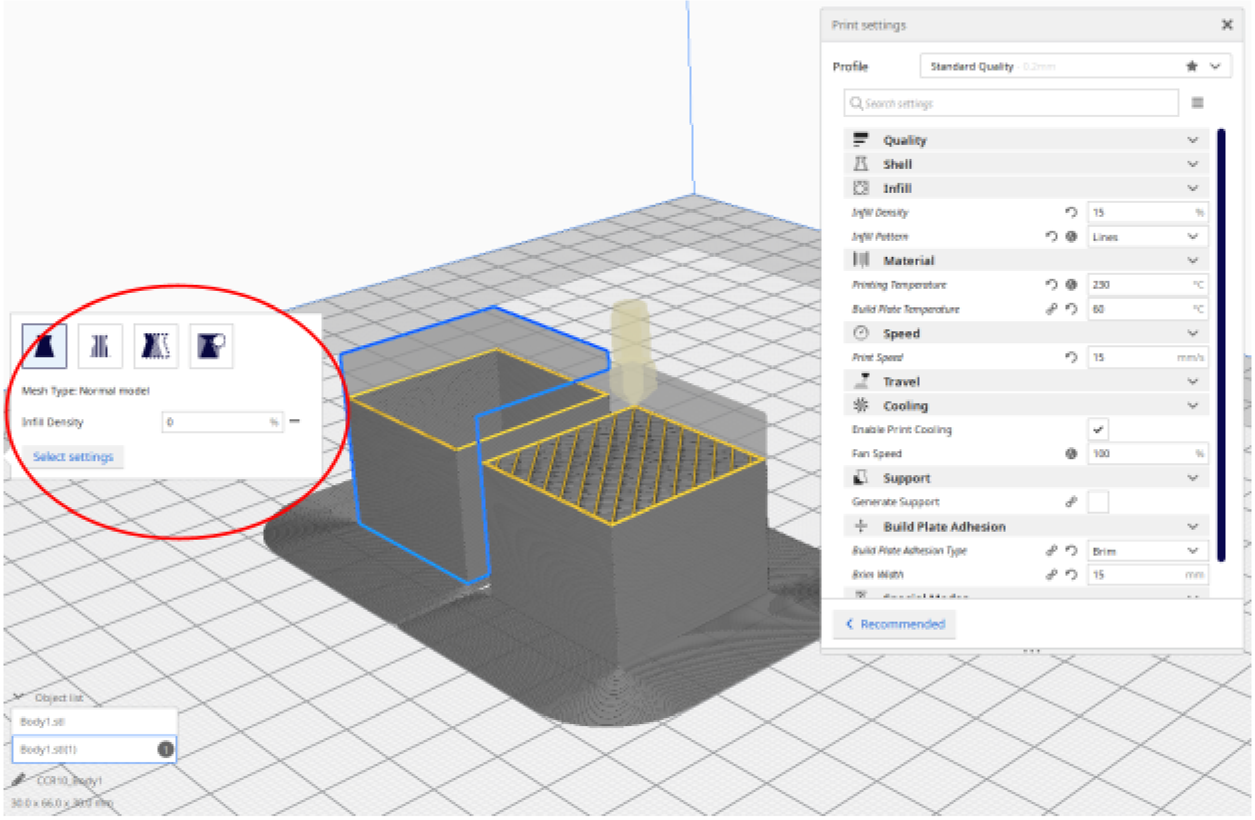
To vary the infill, we used two sets of settings in cura. The first set is in the main setting pane, where we set the infill and other print settings like temperature for the lattice as well as the skin. These settings are shown below in figure 37.



Profile: Standard Quality - 0.2mm
Infill Density: 15 %
Infill Pattern: Lines
Printing Temperature: 230 °C
Build Plate Temperature: 60 °C
Print Speed: 15 mm/s
Enable Print Cooling: ☑
Fan Speed: 100 %
Generate Support: ☐
Build Plate Adhesion Type: Brim
Brim Width: 15 mm

Figure 37: Main Infill Settings in Cura

We then accessed the per object settings to override the infill in one part. This allows us to print two parts with two different infills. It is important to note that infill is not the only setting that can be overwritten using per object settings. Below in figure 38 you can see that the cube on the left is set to a much lower infill than its partener on the right.



Profile: Standard Quality - 0.2mm

Infill Density: 15 %

Infill Pattern: Lines

Printing Temperature: 230 °C

Build Plate Temperature: 60 °C

Print Speed: 15 mm/s

Enable Print Cooling: ☑

Fan Speed: 100 %

Generate Support: ☐

Build Plate Adhesion Type: Brim

Brim Width: 15 mm

Mesh Type: Normal model

Infill Density: 0 %

Figure 38: Per object settings in Cura

7.2 Design and Implementation

After setting the goals required for the redesign, the design and implementation was then accomplished. This involved designing how to increase manufacturability as well as how these designs were then implemented and used.

7.2.1 Lattice

After figuring out which slide-fit to go with we decided on changes to the Lattice system because it has the biggest role in being the supportive matrix for the entirety of the head. This consists of changes to the two neck sides, two head sides, and crown lattice pieces. To start the development and design of new pieces we drew out partial changes and ideas and presented them to the group. These drawings are shown in the figures below.

To start Figure 39 listed below showcases four connectors being removed and being replaced by a puzzle like slide-fit. This was designed based upon the idea that this lattice holds the entire head so a strong connection needed to replace the four connectors that were removed. This was then attached onto the Stewart platform.

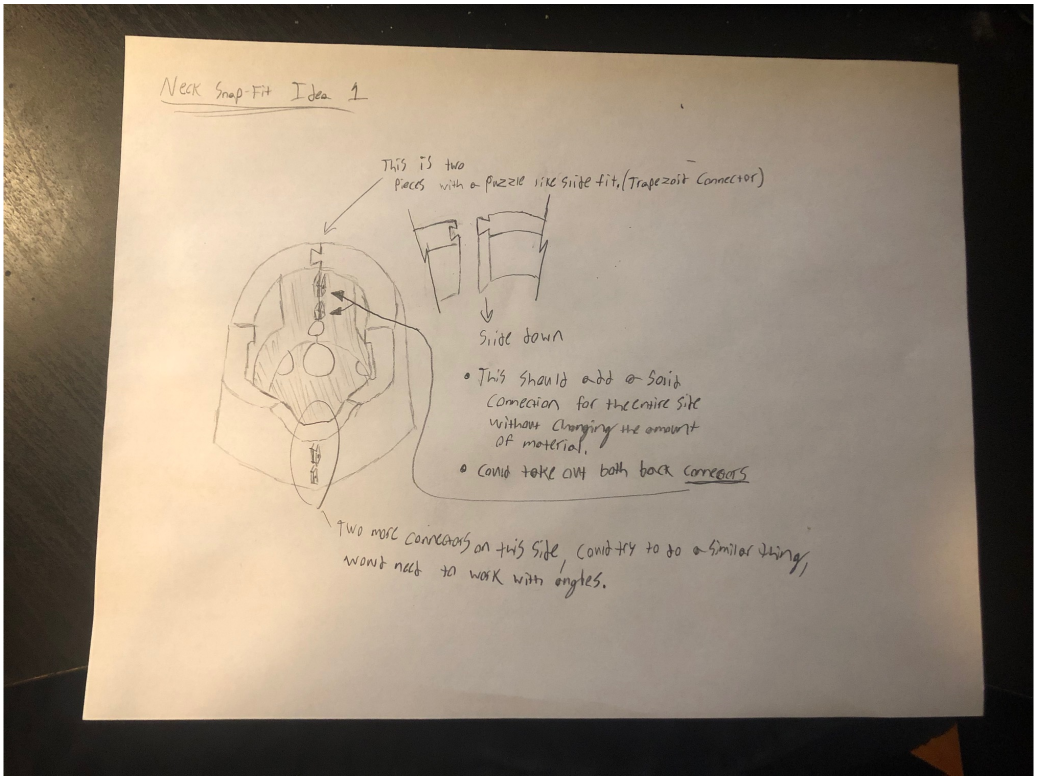


Figure 39: Neck Slide fit design to remove four connectors

The next design consists of ways to connect the side head lattice with the neck lattice. This is first listed in figure 40 below which provides the background that 4 screw inserts are used and 4 screws are used in the original design. Then figure 41 showcases the first design for a gutter-type slide fit that was rejected due to the weakness of that type of slide-fit. After that figure 42 goes forward with the same type of trapezoidal puzzle type slide fit present for the neck lattice connection, except rotated on its side. This is designed for the force of the subsystems pulling this slide-fit forward. This results in a tight slide-fit that can handle the forces present from the subsystems.

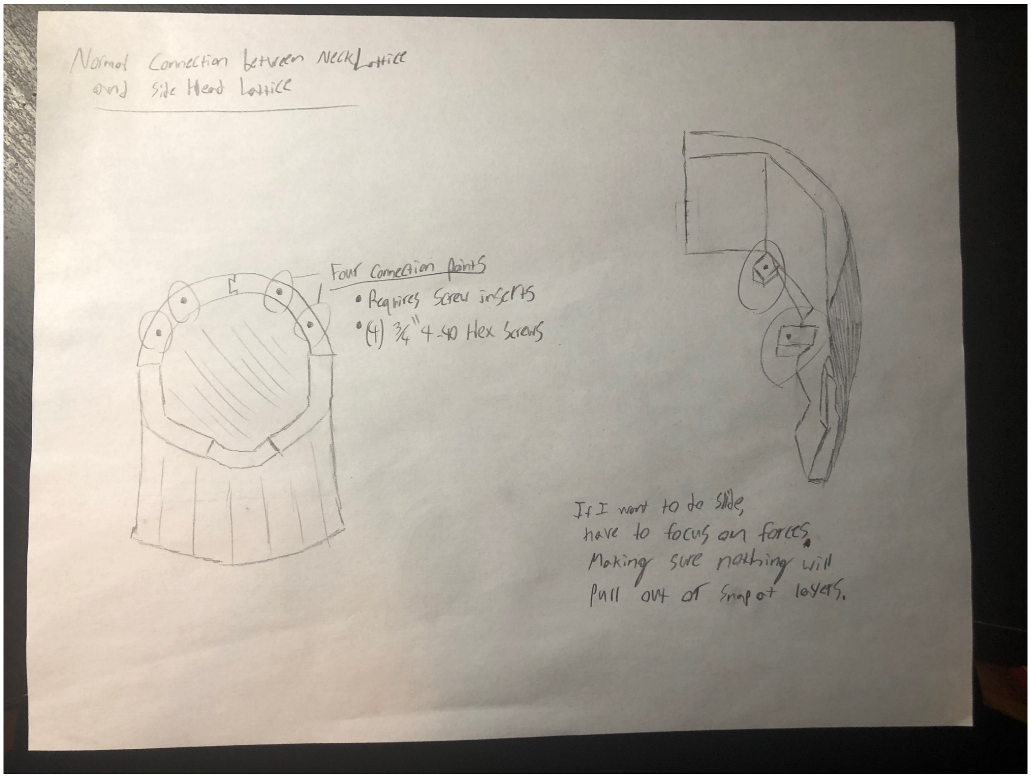
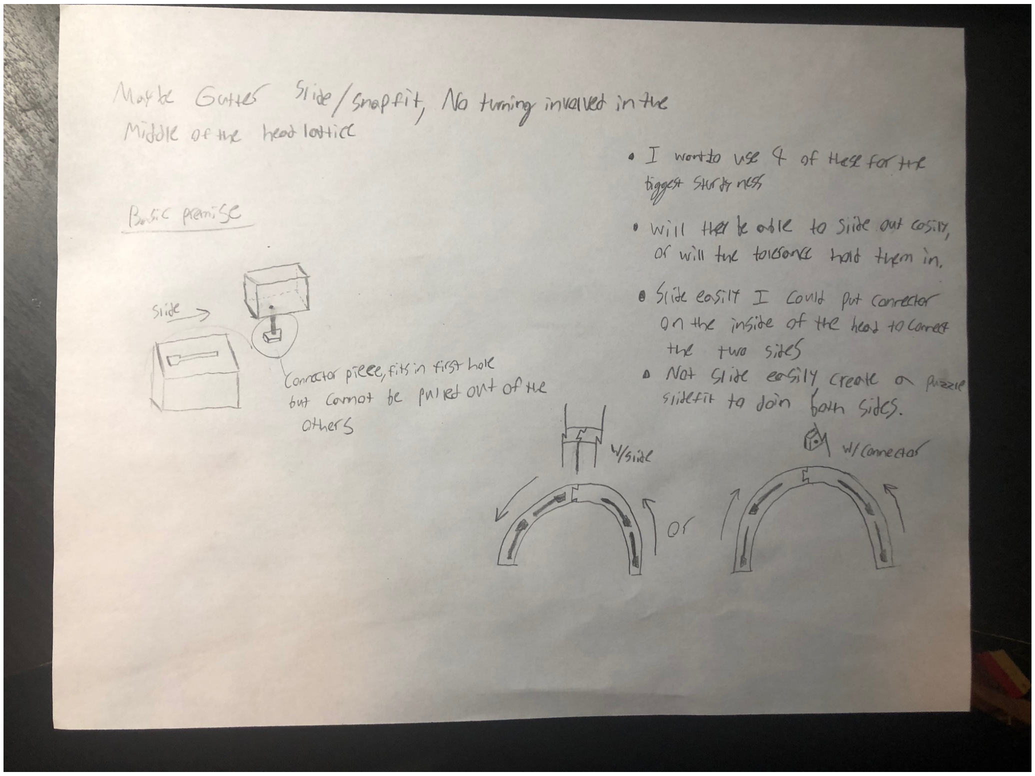


Figure 40: Neck to side-head slide fit design to remove four connectors

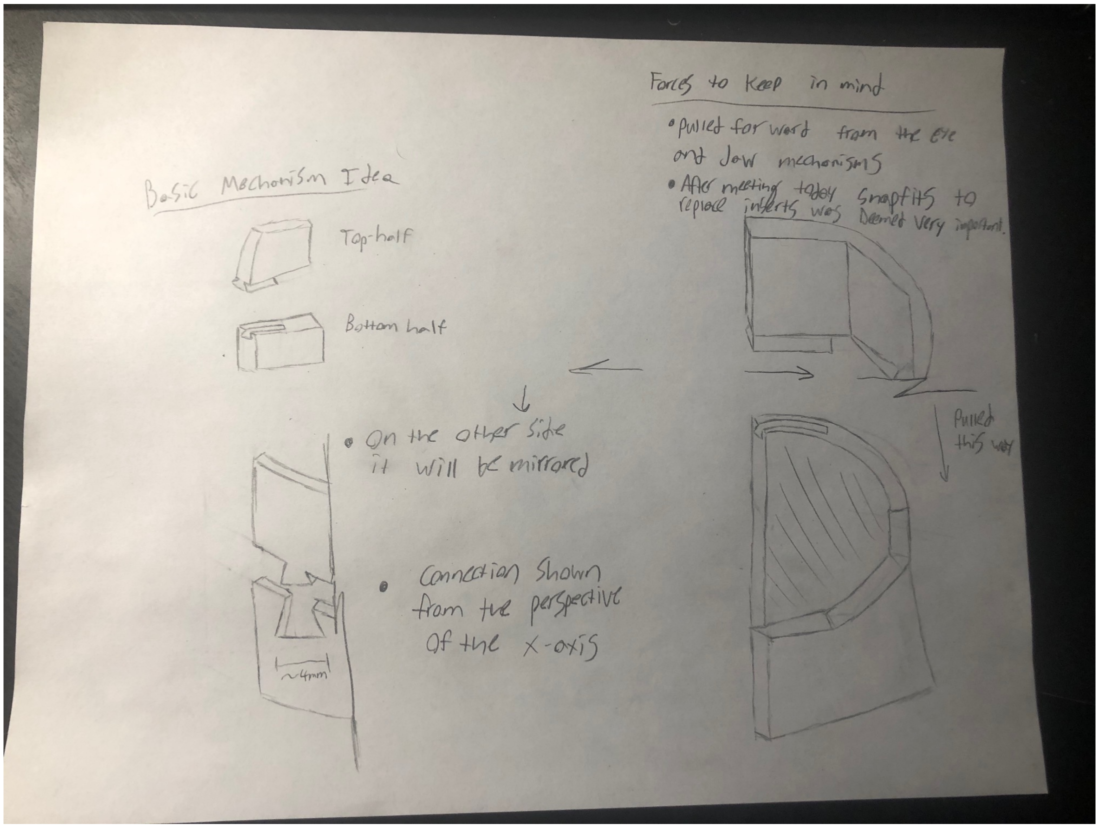


Maybe Gutter Slide/Snapfit, No turning involved in the Middle of the head lattice

Basic premise

- I want to use 4 of these for the biggest sturdyness
- Will they be able to slide out easily, or will the tolerance hold them in.
- Slide easily I could put connector on the inside of the head to connect the two sides
- Not slide easily create a puzzle slidefit to join both sides.

Figure 41: Neck Slide fit design utilizing gutter style slide-fits



Basic Mechanism Idea

Forces to keep in mind

- pulled forward from the eye and jaw mechanisms
- After meeting today snapfits to replace inserts was Deemed very important.
- On the other side it will be mirrored
- Connection shown from the perspective of the x-axis

Figure 42: Final neck slide fit design idea utilizing a trapezoidal puzzle piece like slide-fit

Lastly was the design of connection between the crown lattice and the side head lattice. This consists of two design ideas but the second was rejected due to being complicated to design and hard to insert the screws. The one shown on the left was used and has the crown split into two sections and a trapezoidal puzzle slide fits for connection as well as a connector between the eyes. This is shown within figure 43 below.

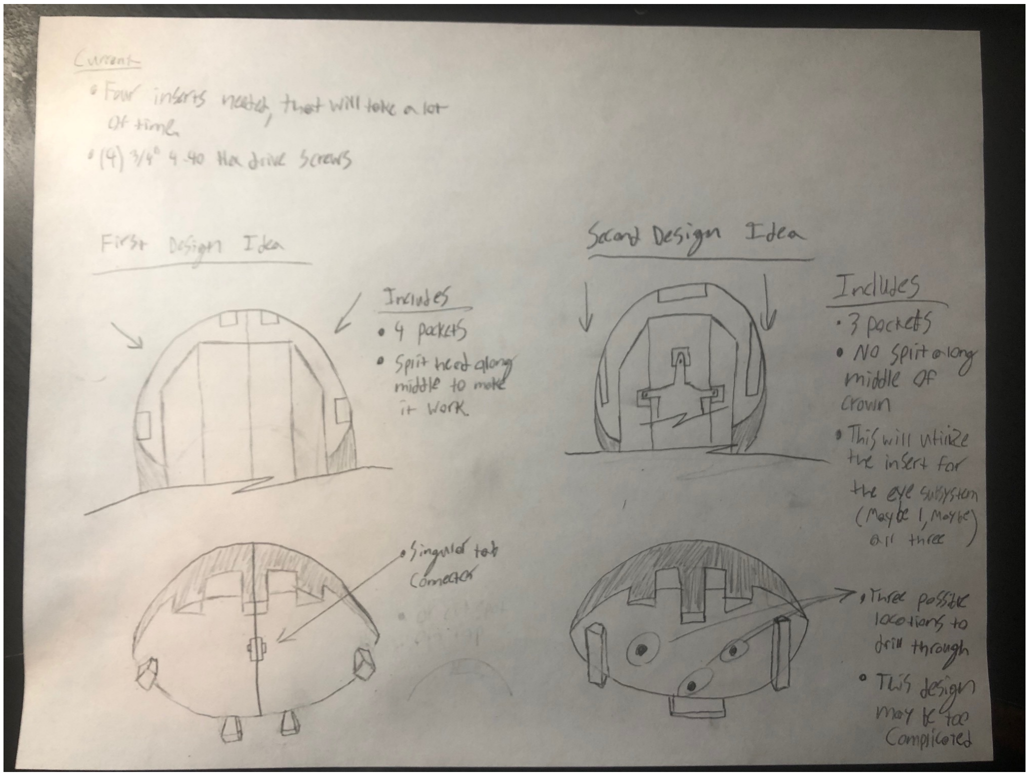


Figure 43: Crown to side-head lattice design idea utilizing a trapezoidal puzzle piece like slide-fit, utilized idea(left), scrapped idea(right)

As most of the above designs consisted of multiple options, one of them needed to be decided upon. After a certain design was accepted, as described above, we developed it within a CAD software such as Autodesk Inventor or Solidworks. Within these design changes, we took out pieces from the parts that were used for the old connectors to free up more space and not confuse the builder of the animatronic. This will be described using before and after pictures of all sections of the lattice below. We then printed the parts in accordance to the scale difference that the tolerance trials figured out, in our case that was a 0.75% scaling difference between the plus and minus sides. We then tested to make sure the slide-fits were secure but moveable, and also that it was printed to the design specifications.

All three of the lattice portions were changed to introduce an ease of manufacturability slide fit design. This all started with the two neck lattice pieces shown in figure 44 below. The removed connectors are shown circled in red.

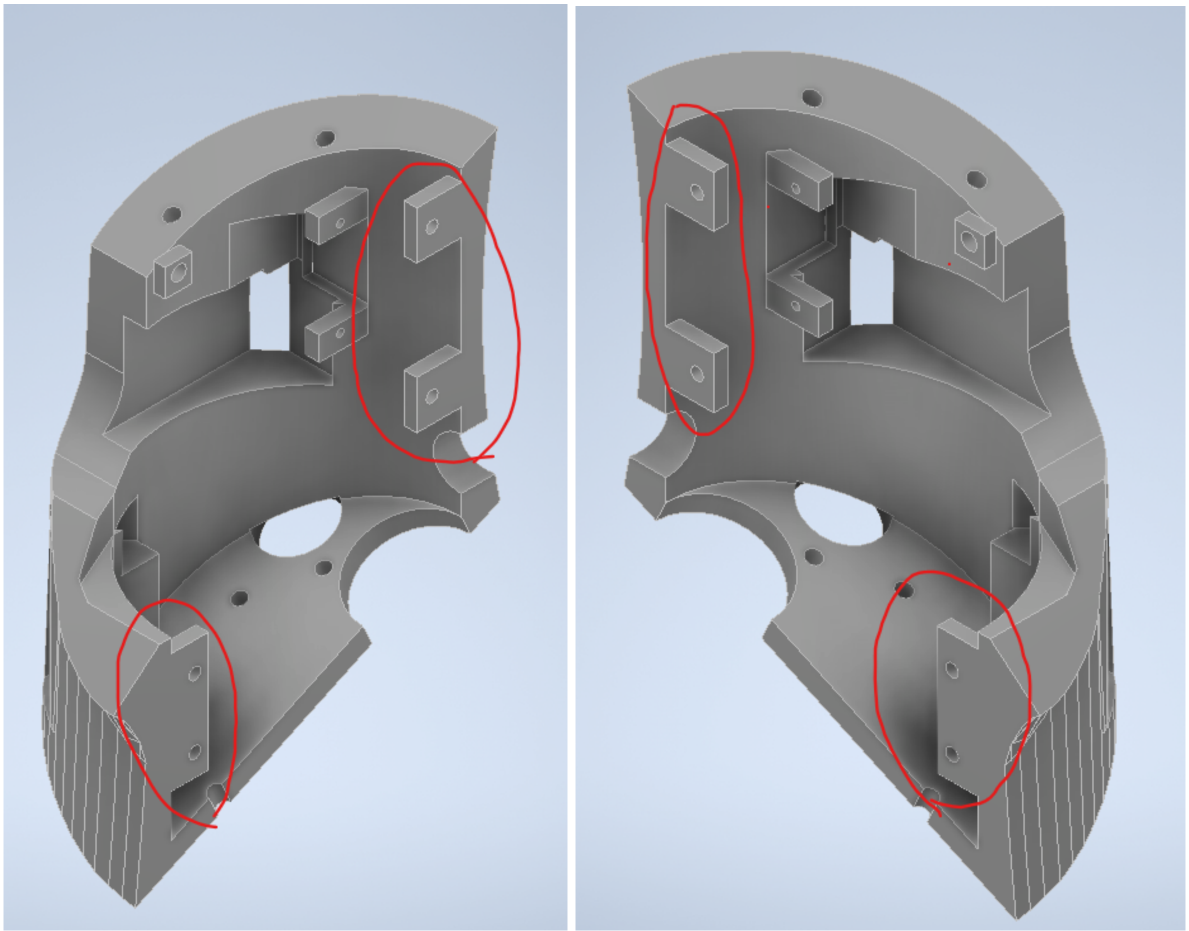


Figure 44: Two halves to the neck lattice showcasing the removed connectors circled in red

Both needed to be strong as they had to hold the weight of all the subsystems. This led to the creation of the part listed in the figure 45 below which showcases the new slide-fits circled in blue.

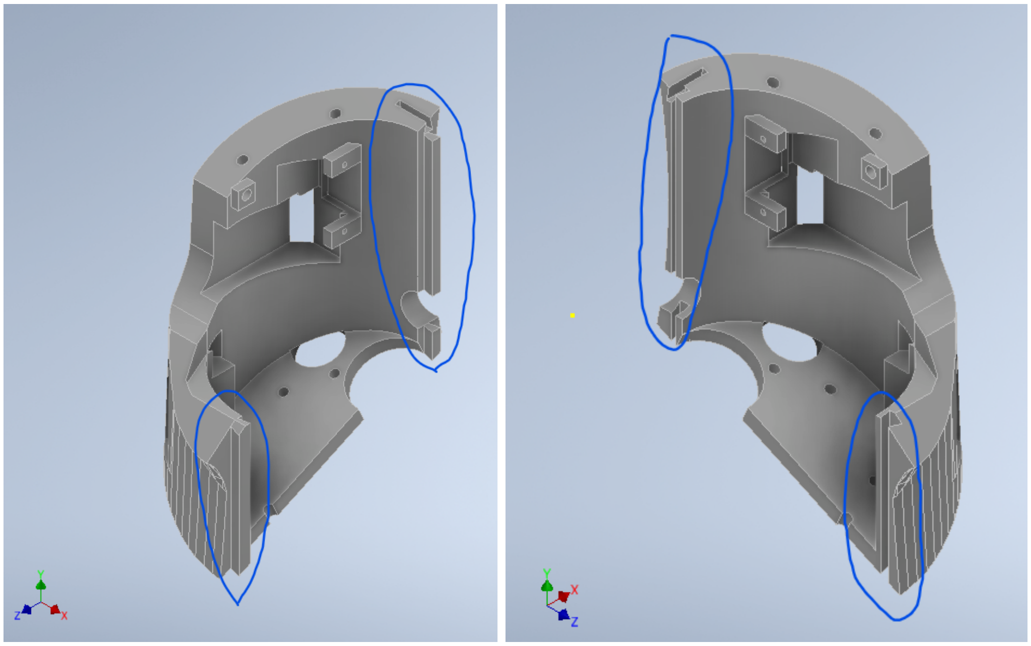


Figure 45: Two halves to the neck lattice showcasing the new slide fit design and the removed tabs from the previous figure.

This specific change took out the need for the four tab connector pieces that are present along the edge of the piece shown in the previous figure. This whole part could then slide into the other half and be attached to the Stewart platform. This creates a secure hold and takes into account all the forces the neck would need to withstand.

The next piece of the head that a slide fit design was implemented into was the side of the head lattice. The original side-head lattice is shown in figure 46 below and has the removed or non-utilized connectors circled in red.

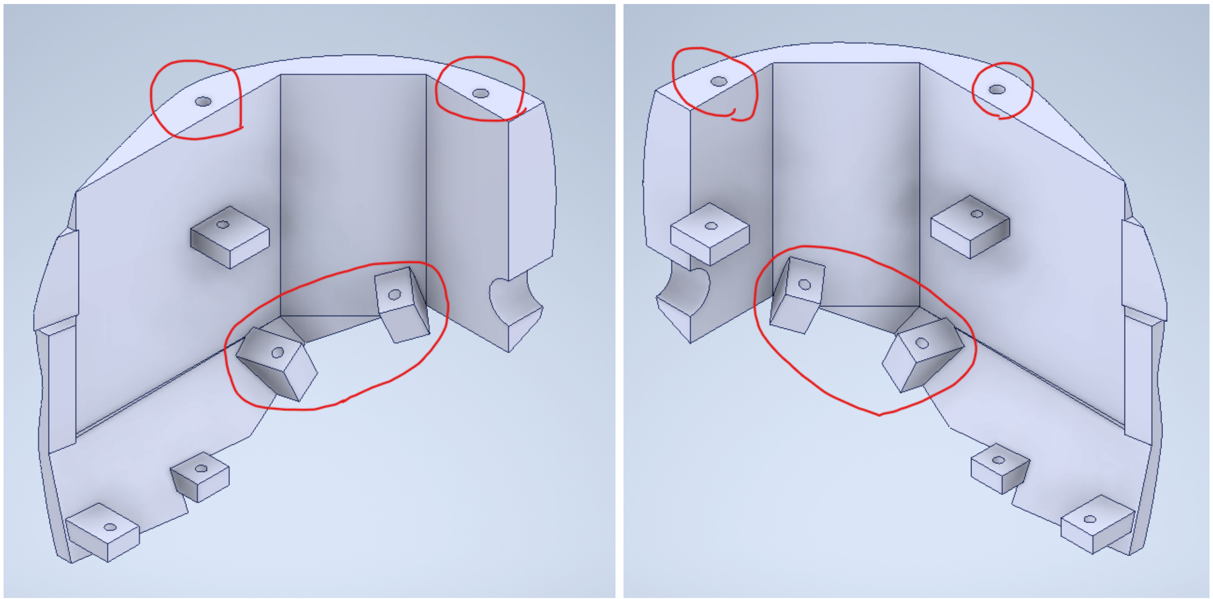


Figure 46: Two halves to the side-head lattice showcasing the removed or non-utilized connectors circled in red

This needed to be able to withstand the multiple forces that would pull the side of the head forward, this was accounted for by the creation of a slide fit that only got tighter as it would be pulled forwards. This lattice section is shown in figure 47 below with the new connectors circled in blue.

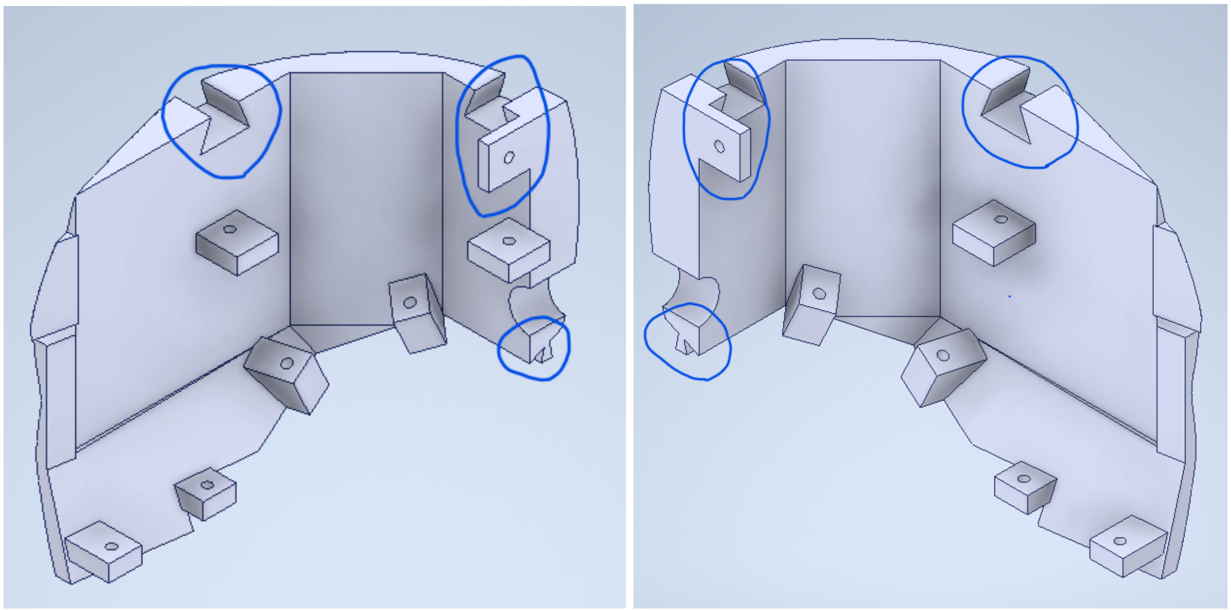


Figure 47: Two halves to the side-head lattice showcasing the new connectors and slide-fits circled in blue

A simple tab connector was added along the back face in order to have increased durability. This removed the need for four screw inserts, a soldering iron, and 4 M4 screws from the design.

Lastly was the designing of the connection between the crown lattice and the side-head lattice. As this piece held no subsystems or parts it did not need large amounts of designing. The original design is shown in figure 48 below with the removed or non-utilized connectors circled in red.

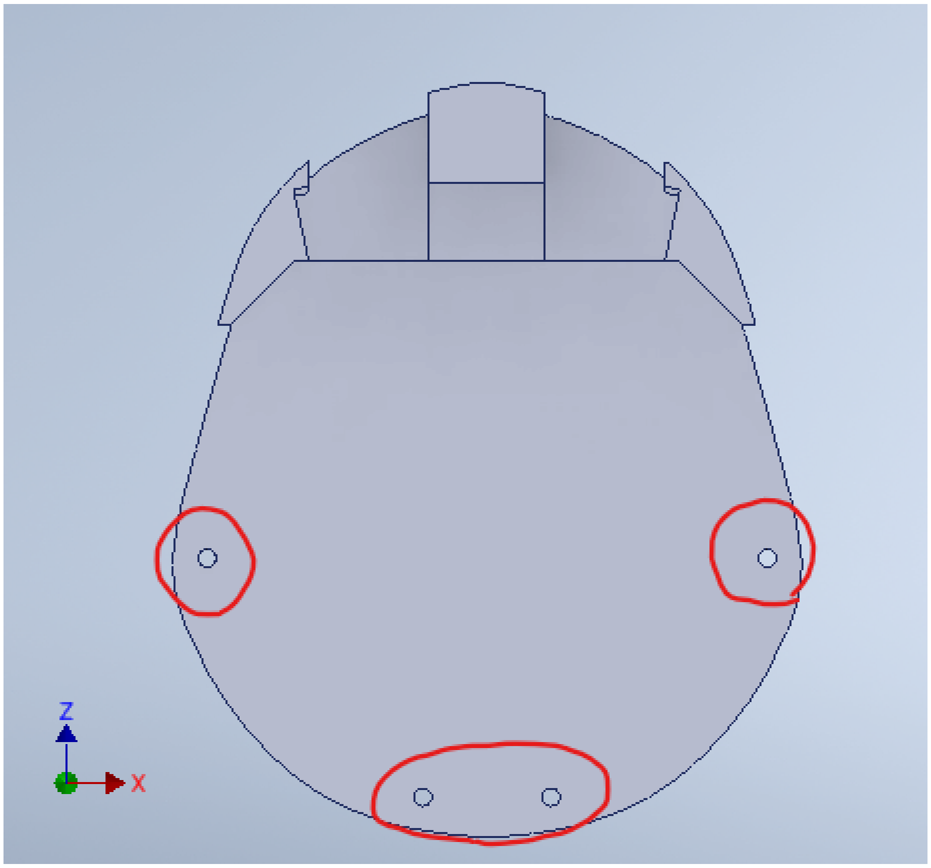


Figure 48: The Designed Crown Lattice Showcasing The Removed Or Non-utilized Connectors Circled In Red

The crown was originally a solid piece but for this design it was split in two and uses a single screw, and 4 slide fits for attachment. This reduced the need for four screw inserts, and four M4 screws. This is all shown in the figures 49 listed below with the new connectors circled in blue.

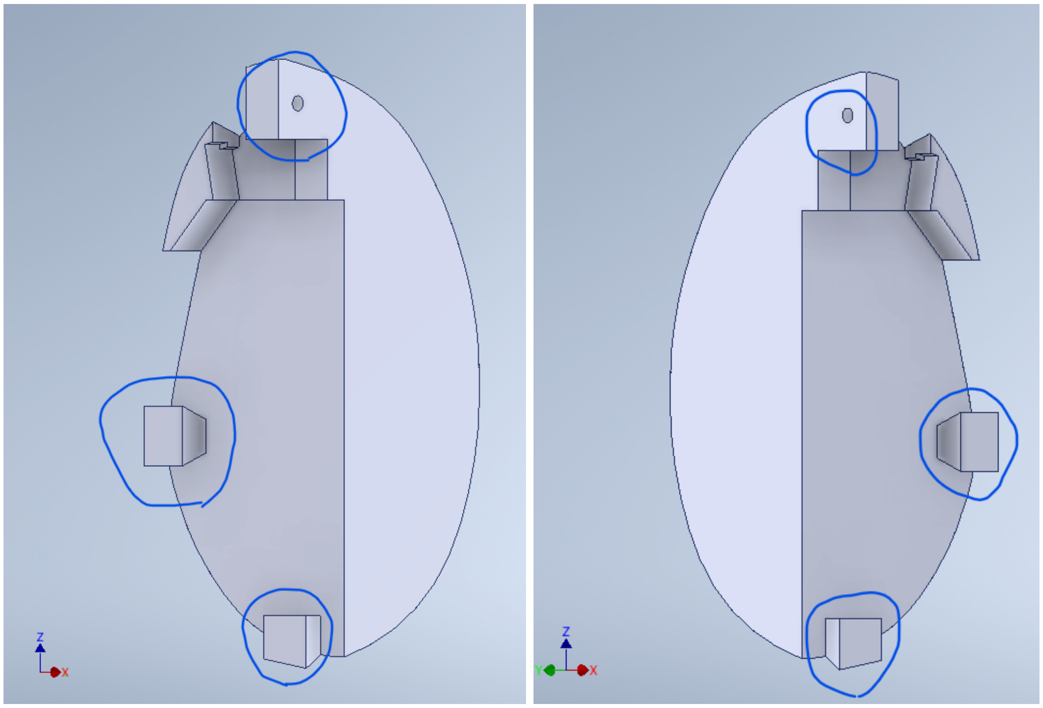
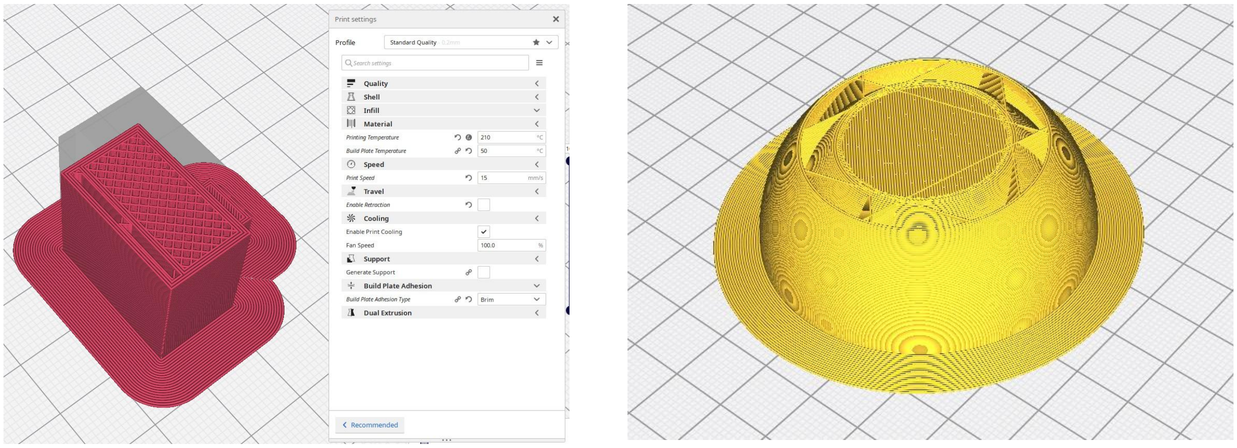


Figure 49: The Designed Two Halves Of The Crown Lattice Showcasing New Connectors And Slide-fits Circled In Blue

7.2.2 Skin

Once we had the capability of printing with multiple infills, we needed to develop a skin-like texture using TPU that could be completed in one print, extruding both the solid and flexible components simultaneously. We needed to develop print settings for both the solid parts of the lattice as well as the soft skin sections. To begin developing these settings, we created two test prints. The test prints were a half sphere and a rectangular prism with a slide fit. We varied the thickness of the outside/skin layer so they ranged from 2mm to 5mm at the lowest possible infill to determine what settings would result in the most skin-like texture. We varied the infill of the solid inner sections so they ranged between 85% and 100% infill, to determine what setting enabled us to use the least amount of plastic while still retaining a rigid structure.



Profile: Standard Quality - 0.2mm
Printing Temperature: 210 °C
Build Plate Temperature: 50 °C
Print Speed: 15 mm/s
Enable Retraction: ☐
Enable Print Cooling: ☑
Fan Speed: 100.0 %
Generate Support: ☐
Build Plate Adhesion Type: Brim

Figure 50: The Test Models in Cura

We found that the optimal infill for the solid section was 95%. This created a rigid structure, similar to PLA in its performance, specifically in sections over 12.5mm. Over 95% infill resulted in too much plastic being extruded onto the model as it printed, resulting in excess plastic and increasing the overall dimensions of the model. This reduced the accuracy of our prints. It also prevented the slide fit from performing as the size of both the male and female components increased well past the required tolerances. The skin infill was determined by how low an infill we could set while still achieving consistent print success. This number ended up being 5% infill.

Skin thickness was more subjective in nature. We tested a range of 2 to 5mm and decided on a 4mm skin layer. More in-depth testing can and should be done to determine what thickness is truly optimal. However a team, we decided that for testing purposes, the 4mm skin was the closest replica to human skin.

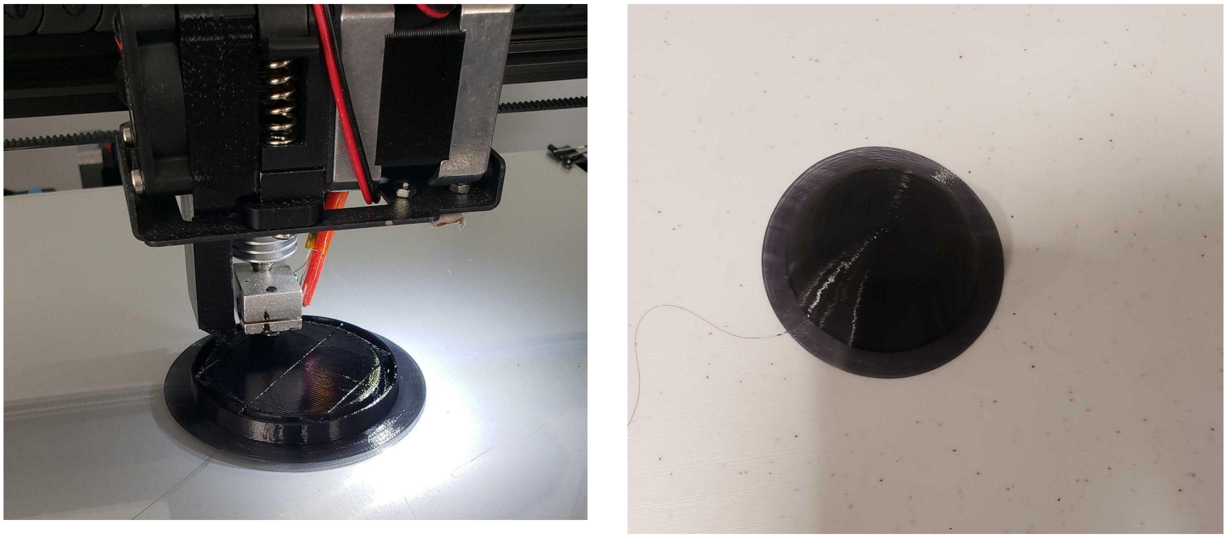


Figure 51: A 4mm Skin Test Print

Once we completed these test prints shown in figure 51, we developed a table outlining all of the settings for both the skin and the solid sections of the lattice (see table 3). Many of these settings are TPU specific and can be taken from the packaging on TPU filament. However, it is important to note the Infill Density as well as the Retraction setting.

Table 3: TPU Settings for Skin and Solid Sections

TPU Settings	**TPU Skin**	**TPU Solid Sections**
Temperature Bed	60 °C	60 °C
Temperature Extruder	210 °C	210 °C
Infill Density	**5%**	**95%**
Infill Pattern	Cuboid	Lines
Number of Outer Wall Layers	2	2
Retraction	Disabled	Disabled

With these settings established, the next challenge was to create the necessary CAD models to begin printing the skin. This proved to be a challenge as the existing model of the lattice was generated using surface modeling in a sculpting software not traditional solid modeling in solidworks or a similar program. Our initial efforts involved rescaling a copy of the model to create the skin as well as creating a copy of the skin face and moving it out 4mm shown in figure 52. These worked for early prints; however, these methods were not constantly replicable or accurate between different parts of the lattice, some methods worked for the neck, but not the top of the head and vice versa.

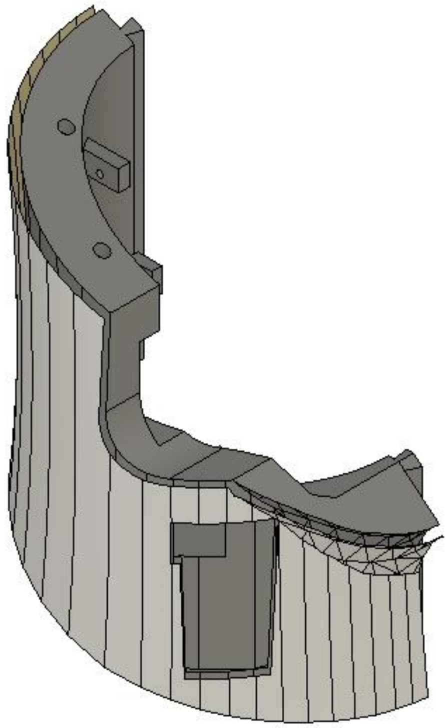


Figure 52: Early Version of Skin Using Surface Modeling

We needed to develop a more accurate and replicable method. To do this, we switched from traditional CAD practice to using a *loft* to create the skin. This process was done in Autodesk Fusion 360 and is repeatable and possible in Inventor, Solidworks and Creo. The process described below, outlines how to use the loft command to create a smooth accurate skin.

The first step is to subdivide the entire part with a series of parallel planes. We used 25 planes. The more subdivisions that are used, more smoother and more lifelike the skin will appear. It is important to note that the more planes used, the longer the process will take._____

The first step is to subdivide the entire part with a series of parallel planes shown in figure 53. We used 25 planes. The more subdivisions that are used, more smoother and more lifelike the skin will appear. It is important to note that the more planes used, the longer the process will take.

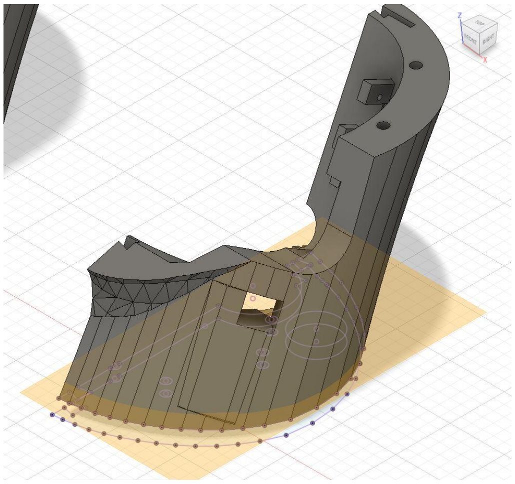


Figure 53: Subdivided Lattice with planes

Once all the planes are created, we projected the outline of the lattice onto each plane. This created a series of sketches that represented the lattice piece. This series of sketches is shown below in figure 54.

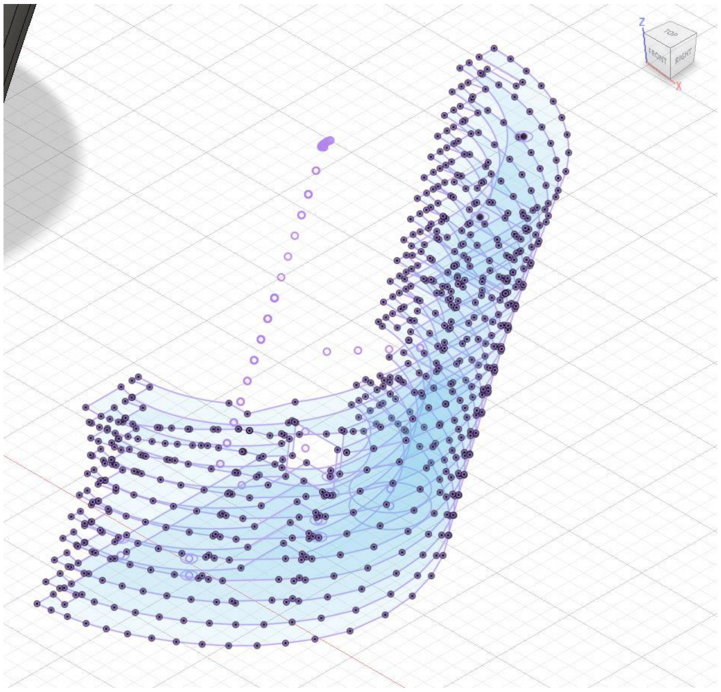


Figure 54: Sketches representing lattice

Each sketch was then individually edited using the offset command to create a 4mm offset of the lattice on each plane. An example of a sketch with the offset is shown in figure 55. This offset area of the sketch that can then be *lofted* to the one above or below it.

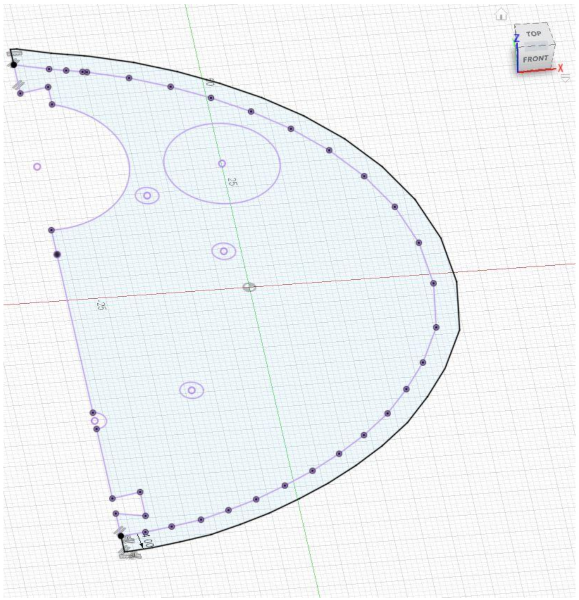


Figure 55: Sketch with offset

Once each plane/sketch had a 4mm offset, a *loft* between each layer was created. In some software, it is possible to do one continuous loft where each section is included; however in the example in Figure 56 lofts were performed individually between sketches.

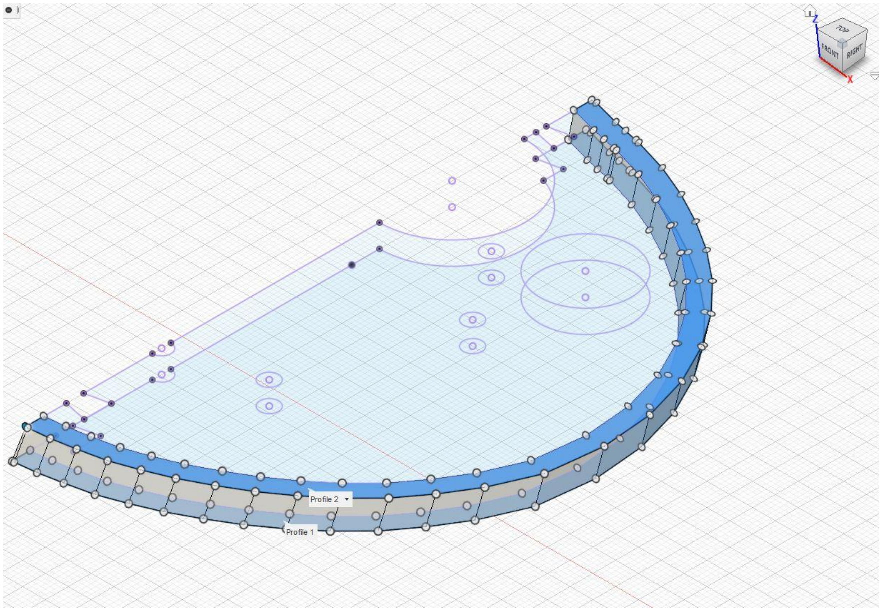


Figure 56: Loft Between two sketch planes

As we extended the loft up the lattice, creating the skin, areas that needed to be hollow through the model and the skin were covered up. We removed these using a simple cut/extrude. This created crisp lines at all the edges of the lattice and the skin where holes and edges needed to be. Figure 57 shows an hole being covered up by the skin.

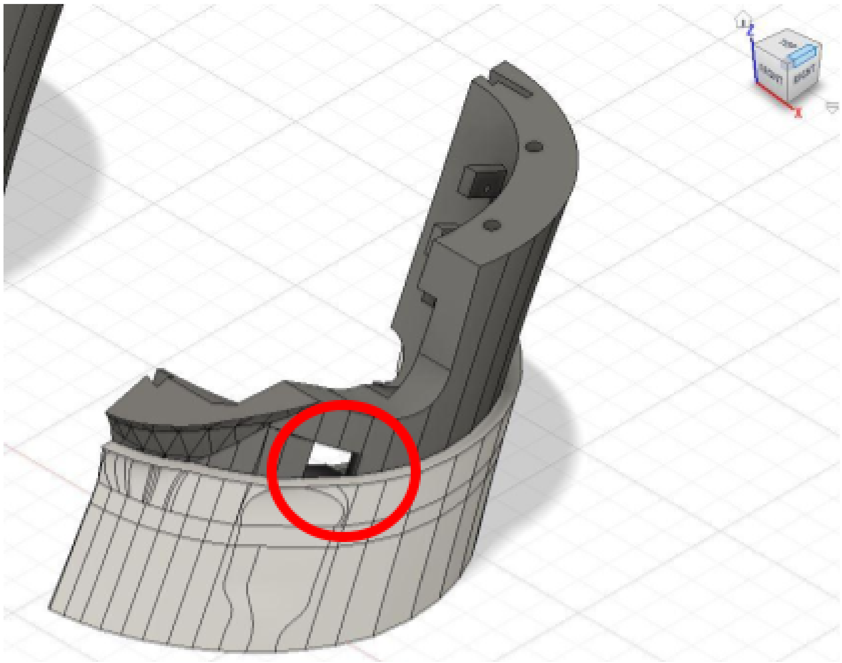


Figure 57: Hole being covered by skin

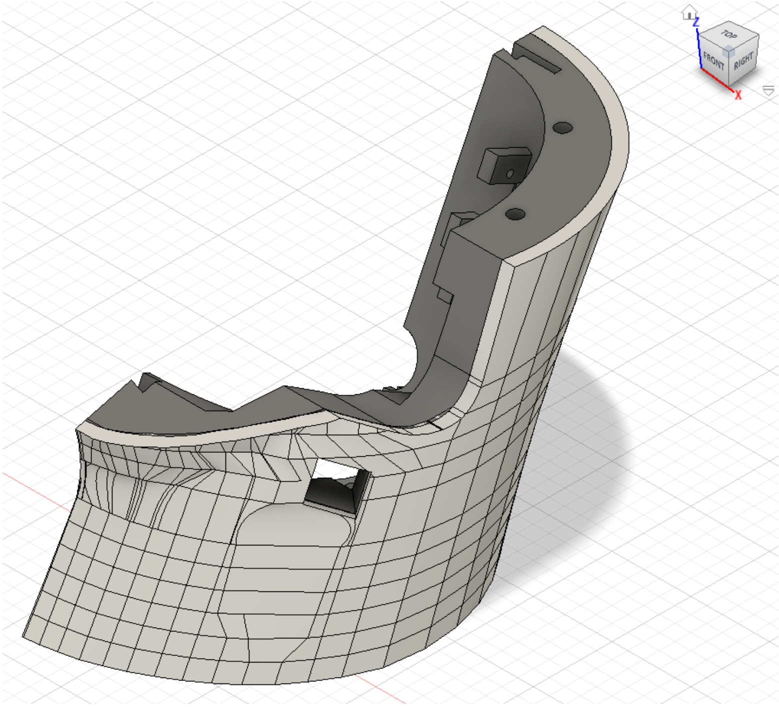


Figure 58: Neck Lattice with complete skin

Once the *loft* was complete we were left with a complete model of the lattice shown in figure 58. This included two sections. There is an inner section to be printed as a solid, shown in grey, and an outer skin section to be printed as a soft flexible outer layer, shown in white, using the settings shown above. After this point, the process needed to be repeated for the other lattice components, printed and integrated with the rest of the animatronic head.

During the process of designing and manufacturing, the final lattice with 3D printed skin many trials were completed to compare and refine the process.

The first set of TPU trials we completed was to print parts of the lattice unmodified at low infills to gauge what low infill TPU (0-20%) infill would feel like, when applied to the smooth geometry of the head. Figure 59 shows an early TPU print of a model from Cohen et al [6]. This model was done at 0% infill which resulted in difficulty printing and poor layer adhesion. These prints helped us to decide that TPU was an avenue worth pursuing as both the texture and flex of the prints reminded the group of skin.

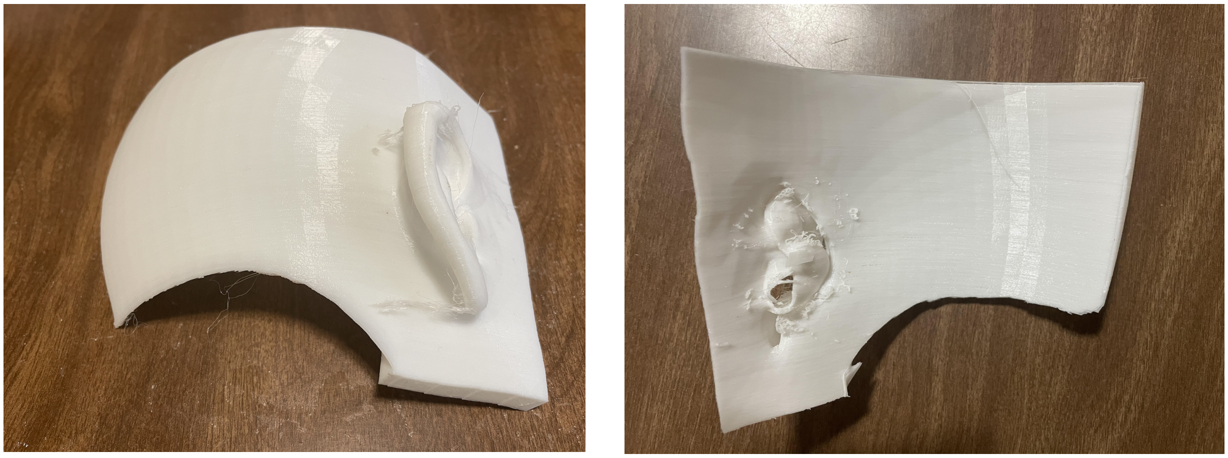


Figure 59: Exterior and Interior of TPU test print at 0% infill

The next set of tests were to completely print the lattice, solely in TPU at a high infill to determine if the TPU at a high infil was rigid enough and if the texture was an improvement over

PLA. The TPU lattice was printed with slide fits to determine if the high infil TPU was strong enough for slide fits to still function as needed.

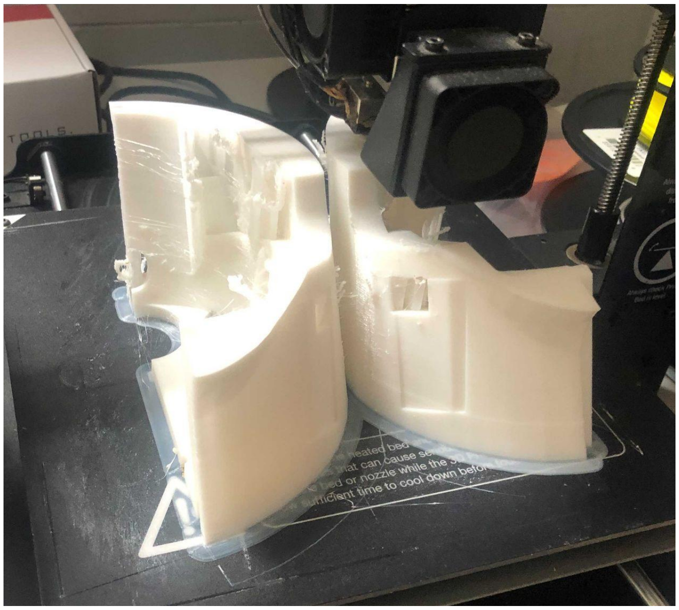


Figure 60: TPU lattice without skin printing

As shown in figure 60, the TPU was printed in pairs, to both save time and so that functionality could be tested. Initial prints of the TPU were printed at 80% infil, however this proved to be too flexible. We continued to reprint these models till the desired rigidity was achieved at 95% infil. Once we reached 95% we stopped increasing the infill as higher rigidity was not needed and increased density would also increase print times and cost.

The final set of tests we completed were used to determine what a layer of skin over the rigid TPU would feel like. We used these tests to determine what infil the outer layer of skin would have. We printed just the skin layer separately from the lattice model so we could rapidly try out different thickness and infill settings. Figure 61 shows two of the TPU test skins one at 15% infill and the other at 10%.

Figure 61: TPU skin test prints (Left 10%, Right 15% infill)

These tests helped us narrow down that 4% infill was the setting we wanted to move forward with as well as 4mm of thickness. While completing these trials we compared the feel of these TPU skins to the silicon skin we inherited. Comparing the two we determined that the silicone skin did feel slightly more like human skin, but not enough to justify the increased cost and manufacturing time vs TPU skin. Figure 62 shows one of the TPU alongside the silicone skin.

Figure 62: Silicone skin alongside TPU skin

Once we narrowed down the settings with the above trials, we completed the steps for generating a TPU skin on the lattice for the variable infill 3D printing. We took these models and using Cura's ability to print different parts at different infills we completed tests of the lattice and skin printed as one piece. These prints of the lattice with skin took longer than expected, around 40 hours each, but due to all of the previous testing went smoothly as shown in figures 64.

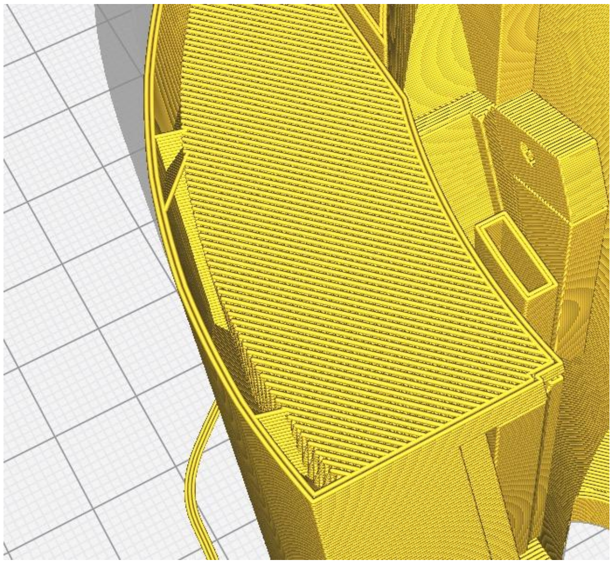


Figure 63: Close-up of Lattice with Skin in Cura - Variable Infill

Figure 64: Completed Print of Lattice with Skin in TPU

The variable infill TPU lattice with skin is both cheaper and follows a more intuitive process than the previous year's skin. It also lends itself to the DIY nature of the animatronic head, needing only a 3D printer to produce. The soft TPU at 5% infill and at 4mm thick is soft and has enough give to replicate the feel of human skin. This low-cost method of variable infill 3D print with thermoplastic polyurethane is not only a powerful tool for creating soft outer layers on medical training tools, but has the potential for applications in other industries.

Chapter 8: Electronics and Code Structure

H.A.L had a plethora of mechanical systems, all of which involved different sensors and actuators that needed to be controlled while maintaining realism and functionality. The electronics and control system was designed to fulfill the requirements that are detailed in section 4.3.2.6. The Peripherals and Implementation section discusses the initial plan for the electronics and control scheme and the steps that were taken to produce the final design. Based on the biological research described in the sections below, the system includes sensors that could replicate the human senses and abilities; sight, touch, hearing, movement. From varied heart rates to appropriate neck and eye range of motion, each feature was designed with that goal.

8.1 Peripherals and Implementation

8.1.1 Microcontroller

The Teensy 3.5 microcontroller carried over as the microcontroller for the system. The controller runs at 120MHz, has 27 I/O pins (20 PWM pins), 6 sets serial data lines, I^2C and SPI communication, arduino IDE compatibility, and all with a smaller physical footprint than comparable microcontroller. The Layout of the board is shown in the figure 65 below.

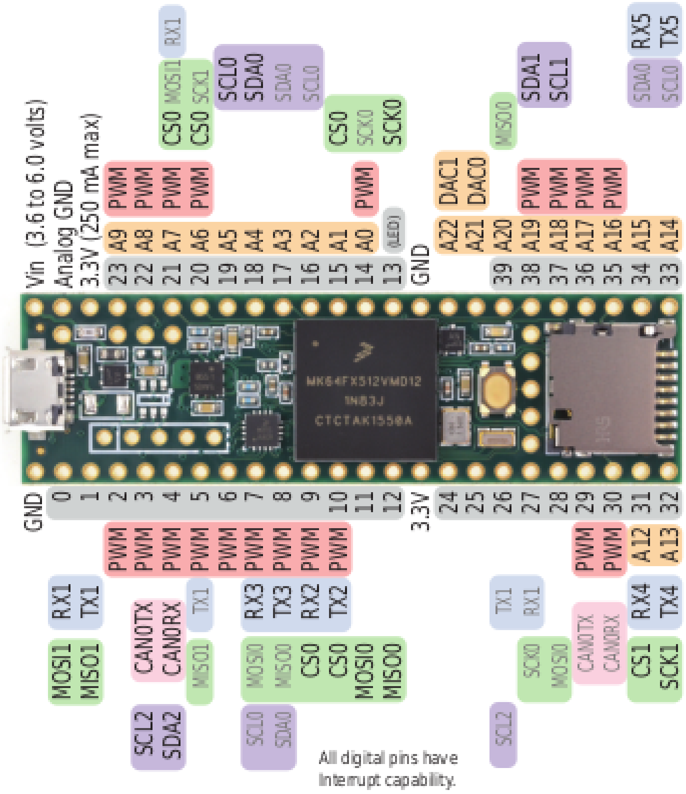


Figure 65: Teensy 3.5 Pinout Diagram, reproduced as is from [21]

The Teensy and Arduino IDE interface is extronararily easy, the teensyduino library can be found on the PJCR website [22]. However, libraries can be fickle due to naming conventions being identical. This is easily debugged by hiding or deleting the arduino libraries from the library folder.

8.1.2 Power

The peripherals were powered through different li-po batteries, 7.2V, and two 5V. The neck servos ran on the 7.2V battery. One 5V li-po went to powering the Teensy through the micro-USB port, this li-po also supplied the 5V 1A required for the Nextion touch screen. The other 5V li-po went to Adafruit PWM Servo boards.

8.1.3 Sensors

8.1.3.1 Camera

To mimic the sense of sight for our animatronic head, a camera was used. This would allow H.A.L. to have the ability to do simulations such as finger tracking for concussion checks. The Pixy2 camera was selected for its compatibility with the teensy microcontroller, availability, low price, and reliability of cameras designed for object tracking. The camera module footprint is 42mm x 38mm and the camera lens is smaller than 13mm in diameter. The Pixy2 has a power consumption of 140mA at 5V which is within Teensy's capabilities. To connect the Pixy2 to the Teensy Board need the 4 wires, VCC, GND, SDA, and SCL in the configuration shown in Figure 66.

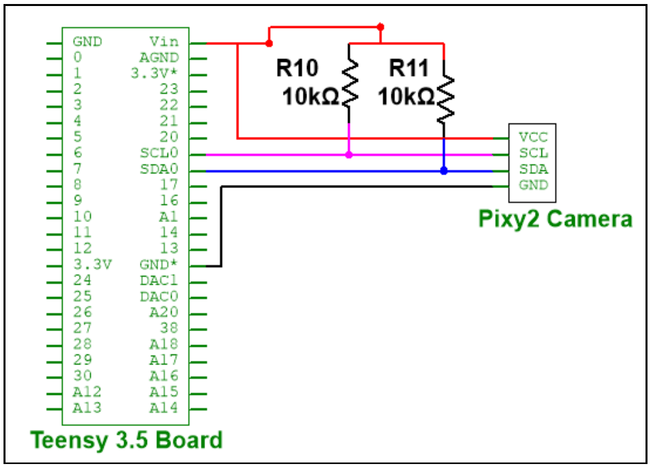


Figure 66: The Pixy2 Wiring Diagram by Cohen et al

To set up the Pixy2 camera, a program called PixyMon was used to tune the settings of the camera. The Pixy2 can be trained to identify up to seven objects or colors, these identified objects and colors are called signatures. With the availability of the blue latex gloves, that color of blue was chosen to be the signature the camera was tuned to.

On the code side of the Pixy2 camera, these signatures are called blocks. The function “getBlocks()” is called to return data about the object, the parameters used for the eye tracking are x and y. Those parameters give the location of the object in the field of view, for X the value ranges from 0 (all the way left) - 316(all the way right) and for Y the value ranges from 0 (all the way up) - 208 (all the way down). The Pixy2 library does support multiple objects and would use arrays to store the different info of each block.

8.1.3.2 FSR

The FSR sensors were incorporated to give the system physical stimuli. The FSRs work on changing its resistance value based on the force it is under. The resistor has a range of infinite resistance (no pressure applied) to 200Ω (maximum pressure applied) and only drawing 1mA. The FSRs can detect forces between 0 -100N. Both the small and large FSRs were wired to the Teensy as shown in Figure 67 below.

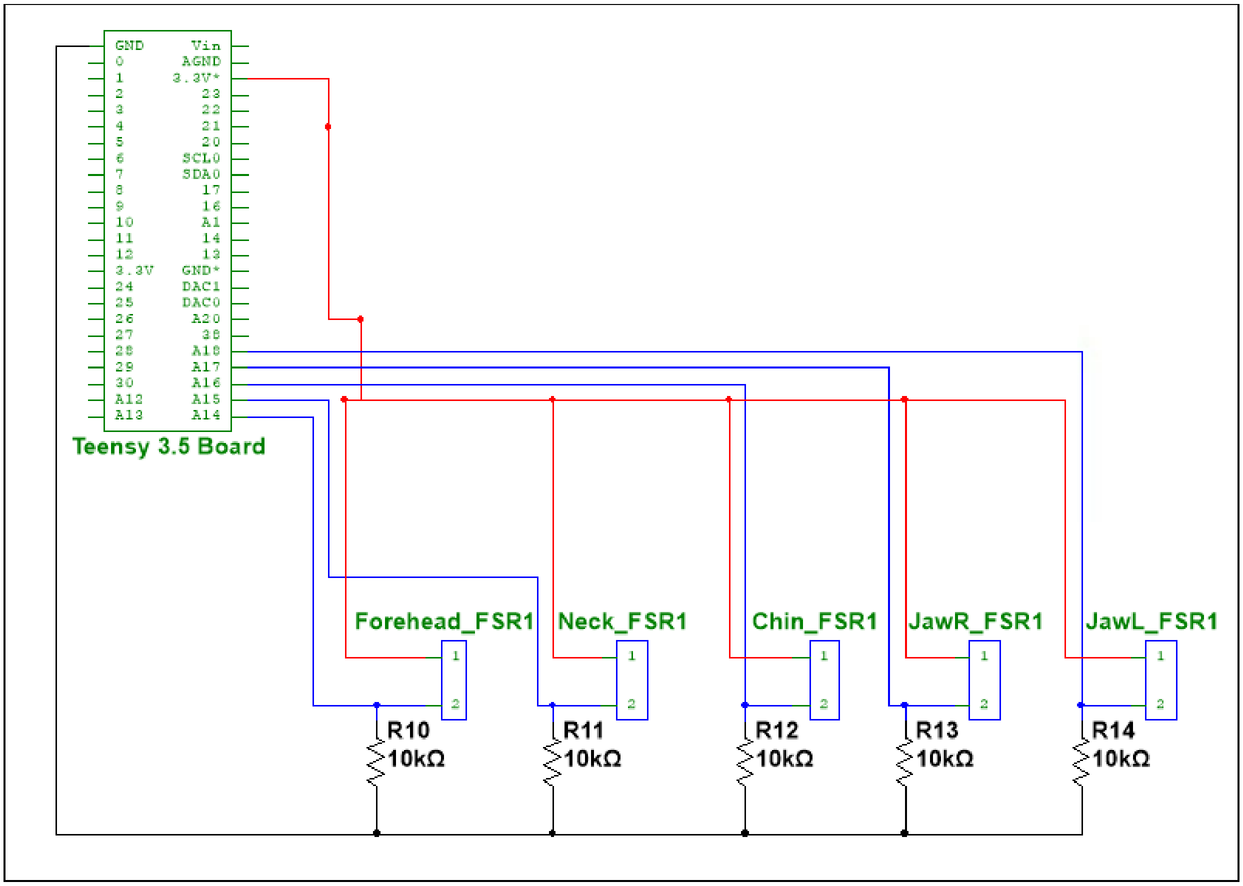


Figure 67: Wiring Diagram for FSRs by Cohen et al

The circuit is a voltage divider with the FSRsbeing the variable resistor using the equation below.

$$V_{out} = V_{in} (R_2/(R_1+R_2))$$

In where V_{in} is +3.3V, R_1 is the FSR, R_2 is the 10kΩ resistor, and V_{out} is the readout. From the voltage divider , the V_{out} was read by the teensy using the “analogRead()” function.

8.1.3.3 Microphone

A Microphone Sound Sensor Module for Arduino was utilized to detect changes in sound and determine if the user was speaking to the system. The module is rated for a frequency response of 50Hz - 20KHz and has a sensitivity range of 48dB - 66dB. There are 3 pins used for the module including pins for +5V power, ground, and AO as shown in Figure 68 below.

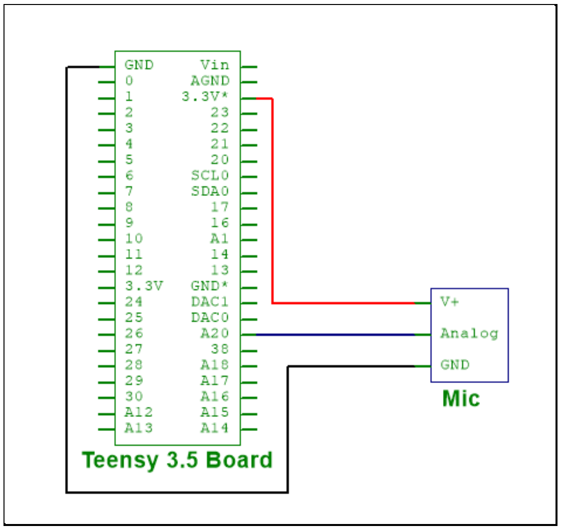


Figure 68: Microphone Wiring Diagram by Cohen et al

Although the microphone has a DO pin, it did not constantly produce a digital high signal even with adjusting the sensitivity. Any changes in the environment, slight disturbances to the potentiometer, or pauses in dialogue, caused the DO pin to flicker between a low and high signal. Due to this, AO pin was used, the “analogRead()” function was used to take in the data. The data was filtered and processed to and if triggered gave a pre-programmed response.

8.1.3.4 Amplifier and Speaker

A speaker had been implemented with a Amplifier and and an 8Ω loud speaker. An SD card was used to store pre-recorded .WAV files that could be played on the speaker. The Teensy Audio Library can output the audio through various means but the DAC was used for this application. Both the DAC0 and the DAC1 pins were used because the audio file was formatted for stereo channels. The wiring for the circuit is shown in figure 69 below.

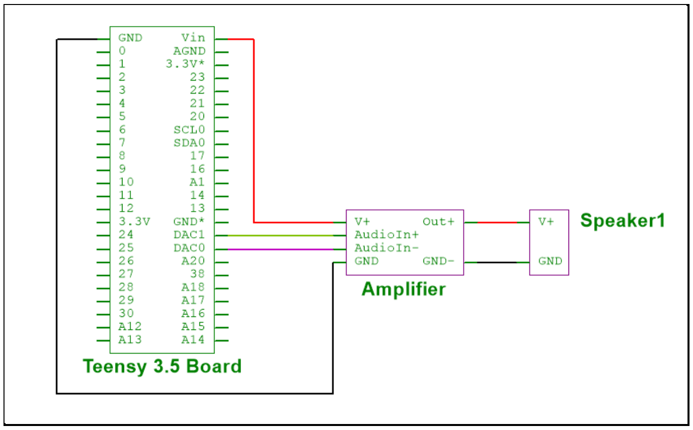


Figure 69: Speaker Wiring Diagram by Cohen et al

To use the library correctly, the .wav files must have a 16-bit resolution, a sampling rate of 44.1kHz, use stereo audio channels, and have file names in all capital letters (ex. “HELLO.WAV”). On the Arduino side, using the Audio.h library, the function “ playWav.play(filename)” was called to play the pre-programmed response.

8.1.4 Actuator

8.1.4.1 Servos and Servo Drivers

There were 3 different servos used in H.A.L, with different specs, voltages, and drivers. In the table 4 below, details about the servos are given.

Table 4: List of Servos; Names, Quantity, Voltage, Subsystem

Servo Type	Quantity	Voltage Requirement (V)	Subsystem
Turnigy D65MG	12	5	Eyebrows, Eyelids, and Eyeballs
TowerPro SG90	4	5	Jaw
MG995R	6	7.2	Neck

For the neck servos, they were wired directly to the board and power separately. The function writeMicroseconds(int) function was used to control these servos. For the 5V servos, the Adafruit 16-channel PWM Servo Driver from the previous prototype was used to free up I/O pins and control the servos with ease. The servo driver can only take 5v through the power ports. The wiring of a daisy chained pair is shown in figure 70 below.

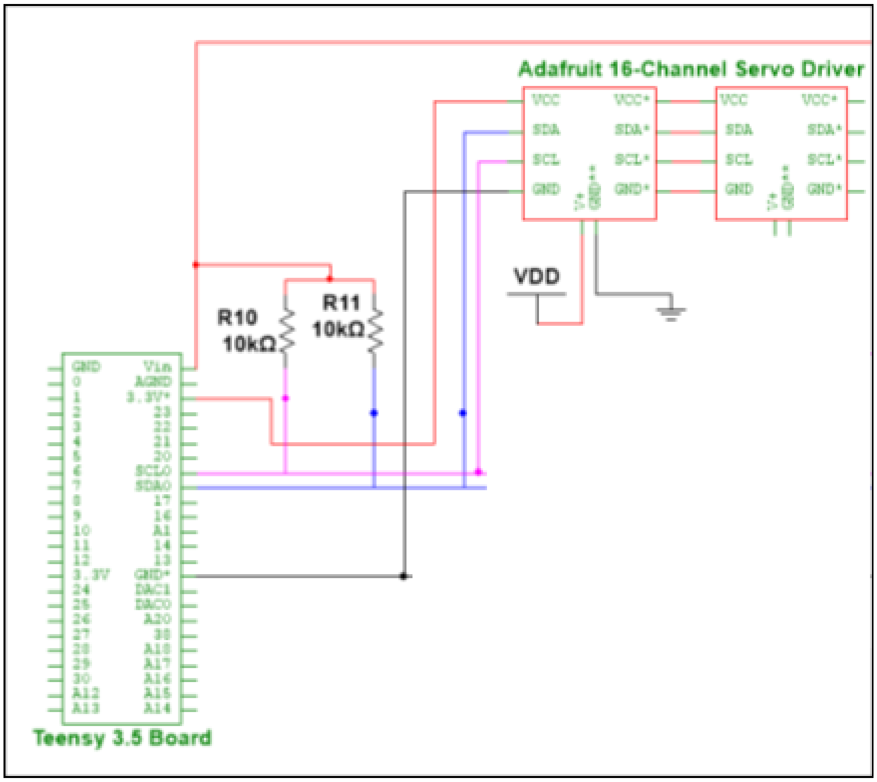


Figure 70: Example Wiring Of Daisy Chained Pwm Servo Drivers by Cohen et al

8.1.4.2 Solenoids

The carotid artery pulse was simulated with two solenoids. The teensy did not power the solenoids due to DIO only supplying 10mA compared to the .5A that is required to fire them. The Teensy instead was used to supply the 5V to the TIP 120 NPN. The diode allowed the 5V 1A power supply solenoids. A diode was used to prevent any reverse voltages to damage any of the components, 1N4004GP were used. The DO pin from the board was connected to the base of the transistor with a 220Ω resistor to prevent the transistor from being damaged. The configuration of the electrical diagram is shown in Figure 71.

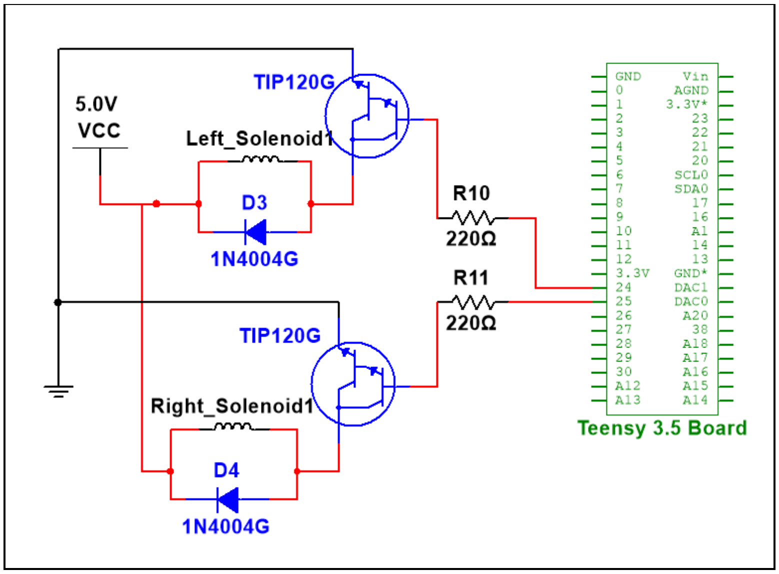


Figure 71: The Wiring Of The Pulse Subsystem by Cohen et al

The maximum human heart rate can be calculated based on age, but will generally not exceed 220 BPM. Using the “digitalWrite()” function to actuate the solenoids, they were found to work at 220 BPM, although the optimal maximum for the solenoids was lower at 160 BPM. Even with this slight discrepancy, the solenoids were able to reproduce a range of heart rate including irregular. To replicate irregular heartbeat patterns, the “random()” function was used. The Pulse.h files contain the various functions required to operate the solenoids.

8.1.5 UI

The Nextion 2.8” resistive touch screen was used as the UI for the animatronic. The screen can be controlled by either the user's finger or a stylus. The Nextion editor and Nextion.h library from their website were used to create the GUI. The touch screen communicates through serial and is powered separately by a 5V 1A supply as shown in the figure 72 below. The manual makes it clear that a power supply with tight specs is needed, specifically stating that power below specification will damage the screen.

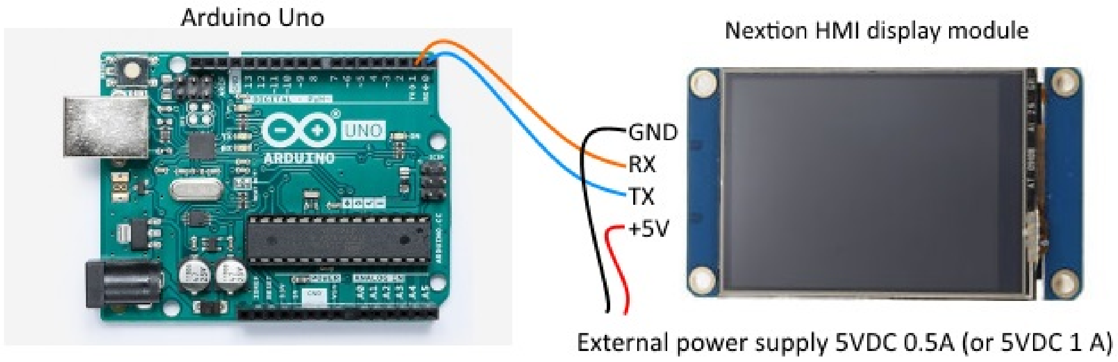
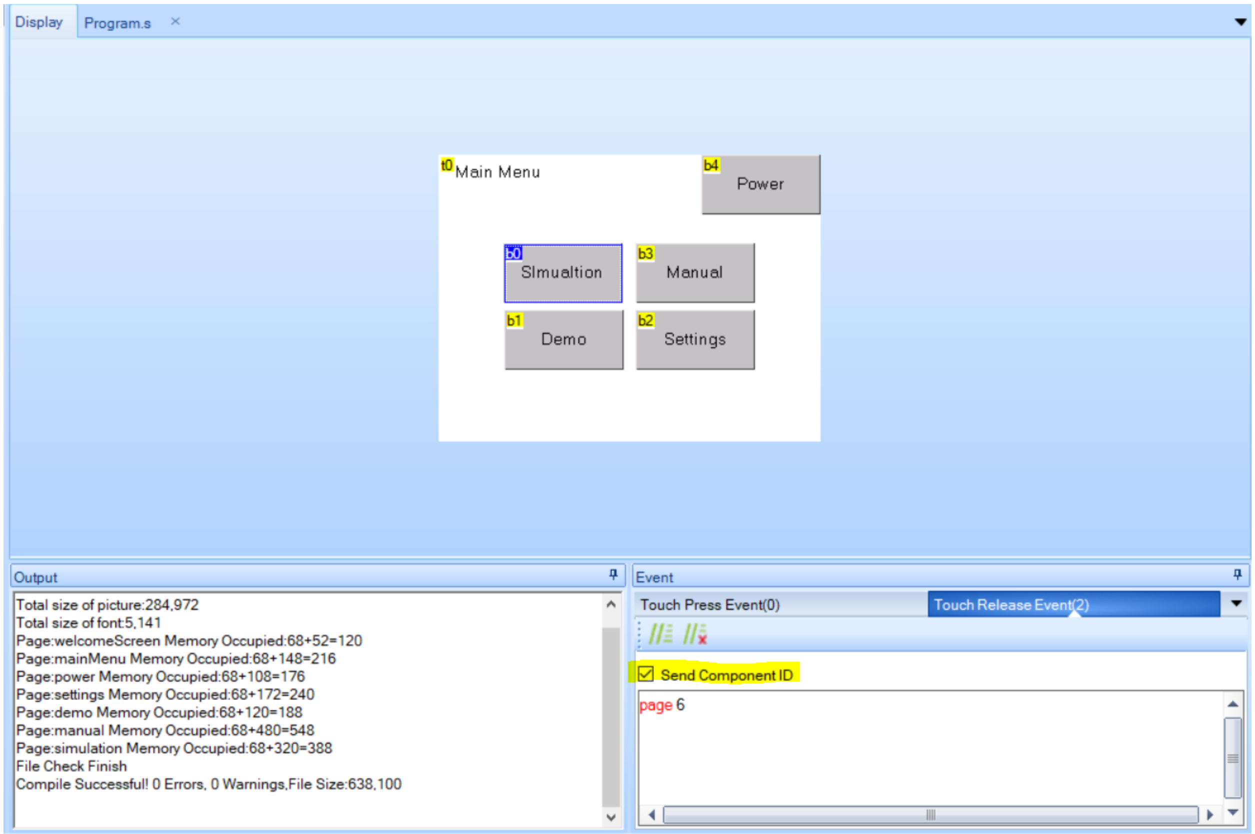


Figure 72: The Nextion Touch Screen Wiring, reproduced as is from [23]

Programming a button requires both the nextion editor as well as arduino code [24]. On the nextion editor side, the send component ID box needs to be checked for either a touch press event or touch release event as shown in figure 73 below



```
Total size of picture:284,972
Total size of font:5,141
Page:welcomeScreen Memory Occupied:68+52=120
Page:mainMenu Memory Occupied:68+148=216
Page:power Memory Occupied:68+108=176
Page:settings Memory Occupied:68+172=240
Page:demo Memory Occupied:68+120=188
Page:manual Memory Occupied:68+480=548
Page:simulation Memory Occupied:68+320=388
File Check Finish
Compile Successful! 0 Errors, 0 Warnings,File Size:638,100
```

☑ Send Component ID

```
page 6
```

Figure 73: Nextion Editor Event Panel

If using the Nextion Arduino Library, the steps for programming a button are; declaration of the button and as a touch feature, and the execution script of the button.

To declare a button using the nextion library, use the following template:

```
NexButton NAME = NexButton(pageID, objectID, "NAME");
```

pageID and objectID are given in the nextion editor and the name is user defined. For readability a naming convention is pXbY, p for page, X for the page number, b for button, and Y for the button number. Other features, such as the dual state button, can be defined as bt; an example being pXbtY.

To define the button as a touch event on the arduino, the button needs to be in the nex_listen_list[] array as a reference operator, &, and the element was given. The null terminator is needed. An example is shown below.

```
NexTouch *nex_listen_list[] = {&NAME , NULL}
```

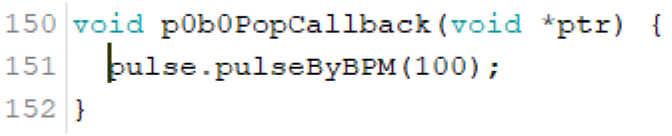
In the void setup of the script this line declares the function for the button, attachPop defines a release button and attachPush as a press button.

```
NAME.attachPop(NAME PopCallback, &NAME);
```

The function for a button is written below.

```
Void NAMEPopCallback(void *ptr) {//do something}
```

An example of a pulse demo is shown in the figure 74 below:



```
void p0b0PopCallback(void *ptr) {
  pulse.pulseByBPM(100);
}
```

Figure 74: Example Of Button With Code To Call A Function

In the void loop, this line starts the touch screen:

```
nexLoop(nex_listen_list);
```

Chapter 9: Results

The following chapter showcases the results of our project. In this section we discuss how our additions improved manufacturability and how each of our redesigned sub systems turned out. We include discussion on the improvement provided by introducing snap fits and how much time is saved through the removal of hardware. The following subsections go into detail on the improvements made on various systems that make up the animatronic head.

9.1 Manufacturability and Replicability

The manufacturability and replicability of the head was enhanced greatly with this year's project. The main contributor to this is the changes made to the lattice system. The slide-fits on the lattice improves ease of assembly and make it faster to assemble as well. This is due to creating less room for user error, being able to put it together without tools, and getting rid of hard to install connectors. In total the number of connectors was reduced by 20, and the design changes also removed the need for a soldering iron. This reduction in connectors also helps with replicability as less materials, and tools are required to be bought in order to assemble the animatronic.

9.1.1 Snap fits

Slide-fits are a great idea in order to have connectors already established on a part. This was the main idea that we ran with as we saw a large amount of potential in terms of replicability and manufacturability of the entire design. The one point of interest in the creation of a proper snap-fit is the use of tolerancing trials to figure out the correct tolerance between the two sides of the slide-fit. These are specific to the 3d printer and need to be done in order to create a feel for a good connection, with the resulting best tolerance for our 3D printer being 0.75% difference in scale. The resulting snap-fits that we created were all trapezoidal puzzle type slide-fits. These worked great and provided a solid connection with the utilized tolerancing of a 0.75% difference between the two halves of the slide-fit. Overall if these were expanded onto the rest of the subsystems, assembly time, manufacturability, and replicability would be enhanced greatly.

9.2 Mechanical Components

Improvement of mechanical components was a major segment in our project. Assuring that improvements be made to the design and functionality of various components was heavily emphasized by our advisor going into the project. Below are our results working on the various mechanical components of the project.

9.2.1 Neck Mechanism

Our group made great strides while improving the design of the neck mechanism. Implementation of a stewart platform solved many problems the previous design had. The neck's degrees of freedom was raised to six from its previous three. The platform's six legs also increased the stability and strength of the neck. This means the neck is now more than capable of supporting the weight of the neck.

9.2.2 Oral Cavity

Modifications made to the oral cavity were small but crucial. The major change was adding two holes for hardware. This hardware is used to affix the oral cavity to the jaw. This removed the requirement for adhesives during assembly. There were also two large clips on either side of the oral cavity that were removed. These clips interfered with the jaw mechanism making it impossible to mount. Due to this, we affixed the lower lips differently as the clips were no longer part of the design and luckily were not needed for a secure connection. Lastly, a ramp was added in the rear of the oral cavity. This ramp makes it less likely for any foreign objects, such as tubes or the like, to get caught on their way to the trachea during EMT training scenarios and aids in waterproofing the oral cavity..

9.2.3 Jaw

The jaw was modified solely to affix the lower portion of the oral cavity to the jaw using the new hardware instead of glue, as discussed in section 10.2.2. The jaw now includes a planar surface with two holes which line up with those added to the lower oral cavity.

9.2.4 Lips

Due to the stiffness of the lips, the group decided to separate them into top and bottom pieces. Additionally, the pieces were printed with a stiffer material to enable a faster print as the flexibility was not important to the functionality of our design. This allowed the jaw mechanism full actuation without being restricted by the lips.

9.2.5 Lattice

Due to the ongoing COVID-19 pandemic, it was not possible to conduct extensive testing of the skin, which would have required many people to touch and manipulate the skin. However, even with this roadblock, we were able to collect limited data within our group and with our advisor, comparing the TPU skin to the PLA skin. This data is not from a large group and should not be considered representative or hard evidence for the advantages of TPU skin over PLA. However, the TPU skin was preferred by the group unanimously, which indicates that a full study should be conducted to either confirm or reject the TPU skin as a prefered material and method.

9.3 Electronics and Coding Results

9.3.1 Microcontroller

The single threaded execution created a limitation on the abilities of H.A.L. There was no ability to break out of the button's function. The coded button insection 9.3.5 for example had no ability to break out of the loop. Attempts included creating an interrupt to check the serial port for a button signal from the nextion. However, this single threaded ability drastically lowers the ceiling on H.A.L.'s potential capabilities. There is only so much a microprocessor can handle and the current iteration of H.A.L. would improve drastically if the suggestions made in section 10.12.1.

9.3.2 Power

The power supply to the stewart platform shorted and created the connector to heat up and melted the breadboard. The Leads of the li-po were oxidized with white and blue oxide. Other than this incident, the poweringt the sensors and servos were supplied adequately with the setup in section 8.2.2 during the initial debugging.

9.3.3 Servos

The servos for the stewart platform work well, however, they moved with excessive acceleration and jittered during the setup. An attempt to quell the jitter was to place a 470 uF capacitor on the power lines. This might have resulted in reduced jitter but did not stop all jittering, although it is unclear if the power supply described in 9.3.2 was the cause. The power supply might have damaged the internal working of the servos however the servos moved in appropriate fashion.

9.3.4 Solenoids

The solenoids and pulse functions were used for testing the UI system. This subsystem worked well independently. The polling structure and single threaded microcontroller as described in 9.3.1, limited the code from interacting well with the new UI system. The addition to the code was the ability to specify faint and thready pulses, the current mechanism programmed is a spring loaded servo system described in section 10.8.

9.3.5 Hearing and Speech

Contrary to last year's finding, the microphone and speaker system were not on the EMS's priority list. Especially with the highly limited scope of the microphone's ability to interpret language hindered the system from being considered useful. Natural language process was considered, but outside the scope of feasibility.

Alternatives such as a pre-programmed keypad of questions was posed during the EMS interview, however not received with lukewarm responses. This is because this type of training can be done without the need for a mankin.

While both the speaker and microphones do work and are integrated into the code and physical structure of H.A.L., our recommendation is to leave this subsystem as is and implement and improve on other subsystems that the EMS individuals found more important.

9.3.6 UI and Touchscreen

With both the suggestion from the previous year's MQP, the need for more information displayed, and the deallocated memory run time error due to the LCD, a switch to a touchscreen was implemented. Two touch screens were evaluated, the Nextion Basic 2.8" and HiLetgo ILI9341 2.8". The Nextion touch screen was faster to implement and had a higher ceiling in terms of abilities. A helloWorld demo to control an LED was created and pushed to the Github in appendix A. A GUI was designed and a flowchart created, see appendix B. There were three main user pages: demo, simulation, and manual as shown in figure 75 below.

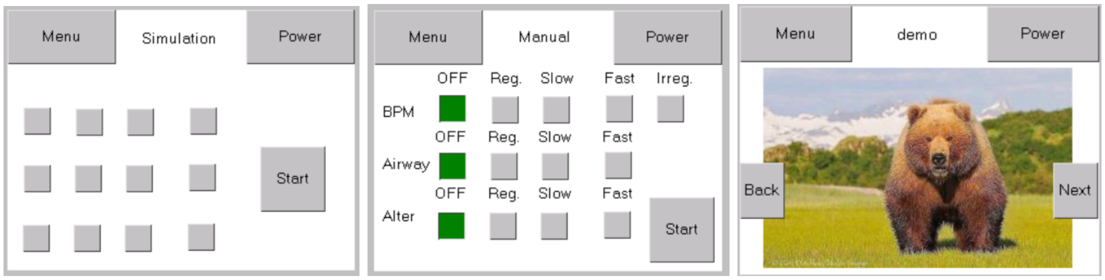


Figure 75: Screenshots of the Three Pages; Simulation(left), Manual (center), and Demo (Right)

The demo page was to be a tutorial on how each subsystem worked and used a carousel of pictures (the bear) to inform the user about the specific subsystem. For example, a graphic of the neck would appear with the carotid artery highlighted and the solenoids would be activated to demonstrate to the user the location and feel. The simulation page was to have preset simulations such as a concession, heart attack, or whatever other medical simulations H.A.L. would be capable of. The manual page would be for the user to set each of the subsystems and press run and have H.A.L. simulate the current set up, much like the previous year's MQP.

The attempt to merge the previous year's code with the new UI structure was fruitless. The polling architecture was the problem, detecting a button push during a simulation was not working. Attempts to resolve this included an interrupt routine as shown in the figure below in pseudocode.

```
#include <TimerOne.h>
Timer1.initialize(milliSecondValue);
Timer1.attachInterrupt(buttonFlag);
boolean BTNStopper = false;
```

```
void setup() {
  Serial.begin(9600);
}

Void NAMEPopCallback(void *ptr) {
      while(BTNStopper == false){
            pulse.pulseByBPM(100);
      }
}
void buttonFlag(){
      if (Serial.available()){
            int inByte = Serial.read();
      }
      if (inByte == stopBTN){
            BTNStopper = true;
      }
}
```

In the buttonFlag function, the stopBTN would be the serial data that the nextion touch screen would send over to the arduino as a signal. This code is supposed to be able to check the serial buffer data and interpret it but this type of interrupt never yielded the desired results. Another potential solution is to use hardware interrupts, the all I/O pins can be turned into hardware interrupt pins. Adding a keyboard with a button for ending a simulation but be the workaround for the current set up.

The serial buffer data was suspected because of similar results with a function called "getValue()", this is supposed to be able to get the status of a dual state button. To circumvent these problems variables were declared in the code and button functions were used to control their value as shown below in pseudocode.

```
Int bpmState;
void p5bt4PopCallback(void *ptr) {
  bpmState = 0;
  Serial.println(bpmState);
}
void p5bt5PopCallback(void *ptr) {
  bpmState = 1;
```

```
  Serial.println(bpmState);
}
```

This did in the desired functionality and this system was used on the demo page, manual, and simulation pages.

9.3.7 Code Structure

9.3.7.1 Overall Architecture

While the object oriented programming developed last year might have allowed for better organization, the polling architect was a significant roadblock. Polling relies on no function being a blocking function, i.e. a function that prevents the script's execution until it is done. Due to the single threaded microcontroller functions like the microphone or eye tracking could prevent all other subsystems from executing.

9.3.7.2 Stewart Platform Code

The new neck mechanism controls a moveable platform through 6 servo motors. To calculate the angle the servos need to be driven to inverse kinematics of the platform was done. To do this done, two coordinates systems are used; xyz (bottom platform), x’y’z’(top platform), and three angular displacements are defined;φ (yaw around z), Θ (pitch around y), and ψ(roll around x). The coordinate system and parameters are shown in the figure 76 below.

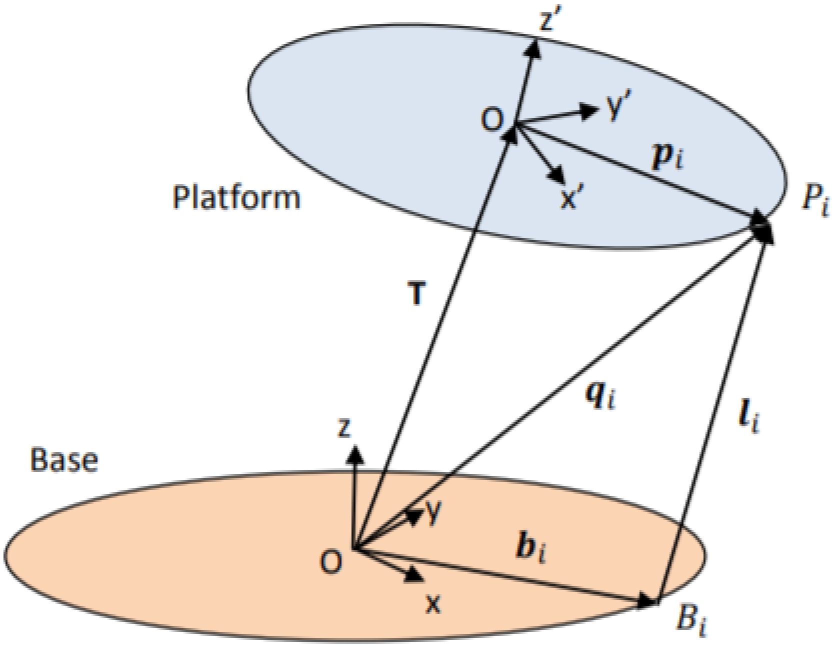


Figure 76: Coordinate System Of The Stewart Platform, reproduced as is from [25]

This yields three rotation matrices and when multiplied together results in a matrix shown in the figure 77.

$$
\begin{aligned}
{}^{P}\mathbf{R}_{B} &= \mathbf{R}_z(\psi).\,\mathbf{R}_y(\theta).\mathbf{R}_x(\varphi) \\
&= \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} . \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{pmatrix} \\
&= \begin{pmatrix} \cos\psi\cos\theta & -\sin\psi & \cos\psi\sin\theta \\ \sin\psi\cos\theta & \cos\psi & \sin\psi\sin\theta \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} . \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{pmatrix} \\
&= \begin{pmatrix} \cos\psi\cos\theta & -\sin\psi\cos\varphi + \cos\psi\sin\theta\sin\varphi & \sin\psi\sin\varphi + \cos\psi\sin\theta\cos\varphi \\ \sin\psi\cos\theta & \cos\psi\cos\varphi + \sin\psi\sin\theta\sin\varphi & -\cos\psi\sin\varphi + \sin\psi\sin\theta\cos\varphi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi \end{pmatrix}
\end{aligned}
$$

Figure 77: The Three Rotational Matrices And The Resultant Matrix, reproduced as is from [25]

The resulting rotational matrix is stored in an array. The home array is made up of three elements, [0,0, z_home]. Z_home is defined as when the two coordinate systems are aligned, the height between the two platforms. A desired array consists of 6 elements; x’, y’, z’, x rotation, y rotation, z rotation. Example shown below:

```
static float homeArr[6] = {0, 0, 0, radians(0), radians(0), radians(0)};
```

The translation array is created by adding the first three elements of a desired array to the home array. With the translation and rotation matrices known, the inverse kinematics to define the servo angle can occur. The servo horn and arms, a variable h and d were used respectively. The origin is defined as B_k, The point of the arm that attaches to the end of the servo horn, and the point of the arm that attaches to the top platform, P_k. An angle. α_k, is defined by the servo horn and a parallel axis. A diagram of these parameters are shown in figure 78 below.

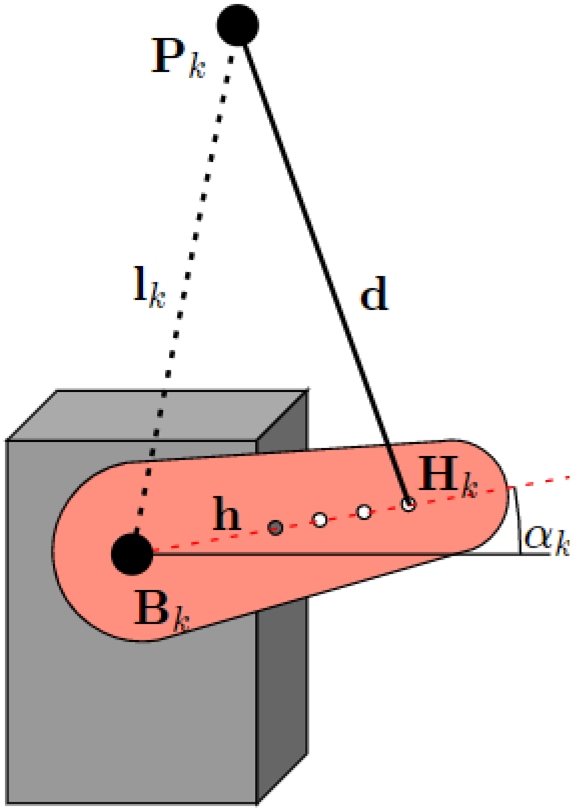


Figure 78: Servo parameters, reproduced as is from [26]

That α_k is calculated by trigamontry, given the value of h, d, and the position of P_k. Then converted to a milliseconds PWM signal.

The "setPos()" in the code is what is called to create angles and drive the motors, it calles on the other functions to do the math described and above and can be found in appendix A. The input to "setPos()" function is an array consisting of 6 elements; x', y', z', x rotation, y rotation, z rotation. Example shown below:

```
static float homeArr[6] = {0, 0, 0, radians(0), radians(0), radians(0)};
```

The result was a head that moved with too much acceleration, motor jitter, and disorienting movement.

An additional step to the code was adding to drive all the servos to the 1500us position and wait until the servo horns with the top platform were attached. This resulted in better movement of the head. Further plans for the calibration of the head are described in chapter 10.

Chapter 10: Discussion and Future Work

This year we made significant forward progress, in many areas of the head, including the skin, the neck and its manufacturability. Even with these forward steps there is still a considerable amount of room for further testing, research and improvement of the system document above. This chapter begins exploring some of those possibilities.

10.1 Manufacturing and Assembly Time

The manufacturing and assembly time could be enhanced even further in the future by focusing a lot more on manufacturability principle. As many of the connectors were designed in a way that they are in hard to reach places, many things could be done to enhance this. For one, any hole that leads to where a screw inserts could have a chamfer along the edge to guide it into the hole. This will increase the efficiency of the assembly time. Slide-fits could also be utilized a lot more to negate the use of hardware

10.2 Base and Neck Enclosure

The main areas of future improvement when it comes to these two areas is by ensuring synergy with the Stewart Platform. The neck enclosure must be split into 3D printable pieces, preferably attached using only snapfits. Due to the new sizing of the neck mechanism and neck enclosure significant changes need to be made to adapt the current base so that both pieces can be adequately secured. Another great improvement that would aid in organization of electrical cables and components would be to replace current components with a PCB. This would also require adaptation of the base to be synergistic with these changes.

10.3 Neck Mechanism

The Stewart platform needs to be mounted to the base. The platform also needs to be tested to ensure it operates in realistic manners. The current status demonstrates that the platform can move with high acceleration. However for smooth and realistic movement, the gyroscope plotting script should be run.

In assembling the Stewart platform, there are two layers of bolts; the ones that connect the servos to the arms and the arms to the upper platform. The bolts that connect the arms to the upper platform create two problems, thin features on the 3D print and fickle installation. Potential solutions to both reduce hardware and improve the part are to add snap fits through the arms.

10.4 Oral Cavity

Looking at possible future work when it comes to the oral cavity we have a whole bunch of options as this is probably the most underdeveloped subsystem when it comes to accurately representing a human being. The first among these being applying another group's tongue device inside the oral cavity. This other group containing the members, during the 2020-2021 MQP year have designed a realistic tongue that uses magnetic actuation in order to perform a variety of motions. With slight adjustments to the oral cavity regarding waterproofing and the storage of hardware needed for the tongue to function this could be applied and allow for simulations involving drinking or swallowing.

Another change that could be made to the oral cavity to make it more anatomically correct would be the inclusion of realistic teeth for dental applications and training. Currently, dental models are extremely important when it comes to training individuals in a safe and forgiving environment before practicing on real patients. So if we could make a patient simulator as lifelike as possible by applying anatomically correct teeth to our animatronic head dentists will have an even better, more realistic, alternative to training on real people. Especially since models are needed in post graduation settings and when learning the procedures and science in dental school there is a visible need for a realistic head with correct teeth to train skills on. This is not an easy task though as current teeth models provide realistic representations of teeth so ours would have to be up to the same caliber in order to give reasoning for transitioning to using our model. Among the models that were found when looking at this potential application we could see that there were several necessary points needed for a accurate set of teeth and one of the current designs on the market guaranteed the following:

- Anatomically accurate Spee curve
- Anatomically accurate Wilson curve
- Snap-in teeth made of melamine resin (hardness similar to human teeth) with artificial root and numbering
- Soft PVC gingiva in natural colour
- Plastic cast base. Can be used for all partial dentures and complete denture
- Black plastic spring element for tooth fixing
- 1 to 2 tooth relationships
- Tooth mobility comparable to a human patient

With all these necessary requirements it would take a long time to construct models and design the oral cavity in order to support this new subsystem but would definitely improve the realness of our model as well as increasing its amount of potential applications in the medical field. Figure 79 depicts bothe the Spee and Wilson curve, two necessary design parameters when it comes to anatomically accurate teeth.

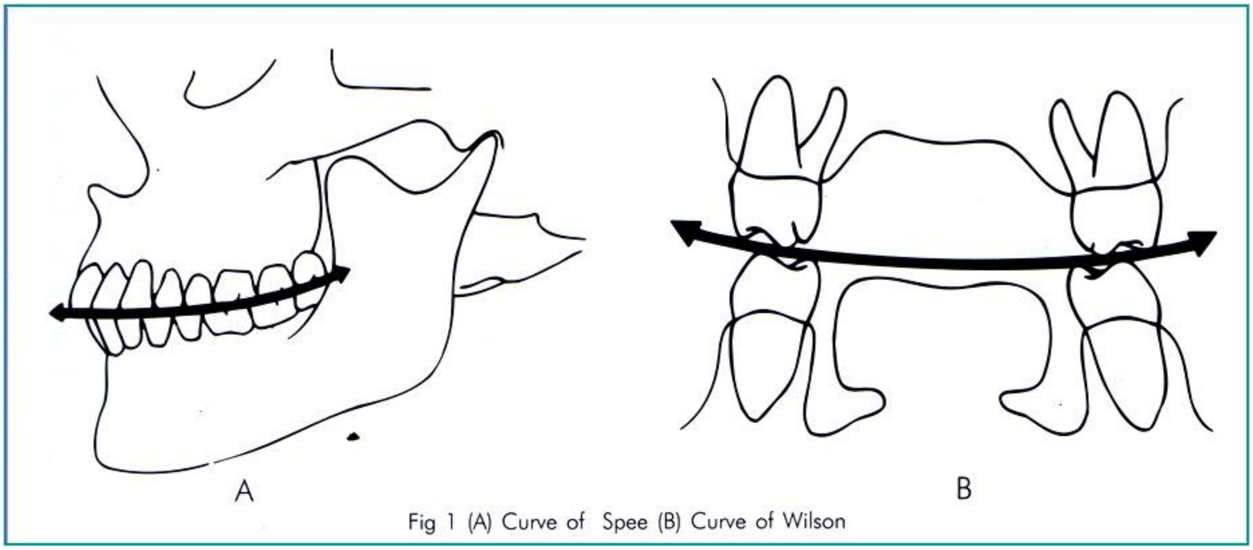


Figure 79: Image Showing Spee and Wilson Curve, reproduced as is from [27]

We also looked into mask testing and found a study which looked into previous research and used video capture technology to show how a smoke generator connected to an artificial set of lungs caused leakage around the mask.

Previous research found that “using aerosolized 3% hypertonic saline solution and photographic techniques, Somogyi et al demonstrated that throughout exhalation, both the non rebreathing and Venturi-type oxygen masks channeled the exhaled gas through side vents, forming a leakage plume of exhaled gas that was directed to either side of the patient.”

Though this looked into oxygen masks we are also trying to see if infectious plumes could be the result of specific masks and in which scenarios certain masks work best. This study utilized a human patient simulator not unlike our artificial head but with a body attached and anatomically correct organs.

- Oxygen flow 4 L/min
- Respiratory rate 12 breaths/min
- Tidal volume of 0.5 L

The way they showed this airflow creating s plumes around the mask was by using a smoke generator directly set up to the lungs of the model so exhaled air included this smoke. This smoke was then illuminated by a strong halogen light to show the 3d extent of this air cloud and sections of this plume were then revealed by a laser light sheet with a 48x zoom digital video system recording the results at an image rate of 30Hz.

- Light sheet (green, 527nm wavelength, 2 W average power, 1-2mm in thickness)
- Video capture images were synchronized with the breath cycles capturing 30 images per second

After placing the images into a video analysis tool (windows movie maker) the images were analyzed and the other half of the exposure was created using symmetry leading to results showing how far infectious gas from a sick patient can travel when wearing an oxygen mask. Figure 80 shows the max distance of 0.4m (shown by the arrow)

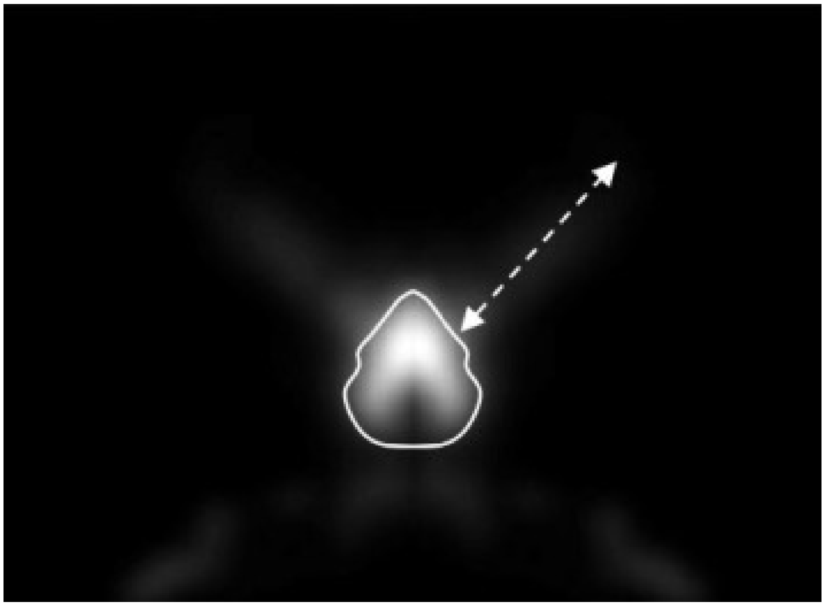


Figure 80: Mask Testing Results Image, reproduced as is from [28]

With Covid-19 going on for months, we already know that while the mask provides some protection for the wearer its main purpose is to protect other people from airborne transmission of the virus. So if we are able to test these masks we can determine how well different masks worn in different ways protect others around you.

We can also potentially produce a video of air moving by using Schlieren Photography which utilizes a parabolic concave mirror, a sharp object and a light source to record airflow.

For a cheap approach we would need:

- Some sort of lens (recommended fresnel lens as it has a large clear aperture)
- A sharp object (razor blade)
- A light source (LED works well)

An example of said system is show in figure 81.

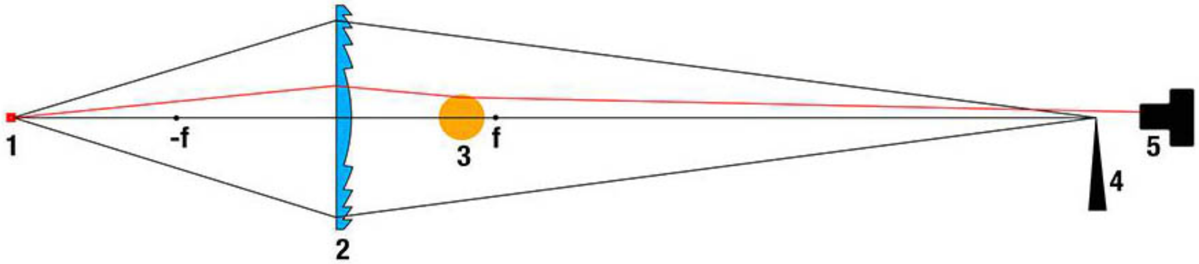


Figure 81: Schlieren Photography Setup, reproduced as is from [29]

1. Light source
2. Lens
3. Heat source/thing you are testing
4. Sharp object
5. Camera

Mask testing would yet again provide more applications for our animatronic head and would be incredibly useful during this time period where masks are necessary and there is no good way to test how mask fitting on the human face affects performance. This application would make our project rather relevant to current world issues but would be a difficult project in and of itself as airflow must be created with some sort of artificial lungs and the oral cavity into the esophageal tract would need to be airtight.

10.5 Jaw

In terms of future work for the jaw and the rest of the oral cavity one focus would be to waterproof this system. This is important as stated above where waterproofing would be necessary for any swallowing or dental training applications. The jaw definitely plays a large role in this as by redesigning the majority of the oral cavity could be made waterproof. The jaw is also a large focus as electrical components used to actuate the jaw would need to be protected from any liquids so that they are not damaged. Fortunately with a redesign of the jaw this risk could be mitigated.

10.6 Lips

The lips have a lot of room for improvement especially when it comes to improving realism. Currently due to time constraints we opted for a design which simply cut in half our current lips so that movement of the jaw was not prevented. As was discussed in the earlier methodology regarding the lips it would be much better to go with a hinge based design for the lips so that they would move with the mouth in a more realistic manner. This will require some designing to make them appear lifelike and also some investigation into the best ways to attach these to the animatronic head but would only improve our design as a whole.

10.7 Eyes

During the EMS interview, feedback on the ability to simulated eye dilation was positive. As noted by the previous year's MQP noted, a photoresistor would be an adique for sensor input. The actuator output was investigated, both the biological and mechanical research was conducted.

In NASA conducted research done in 2012, A unified formula for light-adapted pupil size was created compiling several data sets, dating all the way back to 1922. Using the tool in the Demonstration and calculator section of their paper, could generate a mapping of lux to eye dilation [30].

Two mechanical systems were researched, dielectric elastomers actuators (DEA) and iris mechanisms. Two roadblocks stalled out DEAs during evaluation, first the creation of these actuators are tedious and arduous processes that will be difficult for a layman to do. Secondly the actuators that were researched such as the one in figure 82 used ~5.5 to 7 kV to actuate. This would not be safe to put on this animatronic.

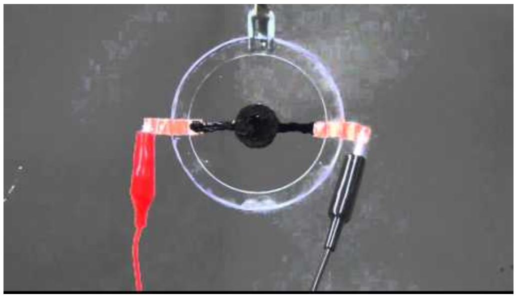


Figure 82: Dielectric Elastomer Actuator, reproduced as is from [31]

Secondly, iris mechanisms also known as apertures were investigated; however, off the shelf units such as the ones in figure 83 are quite expensive. Attempts to minimize, led to similar problems as the DEAs, creation of mechanism this small but layman

Figure 83: Iris Mechanisms, reproduced as is from [32]

A major obstacle for both of those systems as well as this subsystem in general is manufacturing it. Whether it is the making of dielectric elastomers or miniterizing the iris mechanism. Finding a work around solution is the best option. Potentially using the touch screen and do a video of a pupil dilating or just reading the photoresistor's value to the screen.

10.8 Lattice/Skin

Overall, the skin has been a success. The techniques developed for its creation are valuable and have many possible uses in the medical sector as well as in other industries. The ability to 3D print materials where different components have different material properties simultaneously and without any additional manufacturing processes allows for the reduction of cost and manufacturing time. Variable infill 3D printing also allows for the creation of parts in which internal areas that cannot be accessed from the outside have different properties to the exterior, which is a capability unique to 3D printing.

Possible next steps for the skin involve increasing the realism of both the appearance and feel of the skin. One possible improvement would be using an infill pattern that still allows the skin to print easily, but is more flexible when portions of the skin are depressed. Currently the skin has been printed with the CURA infill settings of Cuboid and Lines.

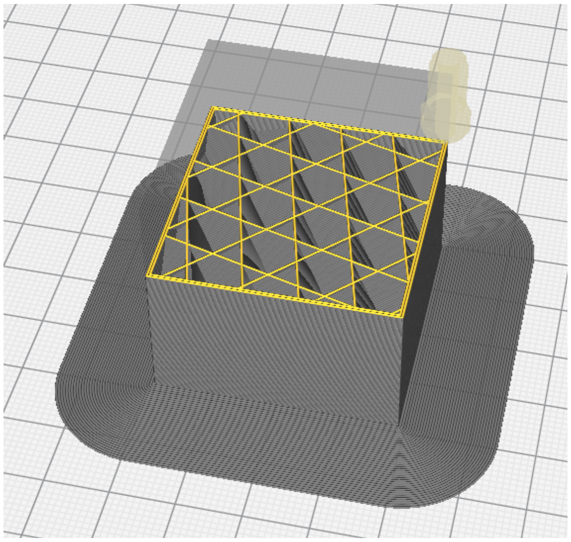


Figure 84: Cuboid Infill

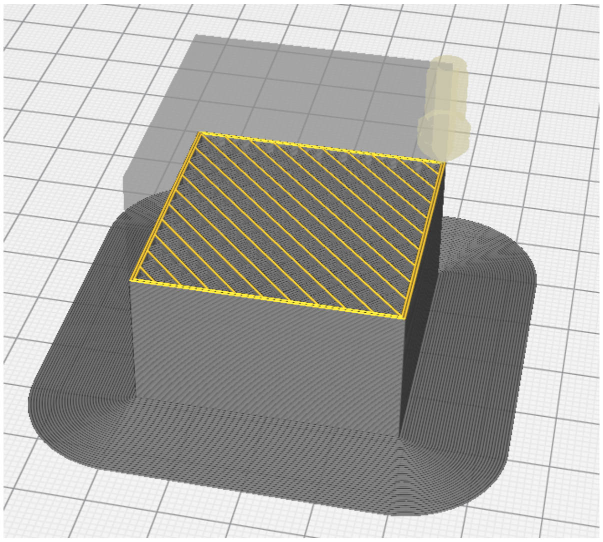


Figure 85: Line Infill

Both of the above infill settings (see Figures 84 and 85) create areas where the skin is more rigid at the connection points between the infill and the outer wall of the skin. These more rigid areas are less noticeable on the cuboid, as the points where the supports attach to the wall are more spread over an area and not simply vertical lines up and down the walls of the skin as in the line infill. Future work can be done to identify or develop a better infill pattern to reduce or even eliminate irregular zones in the skin caused by infill pattern and density.

Another area for improvement relates to both the texture and appearance of the skin, is the surface finish of the extruded TPU. Currently the TPU prints in layers and these layers are visible and, in many cases, can be felt when touching the skin (see Figure 86).

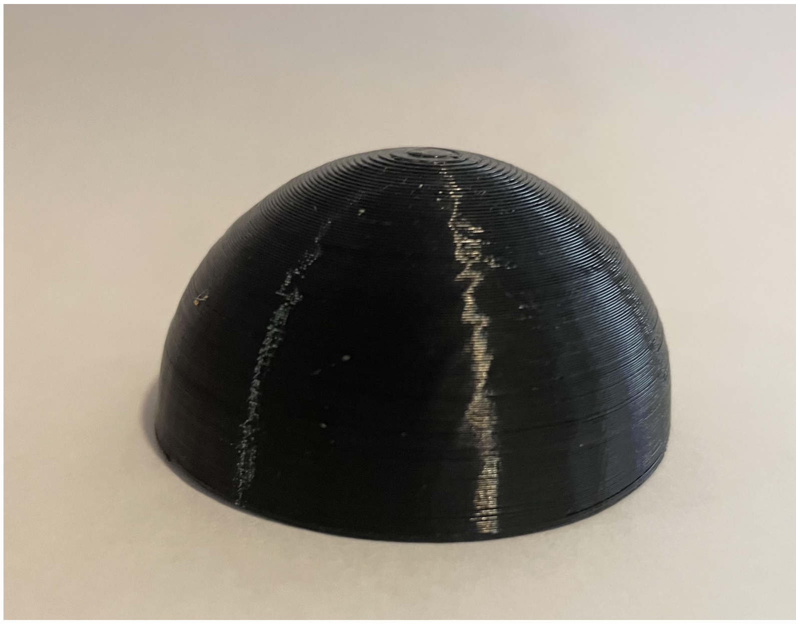


Figure 86: Visible Layer Lines on TPU Test Print

If this texture can be mitigated or removed completely, the realism of the skin would be greatly improved. It is possible to improve the surface finish of ABS 3D printed parts using acetone in both liquid and vapor form (see Figure 87). This is commonly done in enclosed chambers where vaporized acetone is released. These are called acetone vapor baths (see Figure 88).

Figure 87: Acetone Print before and after smoothing, reproduced as is from [33]

Figure 88: Consumer Grade Acetone Vapor Bath, reproduced as is from [34]

Additionally, it may be possible to find a flexible filament or a chemical that reacts similarly to ABS with acetone, allowing for the surface finish of the skin to be improved.

Another possible technique for improving the surface finish is heating the 3D printed part in a controlled chamber. This allows for the separately extruded layers to melt together and create a more uniform shape. This technique would require a heated chamber and precise control of the temperature and time the lattice/skin is exposed to the heat. Another possible method for heating could be a heat gun, however this would be less controllable, but may be a valid way for testing the idea. When investigating this it will be important to ensure that after being exposed to heat, the part retains its original dimensions and is still compatible with the existing 3D printed mechanisms. It is also important that the skin still retains its flexible nature separate from the more rigid lattice structure.

Coating the final print with a thin layer of flexible sealant or resin may also be a potential way to improve the surface finish of the part. The layer coating could provide a more realistic human-like texture to the skin. There are existing well-known coatings for 3D printed objects for PLA as well as ABS, which improve the surface without modifying the part more than necessary (see Figure 89).

Figure 89: Commercially Available 3D Coating from Smooth-ON, reproduced as is from [35]

These coatings may be modifiable or similar coatings may be found for creating flexible coatings over TPU. There are existing flexible resins as well as compounds like liquid electrical tape which is designed to be flexible coating over copper wire. One of these compounds may work well as a final coating over the existing 3D printed TPU lattice with skin.

Building on the methodology we developed and the outcomes we achieved, these options for future work, will create opportunities to both lower cost and time to produce, but also improve the functionality and realism of, animatronic devices for biomedical and other industries.

10.9 Pulse

In EMS feedback on the pulse subsystem, in addition to current capabilities, adding a mechanism to simulate faint and thready pulses was desired. Faint pulses had the use cases such as eldry patients. Thready pulses fell under the category of non-replicable circumstances. The solenoids actuation is binary and therefore will need an additional system to replicate these pulses. A key of the limitation facing this subsystem is the size constraint due to the trachea and oral cavity. There were 3 ideas for the mechanical systems: a spring and servo, linear actuators, and a linkage system. The goal of the system is to reposition the solenoids to create a different user feel.

10.10 Manufacturability

There is a lot of room for improvement when it comes to increasing the manufacturability of our design. Even with the adjustments made to the lattice, there is still a lot of hardware needed to assemble the head. This increases tools, hardware, and time needed to assemble the animatronic head. There is also a lot of improvement that can be done to the CAD database. By adding sections in the Github for previous revisions and files that are a work in progress the design phase for improvement can be sped up and different files could even be made for different applications. Doing something like this could enable our design to be sent around to many different medical fields requiring training and allow for the printing of specialized parts for specific training simulations.

10.11 Electronics and Code Structure

10.11.1 Microprocessor

The single threaded Teensy will not be a suitable platform to control all of H.A.L. 's subsystem in a realistic manner. Transition to a microprocessor such as Raspberry Pi will be a platform able to control all the subsystems. While the Teensy and microcontroller are great at executing single action items such as sensor readings and commanding actuators. The ability of the Pi to do multithreading and multiprocessing at the 16 Ghz will allow more realistic movements and more complex subsystems.

Integrating ROS could be a terrific platform for handling all of these subsystems. A ROS node is an executable script inside your application. A group of nodes combines into a graph, these nodes can run asynchronously, creating much greater control over these subsystems. These nodes can publish to a topic and other nodes can subscribe to that topic. For example, a node could read in data from the touchscreen and publish that to a topic and the pulse node that subscribes that topic can see that it was set to a fast pulse and can execute that script. The advantage of ROS would be to incorporate the pi with tinyduinos. These tinyduinos could be in control of a subsystem.

Much more information about the abilities of ROS can be found on their wiki and individuals such as James Bruton have created tutorials.

10.11.2 Power

While the multiple batteries worked for demos, prototyping, and the development stage in general. Power H.A.L. in the future should be either through wall power or through one li-po. If wall power is to be used, consideration for the individuals making it needs to be taken into account. This means the creator of their own H.A.L should not use a wall power to wire leads. An off the shelve AC to DC convertor should be used.

10.11.3 Servos

With the potential for a plethora of new subsystems, a way to free up the neck servo pins would be to investigate a type of servo called universal serial servo.

Chapter 11: Conclusion

11.1 Personal Reflection

To accomplish the goals we laid out, during this project, we needed prior knowledge, much of which was obtained from classes taught through the WPI Mechanical Engineering Department. Key classes include:

- *Introduction to CAD* (ES 1310)
- *Introduction to Engineering Design* (ME 2300)
- *Modeling and Analysis of Mechatronic Systems* (ME 4322)
- *Project-based Engineering Experimentation* (ME 3902)
- *Design For Manufacturability (ME 5441)*

ES 1310 provided the team with the basic knowledge of solidworks. This allowed us to make parts and assemblies of the Head. This was vital, as being able to prototype parts in CAD saved a huge amount of time.

ME 2300 provided the team with knowledge on how to set up a team based project. Brainstorm and develop new ideas, as well as time manage tasks with time, using techniques like gantt charts. This was vital knowledge as managing a 5 person team remotely during a pandemic would have been near impossible without these skills.

ME 4322 was the study of and analysis of linkage based systems. This included analysis of "real-life" systems using lumped parameter modeling and bond graph modeling. This course served as an introduction to linkage analysis, and allowed the team to ensure that the linkages in the eye and jaw would work when fully assembled. Without this course much of the design for the eye and jaw would have been educated guessing.

ME 5441 was also instrumental in coming up with one of our main goals of manufacturability. This class focused extensively on how certain design decisions can increase manufacturability of a part. In particular it focused on the time needed to use hardware for attachment and how much time can be saved by reducing the amount of hardware needed to put a part together. This helped us make decisions to incorporate snapfits and create a CAD database as it was evident just how important manufacturability and replicability were.

In addition to regular classes each team member participated in WPI's Interdisciplinary Qualifying Project (IQP). These experiences involved collecting data, conducting studies, working in long term groups and composing research papers and presentations. These experiences directly lent themselves to this project, where data collection and developing a strong paper and presentation were critical aspects of the project.

Throughout the project, the skills, knowledge, and intuition acquired through WPI courses and projects were invaluable to our continued design and development of the medical testing prototype. The combination of each team member's personal strengths and skills acquired at WPI helped in creating a prototype of an Animatonic Head.

Chapter 12: Broader Impacts Chapter

12.1 Engineering Ethics

Our project was largely centered around the improvement of human welfare [36], one of the main principles of the engineering canon of ethics. A goal of our project is to make high quality medical training simulations more accessible to medical professionals. Accomplishing this will result in many experienced EMTs entering the workforce and helping people. This will also make it much easier to have and develop EMS programs within colleges.

12.2 Societal and global Impact

The long term goal of this project is to provide an open source, easy to manufacture medical training device. When the project is completed many more schools, universities and medical training facilities that otherwise would not be able to afford one, will be able to make and utilize a high fidelity medical training device. We hope that when this becomes a reality the bar for becoming an EMT will become just a little easier to reach.

12.3 Environmental Impact

With our head being made mainly out of 3d printable materials such as PLA, TPU, ABS, and TPE the creation of the parts needed would not require heavy machinery. Also from our experiences with the material engineering course Plastics many 3d printable materials are actually made out of renewable and non-polluting materials. For example one of the most common types, PLA, is made a lot of times using corn. Because of this PLA can have a biodegradable property. Also with the parts being able to be 3d printed, a complicated manufacturing process utilizing a lot of energy would not be needed to be used.

12.4 Codes and Standards

Our animatronic falls under a code put forth by the FDA for medical devices That code would be the Investigational device exemption code [37]. Some mechanical engineering standards that are utilized would be following the designing standard for creating parts in which an idea is proposed, that idea is designed, it is prototyped, then changes are made and the final product is produced. Dimension and tolerancing standards are also utilized in the creation of our slide-fits. [38]

12.5 Economic factors

The relative cost to a consumer is mainly materials and components. 3D printing material is somewhat inexpensive but access to a 3D printer is another potential cost. The servo motors and hardware are also costs the consumer will have to face. But, when comparing it with high fidelity training dummies, our animatronic is much cheaper. Additional functionality is also an added benefit of our device when compared with competitors. Our project was also developed open source, alleviating the cost of development that many professional grade animatronics face/ Files are readily accessible and easy to replace if needed.

References

[1]“Patient Simulators and Manikins: CAE Healthcare,” *CAE Healthcare - Medical Simulation Training Solutions*. [Online]. Available: https://www.caehealthcare.com/patient-simulation/. [Accessed: 07-May-2021].

[2]“Advanced Suture Kit for Medical Students: Suture Training Kit,” *suturekit*. [Online]. Available: https://suturekit.com/. [Accessed: 07-May-2021].

[3]“Manikin: Manikins vs. Mannequins: Healthcare Simulation,” *HealthySimulation.com*, 08-Jun-2020. [Online]. Available: https://www.healthysimulation.com/manikin/. [Accessed: 07-May-2021].

[4]N. Costiuc, “How Much Does a Human Patient Simulator Cost?,” *HealthySimulation.com*, 18-Mar-2021. [Online]. Available: https://www.healthysimulation.com/30911/human-patient-simulator-cost. [Accessed: 07-May-2021].

[5]Dick, Matthew, et al. *Development of a Modular Animatronic Head*. Worcester Polytechnic Institute, 2019, *Development of a Modular Animatronic Head*

[6]Cohen, Gillian, et al. Humanoid Animatronic Learning Simulator for Medical Interactive Training (H.A.L. S.M.I.T.). Worcester Polytechnic Institute, 2020

[7]“Assembly Instructions (USE AND CARE SHEET),” *CPR Savers & First Aid Supply*. [Online] Available: https://www.cpr-savers.com/assets/images/PDF/CPR-Prompt-Instructions.pdf [Accessed: 07-May-2021]

[8]“CPR Steps: Perform CPR,” *CPR Steps*. [Online]. Available: https://www.redcross.org/take-a-class/cpr/performing-cpr/cpr-steps. [Accessed: 07-May-2021].

[9]Scott, Ian, et al. , private communication, Mar. 2021.

[10]“Snap-Fit Book Final 11-05.” [Online]. Available: http://fab.cba.mit.edu/classes/S62.12/people/vernelle.noel/Plastic_Snap_fit_design.pdf. [Accessed: 07-May-2021].

[11]S. K. Gupta and D. S. Nau, “Systematic approach to analysing the manufacturability of machined parts,” Computer-Aided Design, 27-Jan-2000. [Online]. Available: https://www.sciencedirect.com/science/article/pii/001044859596797P. [Accessed: 07-May-2021].

[12]“Elastic/Plastic Deformation,” *Nondestructive Evaluation Physics : Materials*. [Online]. Available: https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Structure/deformation.htm. [Accessed: 07-May-2021].

[13]“What are the Advantages and Disadvantages of 3D Printing?,” *TWI*. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-3d-printing/pros-and-cons. [Accessed: 07-May-2021].

[14] T. G. Vo, “Stewart Platform,” Free CAD Designs, Files & 3D Models | The GrabCAD Community Library. [Online]. Available: https://grabcad.com/library/stewart-platform-6. [Accessed: 07-May-2021].

[15]“Low-Cost Linear Actuator Based on the Sarrus Linkage,” *Instructables*, 03-Oct-2017. [Online]. Available: https://www.instructables.com/Low-Cost-Linear-Actuator-Based-on-the-Sarrus-Linka/. [Accessed: 07-May-2021].

[16]C. Layosa, “Design Essentials: How to Convert from Rotary to Linear Motion,” *StackPath*, 07-Mar-2018. [Online]. Available: https://www.machinedesign.com/automation-iiot/article/21836482/design-essentials-how-to-convert-from-rotary-to-linear-motion. [Accessed: 07-May-2021].

[17]ThomasKNR, “ThomasKNR/RotaryStewartPlatform,” *GitHub*, 03-Jun-2014. [Online]. Available: https://github.com/ThomasKNR/RotaryStewartPlatform/blob/master/src_arduino_code/platform.ino. [Accessed: 07-May-2021].

[18]G. Kumparak, “Disney showed us the inner workings of its Avatar robot and it's just incredible,” *TechCrunch*, 18-Jul-2017. [Online]. Available: https://techcrunch.com/2017/07/17/disney-showed-us-the-inner-workings-of-its-avatar-robot-and-its-just-incredible/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuYmluZy5jb20v&guce_referrer_sig=AQAAAHea7otWlTsFTfkMJj2s6Fd7lQxsFVWq6sldGOsDDIvPbyzD5VJ6w9I27FxzMaHfroe0E9rvNBjmsVqJqlozdVLUHMeGbLJLcX6soISu6H-y6M5oIaYrWUpe_eECGx6ftwy9YJeZx3vooSXbV9zIFc3HWbVP6mNiSkt2_JBmLiyP. [Accessed: 07-May-2021].

[19]*Thermoplastic Polyurethane*. [Online]. Available: https://polyurethane.americanchemistry.com/Introduction-to-Polyurethanes/Applications/Thermoplastic-Polyurethane/. [Accessed: 07-May-2021].

[20]“Ultimaker Cura: Powerful, easy-to-use 3D printing software,” *ultimaker.com*. [Online]. Available: https://ultimaker.com/software/ultimaker-cura. [Accessed: 07-May-2021].

[21]“Teensy® 3.5 Development Board,” *PJRC*. [Online]. Available: https://www.pjrc.com/store/teensy35.html. [Accessed: 07-May-2021].

[22]*PJRC*. [Online]. Available: https://www.pjrc.com/. [Accessed: 07-May-2021].

[23]“Basics: Project 081a How to use the Nextion Editor with Nextion HMI display,” *Electronics and RoboTechnics*. [Online]. Available: https://acoptex.com/project/6941/basics-project-081a-how-to-use-the-nextion-editor-with-nextion-hmi-display-at-acoptexcom/. [Accessed: 07-May-2021]

[24]“Home,” *Nextion*, 08-Apr-2021. [Online]. Available: https://nextion.tech/. [Accessed: 07-May-2021].

[25]“The Mathematics of the Stewart Platform,” *wokinghamu3a*. [Online]. Available: https://web.archive.org/web/20130506134518/http://www.wokinghamu3a.org.uk/Maths%20of%20the%20Stewart%20Platform%20v5.pdf. [Accessed: 07-May-2021].

[26]R. Eisele, “Inverse Kinematics of a Stewart Platform,” *Inverse Kinematics of a Stewart Platform • Computer Science and Machine Learning*, 24-Feb-2019. [Online]. Available: https://www.xarg.org/paper/inverse-kinematics-of-a-stewart-platform/. [Accessed: 07-May-2021].

[27]Chzechze, “Curve of spee: Intelligent Dental,” *Intelligent Dental | Smarter Oral Care*, 06-May-2012. [Online]. Available: http://www.intelligentdental.com/2012/05/06/curve-of-spee/. [Accessed: 07-May-2021].

[28] D. S. Hui, M. Ip, J. W. Tang, A. L. N. Wong, M. T. V. Chan, S. D. Hall, P. K. S. Chan, and J. J. Y. Sung, “Airflows Around Oxygen Masks,” *Chest*, vol. 130, no. 3, pp. 822–826, Sep. 2006.

[29] T. Kinsman, “A Simple and Inexpensive Schlieren Optical System Using a Fresnel Lens,” *PetaPixel*, 18-Jan-2020. [Online]. Available: https://petapixel.com/2020/01/18/a-simple-and-inexpensive-schlieren-optical-system-using-a-fresnel-lens/. [Accessed: 07-May-2021].

[30]A. B. Watson and J. I. Yellott, “A unified formula for light-adapted pupil size,” *Journal of Vision*, 01-Sep-2012. [Online]. Available: https://jov.arvojournals.org/article.aspx?articleid=2279420. [Accessed: 07-May-2021].

[31]D. J. McCoul, “Dielectric Elastomers for Fluidic and Biomedical Applications,” *NASA/ADS*, 01-Jan-1970. [Online]. Available: https://ui.adsabs.harvard.edu/abs/2015PhDT........94M/abstract. [Accessed: 07-May-2021].

[32]*Post-Mountable Iris Diaphragms*. [Online]. Available: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=206. [Accessed: 07-May-2021].

[33]“Acetone 3D Print Smoothing Guide: 6 Easy Steps,” *All3DP*, 20-Nov-2020. [Online]. Available: https://all3dp.com/2/acetone-3d-print-smoothing-easy-steps/. [Accessed: 07-May-2021].

[34]“Zortrax Apoller Device,” *Zortrax*. [Online]. Available: https://zortrax.com/post-processing/apoller/. [Accessed: 07-May-2021].

[35]“XTC-3D™, High Performance 3D Print Coating,” *Smooth*. [Online]. Available: https://www.smooth-on.com/product-line/xtc-3d/. [Accessed: 07-May-2021].

[36]ASME, “Society Policy: Ethics,” Code of Ethics for Engineers, Feb. 2012.

[37]Center for Devices and Radiological Health, “Medical Device Classification Product Codes,” U.S. Food and Drug Administration. [Online]. Available: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/medical-device-classification-product-codes-guidance-industry-and-food-and-drug-administration-staff. [Accessed: 07-May-2021].

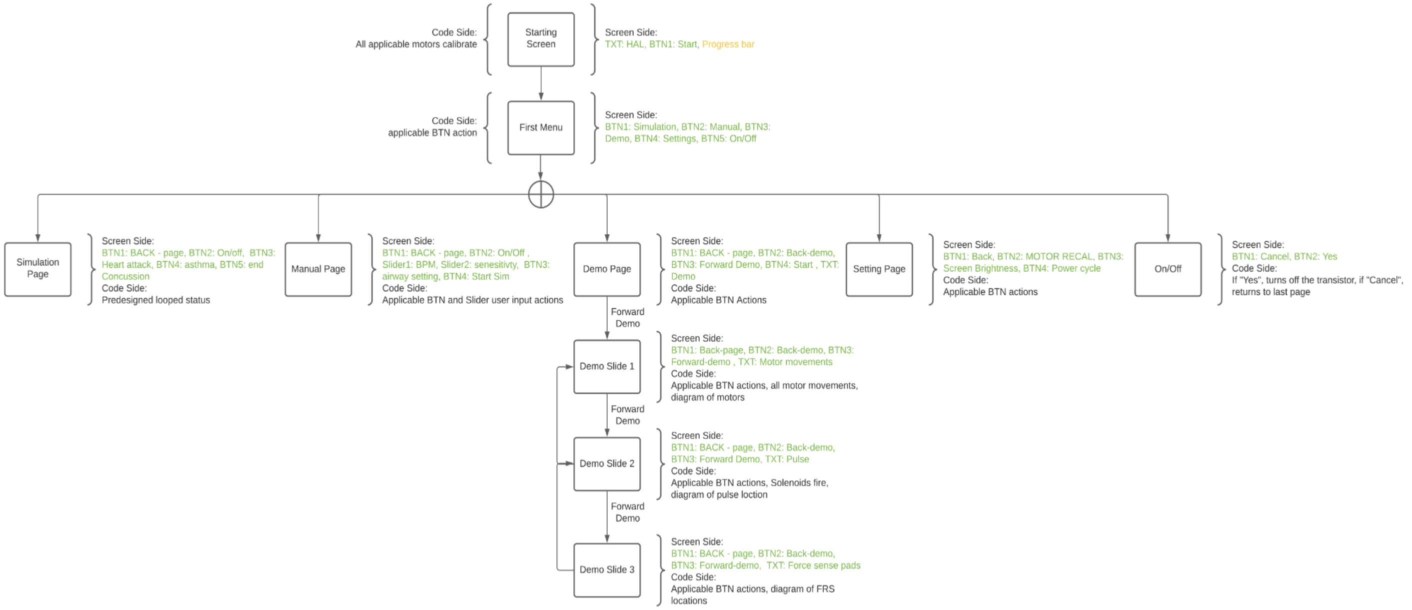
[38]ASME, “Codes & Standards,” ASME. [Online]. Available: https://www.asme.org/codes-standards. [Accessed: 07-May-2021].

Appendices

Appendix A: Full Code and Demo Code

The full code for this year’s project can be found in the “MQPOOPv1” folder in the GitHub Repository linked here:
https://github.com/rkprad/Animatronics

Appendix B: Infographic for GUI



Appendix C: IRB Methodology

Appendix C.1: Informed Consent

Informed Consent Agreement for Participation in a Research

Study Investigator:

Contact Information:

Title of Research Study:

Sponsor:

Introduction
You are being asked to participate in a research study to test the capabilities of our animatronic head designed for EMS training. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study: The purpose of this study is for real EMS personnel to get hands on experience with our Animatronic head designed for medical training and acquire feedback. We hope to gain any and all information/feedback that would allow us to improve our design. We also want to gain feedback on the usefulness of this device and which features met expectations and worked well.

Procedures to be followed: This study will be carried out in a simple manner where we will show you (EMS personnel) the capabilities of our device so that we can gain feedback on shortcomings and successes of our device. This testing and analysis will take a maximum of 15 minutes per participant.

Risks to study participants: There are no huge risks to you as a participant we would just like to notify you that the jaw is capable of pinching down and all electrical components will be carrying electricity and thus should not be touched.

Benefits to research participants and others: The benefit of this study is that you would get hands-on experience with invasive maneuvers and health conditions that can not be shown on normal healthy humans. You will also be able to give any input to improve this training device as a whole and possibly improve the training process you or future EMS go through.

Record keeping and confidentiality: Information on responses regarding criticisms and other feedback will be included in our MQP report and our final presentation but you will not be identified by name. Any and all documents including your confidential information will be recorded in our own private files and not released, if they are included in any released work your information will be removed. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or it's designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:

WPI Faculty Advisor Pradeep Radhakrishnan, Tel. 508 831-6544, Email: pradhakrishnan@wpi.edu

IRB Manager Ruth McKeogh, Tel. 508 831- 6699, Email: irb@wpi.edu

Human Protection Administrator Gabriel Johnson, Tel. 508-831-4989, Email: gjohnson@wpi.edu

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

____________________________ Date: ____________________ Study Participant Signature

____

Study Participant Name (Please print)

___________________________________ Date: ___________________ Signature of Person who explained this study

Additional clauses to add to Consent Agreements, as appropriate: Should a participant wish to withdraw from the study after it has begun, inform the researcher. There are no consequences for early withdrawal but we would greatly appreciate your participation and feedback.

Special Exceptions: Under certain circumstances**,** an IRB may approve a consent procedure which differs from some of the elements of informed consent set forth above. Before doing so, however, the IRB must make findings regarding the research justification for different procedures (i.e. a waiver of some of the informed consent requirements must be necessary for the research is to be "practicably carried out.") The IRB must also find that the research involves "no more than minimal risk to the subjects." Other requirements are found at 45 C.F.R. §46.116.

Appendix C.2: Covid Supplement to Consent

Supplemental Consent -Important Information about COVID-19 and Research Participation

At WPI our primary responsibility related to research is to protect the safety of our research participants.

COVID-19 refers to the Coronavirus that is being spread across people in our communities. We need to provide you with important information about COVID-19, and to tell you about ways your study participation might change because of COVID-19 related risk.

If you are considering joining a study at this time or are currently enrolled in a study, it is important that you consider the following information to determine if study participation is right for you at this time.

How is COVID-19 spread? COVID-19 is a respiratory virus spread by respiratory droplets, mainly from person-to-person. This can happen between people who are in close contact with one another (less than 6 feet). It is also possible that a person can get COVID-19 by touching a surface or object (such as a doorknob or counter surface) that has the virus on it, then touching their mouth, nose or eyes.

Can COVID-19 be prevented? Current ways to minimize the risk of exposure to COVID-19 include "social distancing" which is a practice to decrease the potential for direct exposure to others who may have been exposed to COVID-19, for example by avoiding large gatherings or refraining from shaking hands with others. It is important to understand that since study participation may include increased travel outside of your home and increased exposure to others within a research site it may increase your exposure to COVID-19. At this time there is no vaccination to prevent COVID-19 infection.

What are the risks of COVID-19? For most people, the new coronavirus causes only mild or moderate symptoms, such as fever and cough. For some, especially older adults and people with existing health problems, it can cause more severe illness, including pneumonia. While we are still learning about this virus, the information we have right now suggests that about 3 of 100 people who are infected might die from the virus.

Who is most at risk? Individuals over 60 and with chronic conditions such as cancer, diabetes and lung disease have the highest rates of severe disease from the infection.

What do we do to minimize risk for research participants? There are several ways we try to minimize your risk.

- If possible, we limit the number of times you have to come to a research site.
  - You will visit the room for testing one time for a maximum of 15 minutes
- We ask every research participant if they have the symptoms of COVID-19 or have been in close contact with anyone who has or had COVID-19.
  - We will get in contact with all participants the day before to inquire about possible Covid symptoms; we will also ask participants at the beginning of the study visit and take their temperatures using a no-touch thermometer prior to entering the room.
- During your research visits, we try to reduce the time you are exposed to other people as much as possible.
  - You and one researcher will be alone in the room.
- During the study visit, the study staff must adhere to physical distancing guidelines. You will be seen in an area that allows 6 feet of separation at all times, except when contact is necessary to complete the study procedures for your visit.
  - Contact between the researcher and participant will not be required for this study.
- You will wear a face mask during the visit, and study personnel will be using appropriate PPE, including a face mask, gloves, face shield, and eye protection, as appropriate.
  - We will wear a face mask, gloves and face shield when in the research room.
- All areas where study subject visits will take place will have hospital-approved hand sanitizer available in the area.
- We are following the current clinical guidelines for cleaning rooms and equipment.
  - The room where the study is taking place will be cleaned after each visit and prior to the first visit.

The information related to risks of COVID-19 changes every day. The leaders at WPI are monitoring these risks and deciding how these risks should change our research. If you have questions about COVID-19 and your participation in research, please talk to your study team.

Appendix C.3: EMS Sample Scenario

Scenario: Approached collapsed person, seemingly unconscious. (Use Glasgow coma scale to determine state of consciousness)

- First the EMT will look for factors Interfering with communication, ability to respond and other injuries
- After assessment of inabilities they will start to go through with observations.
- This will consist of looking for Eye opening, the content of speech and movements of both sides of the body
- For observations if eyes are open/looking around already that is a extremely responsive score but if not the next step will be taken.
- This next step contains a stimulus, both verbal and physical cues are used.
- If talked at/shouted at elicits a response the person is a little less responsive, and if touching elicits a response the person is extremely low responsivity.
- The EMS will touch the middle of the forehead between the eyes to elicit a response.
- After eye observations the next step is verbal responsiveness testing with the most conscious response being asking for their name and the date and getting the answer to that two part question.
- A groan is lower consciousness and no response is the lowest.
- Next the EMS will elicit a motor response by asking for an action to be performed.
- This will be asked in a two part form, with the correct two part actions being performed means the person is conscious.
- If the person can only do some of the actions or only understand some of what is being asked they are less conscious.
- After that the highest score out of the three categories signifies the level of consciousness. (This is shown through the sheet linked below from glasgowcomascale.org)
- **https://glasgowcomascale.org/downloads/GCS-Assessment-Aid-English.pdf?v=3**

Appendix C.4: Electronics Specifications

Electronics Specifications:

Components Present:

- Peripherals:
  - Pixy2 camera - 1x
  - Servos
    - Turnigy D65MG -12x
    - TowerPro SG90 - 4x
    - DSS-M15S 270o with Feedback - 3x

  - Solenoid - 2x
- Power:
  - Three power rails; 7.2v, 6v. 5v, 3.3v
    - 7.2V and 6V are lipo batteries
    - 5v and 3.3V are from the teensy

The electronics closest to contact are the neck solenoids and jaw servos.

The solenoids are 5V 1A, powered by a 6V lipo battery.

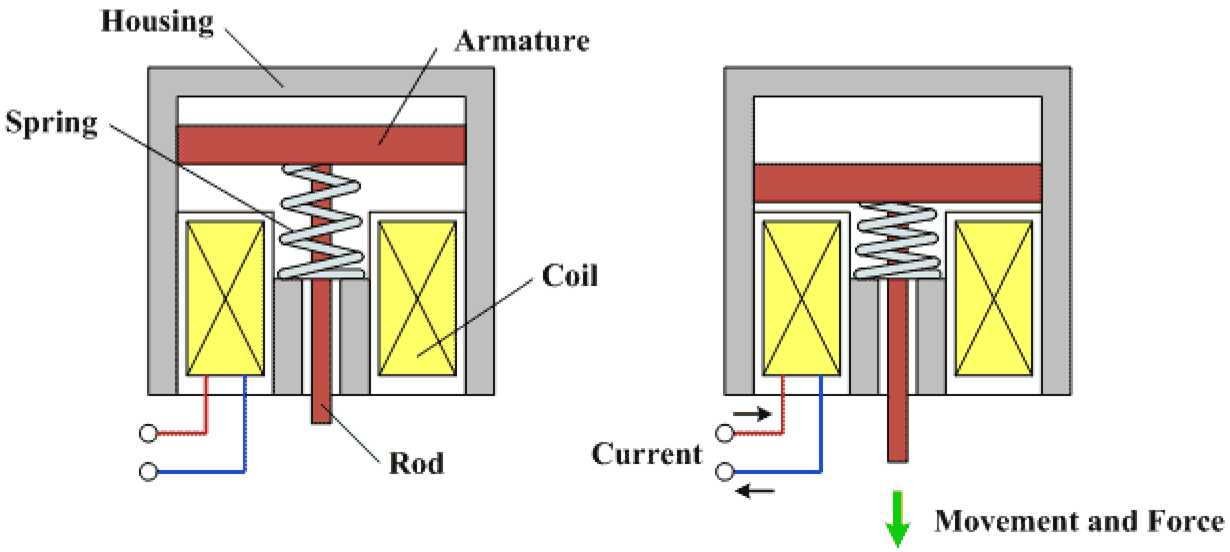


Figure 1: Diagram of a solenoid

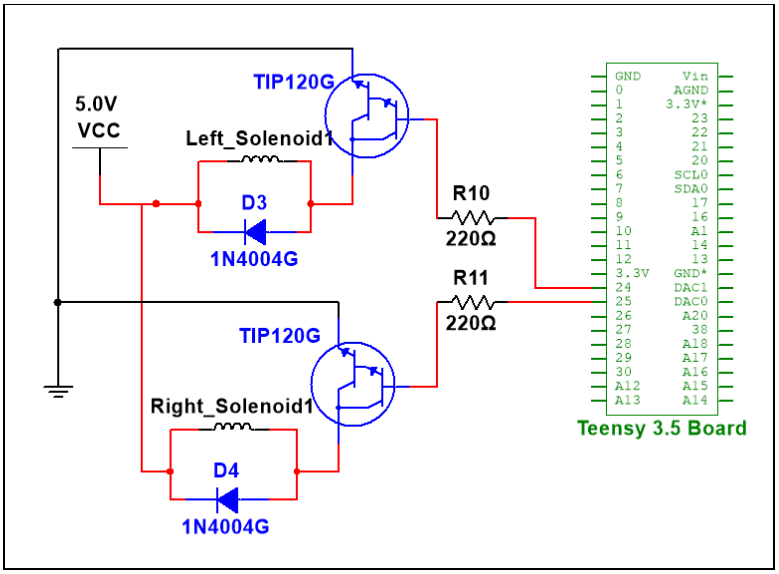
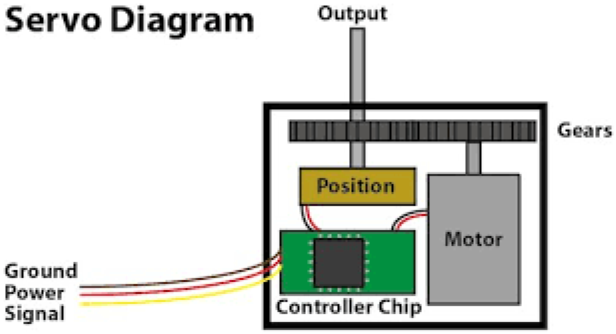


Figure 2: electrical diagram of solenoid wiring

The solenoids coils and wire are insulted and therefore the housing of the solenoids and the rod of the solenoid can be touched while firing.

As well as a silicone screen over top of the rod where the participants would place their fingers would provide another layer of insulation.
The 1N4004G diodes prevent backwa

The Jaw servo is TowerPro SG90, 5V 650 +/- 80mA.



The teensy only provides 10mA to the servos and internally the servos produce 650mA.
The housing of the servo is touchable. The wiring is not exposed to the user.