Designing Integrated Inputs for a Soft Robotic Prosthetic Tongue

Major Qualifying Project

A report submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE in
partial fulfillment of the requirements for the
Degree in Bachelors of Science
In Mechanical Engineering.

Written by:
Logan Chen (ME)

Advisors:
Prof. Pradeep Radhakrishnan (ME)
Prof. Balaji Panchapakesan (ME)

This report represents work of WPI undergraduate students submitted to the faculty as evidence of a degree requirement. WPI routinely publishes these reports on its web site without editorial or peer review. For more information about the projects program at WPI, see http://www.wpi.edu/Academics/Projects.

Copyright Information

The work presented is copyrighted by student Logan Chen and Professors Radhakrishnan and Panchapakesan.

Abstract

The human body is one of the most complex systems in the world, with millions of cells working in harmony to provide seamless transitions between different motions. Throughout history, the study of the human body has not only deepened our knowledge of human motion, but also how well various parts of the body work together, allowing for incremental steps and advancements with rehabilitation of those parts. The goal of this project is to acquire a better understanding of the motion of the human tongue during swallowing, and to develop a miniaturized system that could pose as a prosthesis for people recovering from glossectomy. This miniaturized system consists of two parts, an actuation mechanism and the tongue prosthesis. As many glossectomy patients require the additional removal of the dentures, the actuation mechanism would be embedded into that space and act as substitute for those dentures, which was designed using 3D modeling software on a case by case scenario. Many different iterations were ran through throughout the design process, from linkage systems to centrifugal air pumps, before finally deciding on a final mechanism. The mechanism is comprised of a camshaft, which would drive multiple pistons, pushing fluid into the tongue prosthesis to actuate the motion. The camshaft would allow for a smoother and more consistent tongue motion, and the fluid inside the system gives the tongue a much faster reaction to the actuation.

Acknowledgements

First, I would like to thank Professor Pradeep Radhakrishnan for advising this project and providing me with guidance and encouragement every week. I am especially thankful for all the excitement and motivation Professor Pradeep has brought to every meeting and for working so closely with me on this project. Thank you to Professor Balaji Panchapakesan for giving me the opportunity to work on such an amazing and interesting project. Special thanks to Francis Darmont Araya, as without his passion and drive this project would not be possible. He was an exceptional partner to work in parallel with, and his work on the soft robotic tongue is truly remarkable. Thank you to Thomas Kouttron for helping me machine aluminum impeller blades, saving me valuable time to work on the project. In addition, I would like to thank Worcester Polytechnic Institute for providing me the opportunity and resources to work this project. I appreciate all the time and effort the WPI Mechanical Engineering Department has given to this MQP, especially Barbara Fuhrman who guided me along the steps of purchasing parts and how to file for reimbursement, which allowed this project to go a lot smoother than otherwise possible.

Table of Contents

........1
Abstract........2
Acknowledgements........3
Glossary........6
  Abbreviations........6
  Terminology........6
Table of Figures........7
Table of Tables........8
Chapter 1: Introduction........9
  1.1 Project Goals........10
  1.2 Report Organization........11
Chapter 2: Background........12
  2.1 The Tongue........12
  2.2 Prosthetic Options........14
  2.3 Summary........18
Chapter 3: Concept Development........19
  3.1 Initial Concept Designs........19
    3.1.1 Design Iteration: Linkage Driven Silicone Flap........19
    3.1.2 Manufacturing and Testing: Linkage Driven Silicone Flap........22
    3.1.3 Pneumatically Driven Tongue - Proof-of-Concept Air Pump........23
    3.1.4 Design Iteration: Pneumatic Centrifugal Pump Actuator........26
    3.1.5 Manufacturing and Testing: Pneumatic Centrifugal Pump Actuator........28
  3.2 Fluid Actuation Design........31
    3.2.1 Manual Actuation - Syringe........31
    3.2.1 Design Iteration: Slider Crank........31
    3.2.3 Design Iteration: Camshaft........32
    3.2.4 Manufacturing and Testing: Camshaft........35
  3.3 Summary........37
Chapter 4: Results and Discussions........38
  4.1 Results........38
  4.2 Difficulties and Obstacles........38

Chapter 5: Conclusion and Future Work 39

5.1 Conclusion 39

5.2 Reflections 39

5.3 Future Work 39

Bibliography 41

Glossary

Abbreviations

RPD	Removable Partial Denture
PLA	Polylactic Acid
SLA	Stereolithography

Terminology

Bolus - a small rounded mass of a substance, especially of chewed food at the moment of swallowing
Deglutition - the action or process of swallowing
Epiglottis - a flap in the throat that keeps food from entering the windpipe and the lungs
Glossectomy - the surgical removal of the tongue, usually for oral cancer
Impeller - a rotating component of a centrifugal pump which transfers energy from the motor that drives the pump to the fluid being pumped by accelerating the fluid outwards from the center of rotation
Larynx - the hollow muscular organ forming an air passage to the lungs and holding the vocal cords in humans and other mammals; the voice box
Myocutaneous Flap Reconstruction - a mass of tissue for grafting, usually including skin, only partially removed from one part of the body so that it retains its own blood supply during transfer to another site
Mandible - the jaw or a jawbone, especially the lower jawbone in mammals and fishes
Maxilla - the jaw or jawbone, specifically the upper jaw in most vertebrates

Table of Figures

Figure 1: Muscles that Move the Tongue. Reproduced as is from [8] 12
Figure 2: Oral Cavity after Tongue is Removed. Reproduced as is from [10] 13
Figure 3: The Three Stages of Swallowing. Reproduced as is from [14] 14
Figure 4: Polish Cobalt Magnetic Cast RPD Full Denture Prosthesis. Reproduced as is from [13] 15
Figure 5: Cobalt-samarium Magnet. Reproduced as is from [13] 15
Figure 6: Full Denture Silicone Prosthesis. Reproduced as is from [9] 16
Figure 7: Silicone Prosthetic Installed Inside Oral Cavity. Reproduced as is from [9] 16
Figure 8: Pneumatic tongue body and control pressure sensors. Reproduced as is from [6] 17
Figure 9: Shape Memory Miniature Actuator attached on a Silicone Tongue. Reproduced as is from [12]. 18
Figure 10: Mold of Human Oral Cavity and Dentures 19
Figure 11: Back View of Mold 20
Figure 12: Measurements of the Dental Arches. Reproduced as is from [15] 20
Figure 13: Isometric View of Mandibular/Lower Denture Model 21
Figure 14: Tongue Flap Linkage Design Idea 21
Figure 15: Wave-Like Motion of Tongue Flap from Linkage Mechanism 22
Figure 16: PLA 3D Printed Denture 22
Figure 17: Prototype for Silicone Sheet Tongue 23
Figure 18: Large Syringe 24
Figure 19: Proof-of-Concept Test Fixture for Pneumatic Tongue 24
Figure 20: Flow Diagram of Arduino Controlled Pneumatic System 25
Figure 21: Tongue Prosthesis, Body on Left, Base on Right 25
Figure 22: Effect of Outlet Blade Angle on Head and Volume Flow in a Centrifugal Pump. Reproduced as is from [13] 26
Figure 23: Pressure Difference for Industrial Centrifugal Impeller Pump Blade Angles [2] 27
Figure 24: 6 Forward-Facing Blade Impeller with 33 Degree Angle 27
Figure 25: One of the many Failed Prints for the Impeller Blades 28
Figure 26: Testing Apparatus for the Impeller Pump (Right with Hole Drilled) 29
Figure 27: PLA Prototype for 6 Blade Centrifugal Impeller Pump 30
Figure 28: Aluminum Prototype for 8 Blade Centrifugal Impeller Pump 30
Figure 29: 1mL Syringes 31
Figure 30: Slider Crank Actuation Design 32
Figure 31: Section of a Camshaft 32
Figure 32: Transparent Top View of Camshaft Based Actuation Mechanism, X-Y Axis 33
Figure 33: Front View of Rendering of Camshaft Based Actuation Mechanism 34
Figure 34: Isometric View of Camshaft Mechanism Without Denture 34
Figure 35: Dimensions for the Inner Cavities of the Pneumatic Tongue 35
Figure 36: (Top to Bottom) Motor for Air Pump Prototype in Chapter 3.1.3, Motor for Camshaft Design, Vibration Motor Used in HexBug Nano for Scale 36
Figure 37: Close up of Motor(Black) Connected to Pinion(Pink) + Bevel Gear(Blue) Assembly Driving the Camshaft(Orange) 37

Table of Tables

Table 1: 5-Year Survival Rate of The Least Deadly Types of Cancer from 2007-2013 [5] 9

Chapter 1: Introduction

With the ever-increasing surge of technological advances across the global, from razor-thin smart devices to sleek electric-powered cars, many people have been turning towards health as the next big field for rapid development. As attention turns towards creating better lives through advances in healthcare, cancer is a problem that is often tackled, to little or no avail. Cancer is a group of diseases that involve abnormal cell growth that have the potential to invade and spread across your body [1]. Oral cancer is one of the most common types of cancer, expecting to afflict over 50,000 people in the US annually [4]. While not one of the deadliest forms of cancer, oral cancer - especially in the later stages - can severely affect quality of life.

Table 1: 5-Year Survival Rate of The Least Deadly Types of Cancer from 2007-2013 [5]

Type	Survival Rate
Prostate cancer	98.60%
Thyroid cancer	98.20%
Testicular cancer	95.10%
Skin cancer (excluding basal and squamous)	91.70%
Lip cancer	90%
Breast cancer	89.70%
Hodgkin's lymphoma	86.40%
Leukemia (Chronic lymphocytic)	83.20%
Ocular cancer	82.70%
Bladder cancer	77.30%
Renal cancer	74.10%
Non-Hodgkin's lymphoma	71%
Leukemia (Acute lymphocytic)	68.20%
Bone cancer (all types)	67.70%
Small intestine cancer	67.50%
Cervical cancer	67.10%

Leukemia (Chronic myeloid)	66.90%
Colorectal cancer	64.90%
Oral Cancer	64.50%

When malignant oral cancer cells spreads throughout the tongue, a glossectomy, the surgical removal of the tongue, is performed when no other treatment is shown to work. A glossectomy virtually eliminates the possibility of the cancer cells spreading, and ranges from a partial or hemi to a total removal. Glossectomy provides many complications, with difficulty swallowing, problems speaking, and a high possibility of inhaling food or fluids into the lungs to name a few. To help eliminate these complications and aid patients in rehabilitation, oral prosthesis, ranging from partial to full denture prosthesis, are often employed. While these prosthesis provide aesthetic and static functionality of the tongue, they do little to recreate the kinematic function of the tongue, resulting these patients having a much harder time swallowing food and speaking.

1.1 Project Goals

In order to mitigate the issues plaguing current devices, a new miniaturized mechatronic tongue is being developed. The system being developed consists of two parts namely the tongue prosthesis and the actuation mechanism. Francis Darmont Araya, a Masters student at WPI, is working on the prosthetic tongue mass, while this project focuses on the actuation mechanism. This tongue prosthesis is a silicone actuator that mimics the physical and functional characteristics of a tongue. Mr. Darmont Araya is using a design that employs three separate activation zones which would be actuated by injecting fluid or air inside, causing each of the zones to balloon up. Since the eventual goal is to produce a viable prosthetic, concept designs were generated such that the actuation mechanism for the tongue is embedded into the space available in a denture. By integrating the actuation mechanism within the space of a denture, the actuation design will not hinder the tongues movement and create a realistic looking denture. Hence, the requirements for this mechanism are:

- Miniaturizing the mechanism to allow for integration into the denture,
- Providing adequate pressure to the tongue prosthesis,
- Providing synchronization of the tongue’s movement, and
- Creating a fully functional prosthetic tongue prototype for the purpose of swallowing that will behave and look like a real tongue.

1.2 Report Organization

This report is broken down into five distinct chapters. Chapter 1: Introduction gives some context for the motivation and purpose for the development of this project. The introduction also touches upon the applications of the tongue the main goals that the project seeks to achieve. Chapter 2: Background goes more into depth into the motivation for this project, talking about the tongue itself, and current products on the market that this project seeks to replace. Moving on to the bulk of the report, Chapter 3: Concept Development, which covers the multiple design iterations that were explored. Chapter 4: Results and Discussions gives a summary of the testing results that were obtained throughout the project, and also talk about the difficulties that were faced. Chapter 5: Conclusions and Future Work sum up the entire project, talk about how courses have influenced my approach to this project and overall reflections, in addition to future work that can be done for this project.

Chapter 2: Background

Before development of the tongue prosthesis could be started, there were a few things that needed to be researched and understood. The tongue muscle and its importance was researched, and the shear amount of volume that it possesses in the oral cavity. Prosthetic options currently on the market were also researched to find problems that need to be addressed in the future to provide a more realistic tongue prosthetic option.

2.1 The Tongue

The tongue is a very complex muscle that is incredibly difficult to mimic. Not only is it extremely flexible, but it also can help assist in creating speech patterns and sounds. Shown below in Figure 1 (reproduced as is from [8]) are a few of the muscles that help facilitate the movement of the tongue.

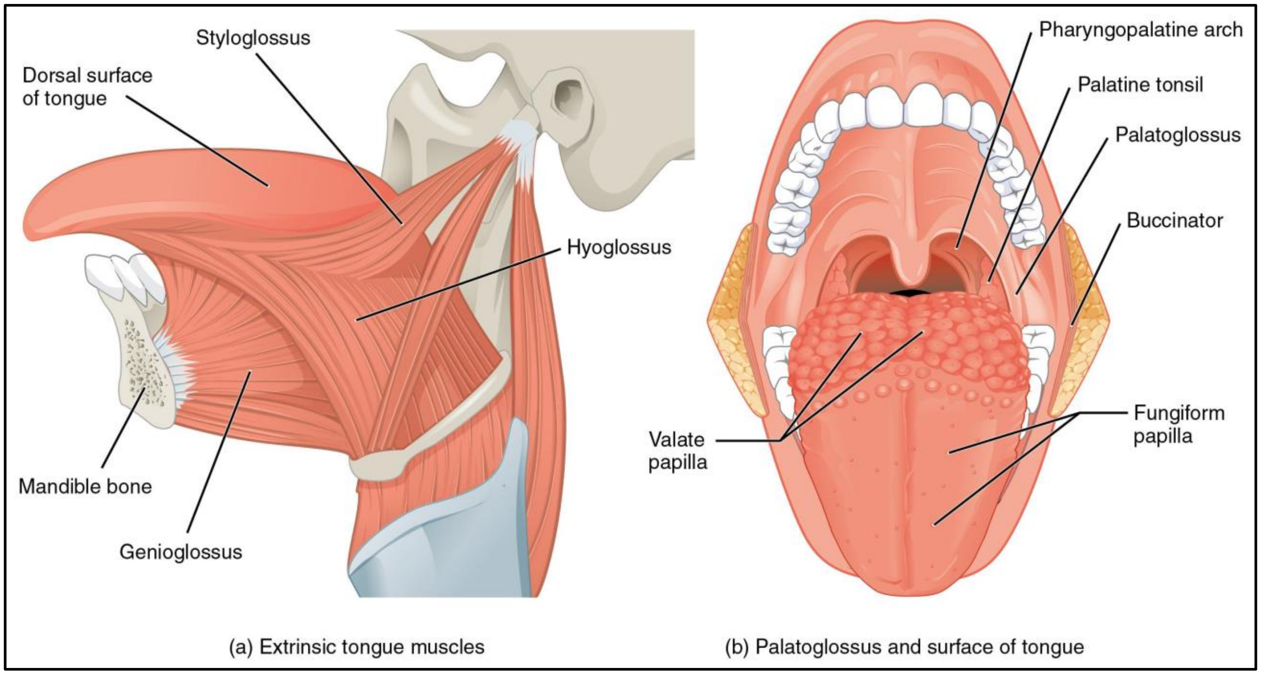

Figure 1: Muscles that Move the Tongue. Reproduced as is from [8]

Tongue muscles are normally separated into two different types, extrinsic or intrinsic. Four extrinsic tongue muscles are outside of the tongue and move the entire tongue in different directions, while the four intrinsic muscles help the tongue itself change shape [8]. These eight muscles completely determine whether or not we can create complex sounds such a speaking, and significantly increase the speed of which a person eats. As previously mentioned, when oral cancer patients are subjected to a total glossectomy, the entire tongue muscle mass is removed, leaving only an empty oral cavity as seen in Figure 2 below (reproduced as is from [10]).

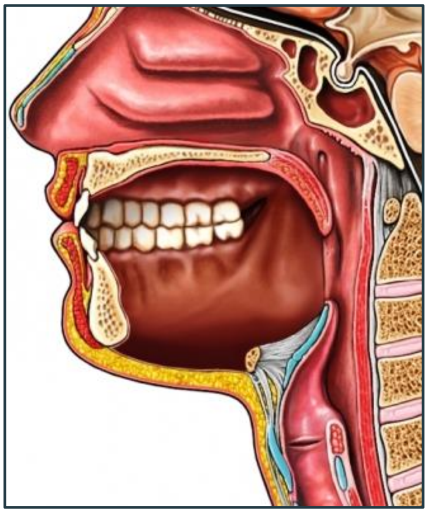

Figure 2: Oral Cavity after Tongue is Removed. Reproduced as is from [10]

Before tackling the tongue's function during deglutition, it is best to understand the overall process first. The deglutition process is typically broken down into 3 stages, the Oral/Voluntary, Pharyngeal/Involuntary, and the Esophageal/Final. In the oral stage, the food is introduced into mouth and placed onto the tongue after being fully chewed up before it is ready to swallow. The tongue then moves the bolus - a mixture of saliva and the chewed up food and fluid - back towards the throat. During the pharyngeal stage, the vocal folds close to keep food and liquids from entering the airway. The larynx rises inside the neck and the epiglottis moves to cover it, providing even more airway protection. Finally, in the esophageal stage, the bolus moves down into the esophagus, which is the muscular tube that contracts and pushes it down into the stomach [11]. Figure 3 reproduced as is from [14] below gives a visual demonstration of how the three stages work.

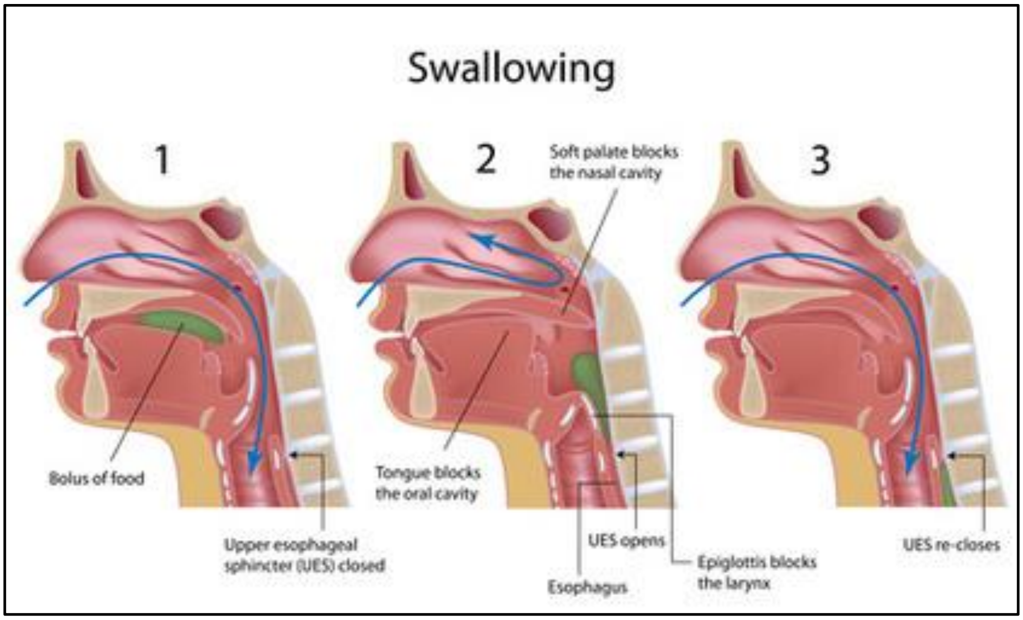

Figure 3:The Three Stages of Swallowing. Reproduced as is from [14]

2.2 Prosthetic Options

When such an important part of the body is removed, it is extremely difficult for the body to get accustomed to life without it, leading to many prosthetics being used for rehabilitation purposes. Two of the prosthetics commonly employed for use by total glossectomy patients are a full denture silicone prosthesis and a full denture magnetic cast prosthesis.

The magnetic cast prosthesis, reproduced as is from [13] in Figure 4 below, utilizes a polish cobalt removable partial denture (RPD) framework with an acrylic resin base. Cobalt-samarium magnets were incorporated in the acrylic resin and on the two tongue components. The denture is held in place by a magnetic implant, reproduced as in from [13] in Figure 5 below, that is surgically implanted into the base of the patient's mouth. The denture is placed on top and snaps into place to line up the magnets. The first tongue component is made of acrylic resin to help the patient swallow food and liquids, while the second component is made of silicone to assist with speech. Some of the disadvantages include magnet corrosion, wear and loss, and the brittleness of the acrylic, requiring the denture to be often replaced. Generally, the prosthetic provides swallowing and speech improvement [13].

Figure 4: Polish Cobalt Magnetic Cast RPD Full Denture Prosthesis. Reproduced as is from [13]

Figure 5: Cobalt-samarium Magnet. Reproduced as is from [13]

The full denture silicone prosthesis is utilized for a total reconstruction of the mouth of an edentulous patient. The designed denture reproduced as is from [9] in Figure 6 was created for a patient that underwent total glossectomy and a myocutaneous flap reconstruction. The prosthesis is composed of silicone (molloplast-B) and a denture-base resin. The silicone tongue is designed to be arched at the anterior one third and at a 15 degree angle on the tip. The prosthesis works as a denture in which it is held in place by the suction created between the denture and the floor of the mouth with the aid of saliva. Several trials and adjustments are performed with the patient and speech therapist to obtain the best fit and effectiveness possible. Noticeable comfort and oral functional improvements are noticeable after six months of use. The finished look of an installed full denture prosthetic can be seen as reproduced from [9] as is in Figure 7 below.

Figure 6: Full Denture Silicone Prosthesis. Reproduced as is from [9]

Figure 7: Silicone Prosthetic Installed Inside Oral Cavity. Reproduced as is from [9]

When analyzing the prosthetics previously mentioned, it can be noted that although they provide aesthetic and static functionality of the tongue, little improvement has been accomplished to recreate the kinematic function of the original muscular organ, and no real active tongue is available. Patients therefore must undergo months of readjustments and speech therapy to reprogram their oral movements. Furthermore, adapting to these intervention methods are only the underlying difficulties associated with the resection of the tongue; Psychological effects such as depression have also been identified to have an increased correlation with head and neck cancer patients because of visible changes in their oral physique motion attributed to swallowing difficulties or feeding tube requirements.

Moving on from prosthetics, tongue mechanisms are currently being developed to mimic the motion of tongues. These mechanisms are not intended to be integrated inside a mouth like a prosthetic, but rather demonstrate the capabilities of a tongue using soft robotics. The following two paragraphs are used to explain the background done by Francis Darmont Araya, and are reproduced with permission.

A pneumatic tongue mechanism created by Lu et al. is reproduced as is in Figure 8. This tongue is structurally composed of silicone rubber Ecoflex 00-30 and polydimethylsiloxane material that are formed to incorporate different airways and chambers. Its design is inspired after the PneuNet structure that the properties of the material for actuation. As the selected chambers are pressurized, the differences in properties of the materials utilized to create the tongue, provide the necessary strain to create the desired motion. The control system is composed of mostly solenoids and pressure sensors. Some noticeable disadvantages is the required source of pneumatic air and the additional external components to control the system. In addition, the current tongue design was not adapted to mimic specific set of human tongue type motions [6].

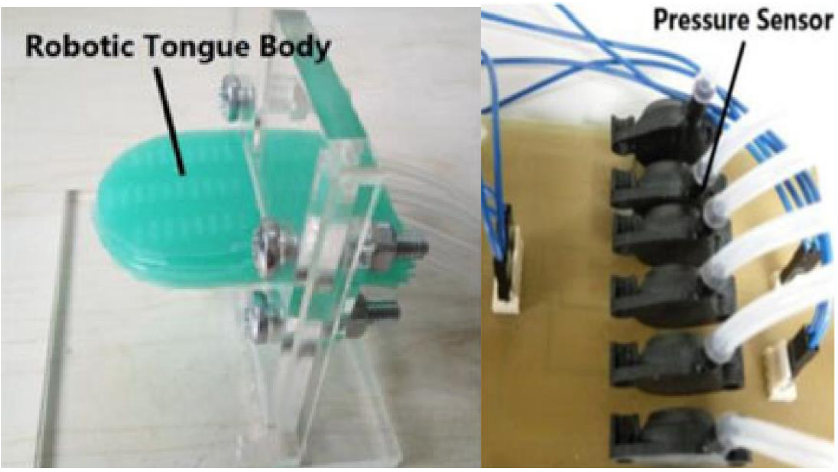

Figure 8: Pneumatic tongue body and control pressure sensors. Reproduced as is from [6]

Another example of a tongue mechanism can be seen in Figure 9 as reproduced by Yamakita et al. in the Takanishi Laboratory, Japan. This tongue mechanism utilizes shape memory alloys and a displacement amplification system to create miniature actuators that can be used to create complex tongue motions. Specifically, the force generator provides muscle fiber like contractions, the non-linear viscoelastic module reacts with a change in viscoelasticity from the force and the lock-release mechanism acts as a muscle relaxer. Some of the visible disadvantages of this system its is single function capability which would require additional actuators for the tongue [12].

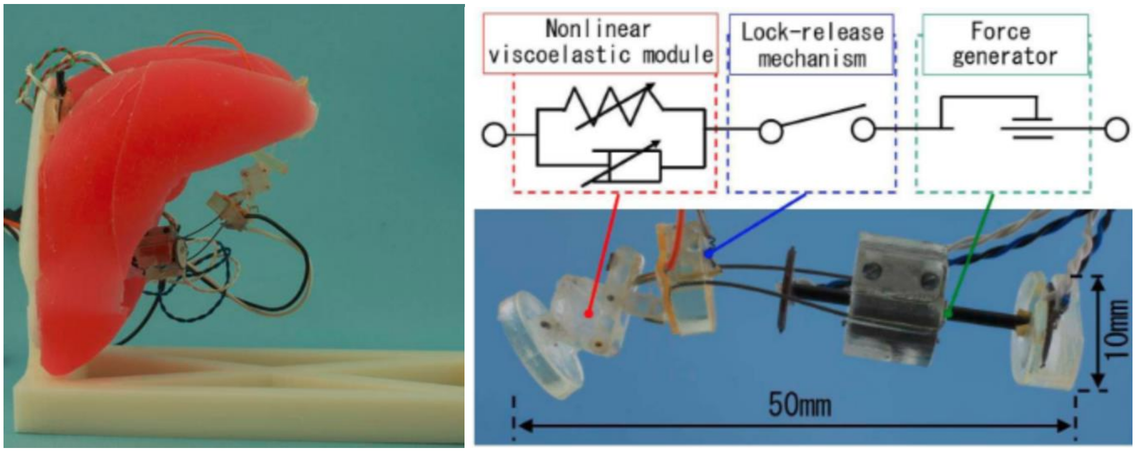

Figure 9: Shape Memory Miniature Actuator attached on a Silicone Tongue. Reproduced as is from [12].

2.3 Summary

This chapter talks about the background of the tongue, prosthetics currently available to oral cancer patients for rehabilitation, and research done on tongue mechanisms. By exploring these topics, a better understanding of the tongue as a whole can be obtained, and the project becomes easier to work.

Chapter 3: Concept Development

This chapter discusses the overall concept design phase and manufacturing of the project. This section goes into detail the designs that were being explored and the camshaft design that was decided upon moving forward along with the rationale behind each of the designs.

3.1 Initial Concept Designs

3.1.1 Design Iteration: Linkage Driven Silicone Flap

One of the first concepts designs that were explored was a linkage-based mechanism with silicone sheet laying between the teeth and the gums of the lower denture. The silicone sheet (later shown in Figure 16) would be the tongue prosthesis itself that would guide the bolus to the back of the mouth and eventually down into the esophagus. The linkage would lay beneath the silicone sheet, and when the patient would swallow, the mechanism would move the bolus down by lifting the silicone flap and lead it down the flap to the throat where it would be brought down to the esophagus. First design was to have a silicone flap as a layer above the gums and below the teeth of the lower denture and have the actuation mechanism beneath.

To test this concept, I first took a dental mold of a Mr. Darmont Araya’s dentures, as seen in Figure 10 and 11, created by Doctor Shaina Darmont and measured it for 3D modelling. By creating these dental molds, we could use calipers to measure the dentures.

Figure 10: Mold of Human Oral Cavity and Dentures

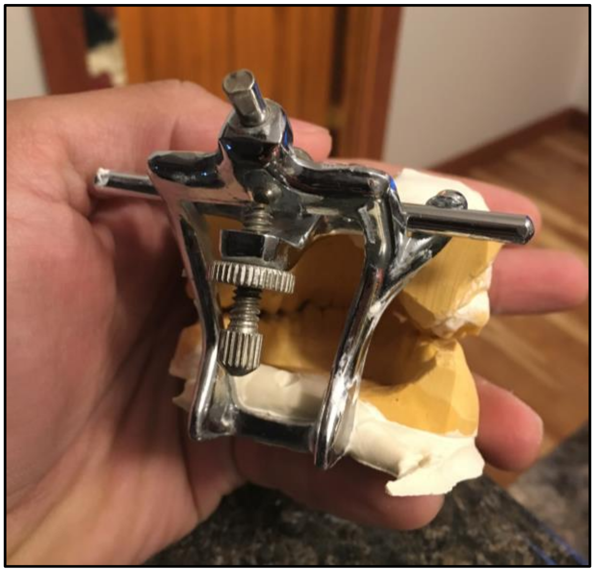

Figure 11: Back View of Mold

By using Figure 12 reproduced as is from [15] below as a template, the mandible and maxilla could be measured and modelled closely to the original. The main focus was the maintaining the same amount of space in the oral cavity, which was between the dentures, and the height of the dentures themselves.

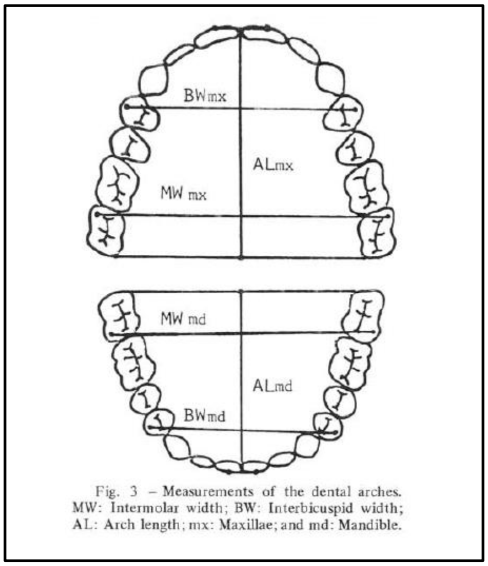

Figure 12: Measurements of the Dental Arches. Reproduced as is from [15]

The model was separated by the teeth and gums and lower denture to allow for the silicone sheet to be fixed within the two parts. The initial 3D model shown below in Figure 9 is designed in SolidWorks. The model on the left is the lower part of the mandible, consisting of the base of the mouth, in addition to the dentures up to the gums. The right model is the denture itself.

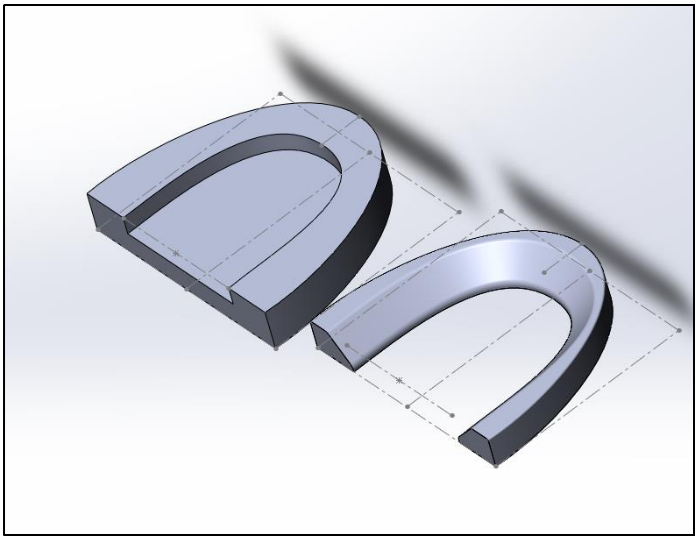

Figure 13: Isometric View of Mandibular/Lower Denture Model

The thought process behind creating the design show in Figure 14 is to have a single motor drive a long linkage that would be rigid during actuation of the motion with the help of something similar to a memory shape alloy. The linkage would slowly scrap along the bottom of the silicone tongue flap, and press the bolus to the back of the tongue, similar to a wave-like motion as seen in Figure 15. A few limitations of this design is discussed in the next section.

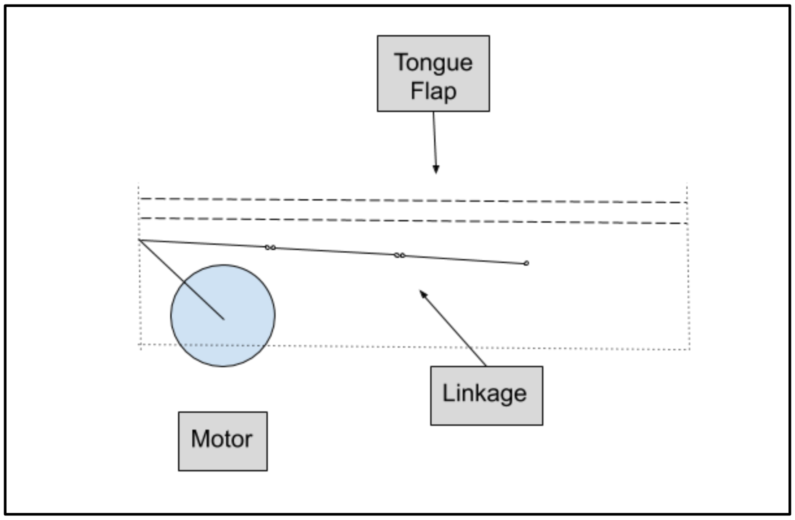

Figure 14: Tongue Flap Linkage Design Idea

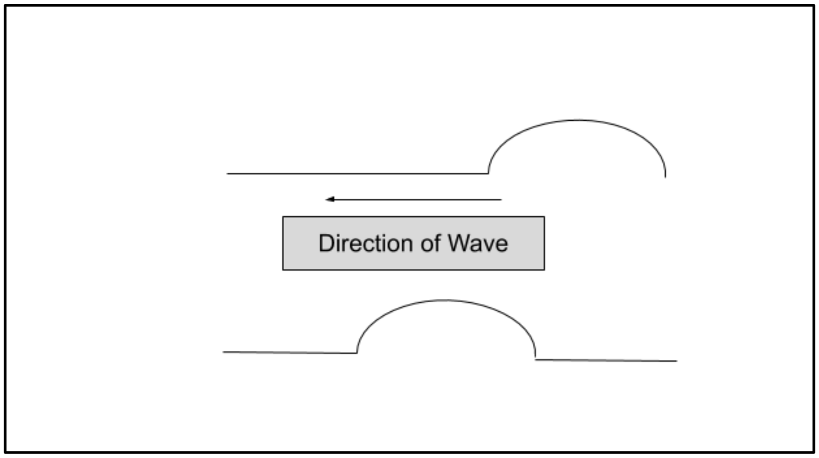

Figure 15: Wave-Like Motion of Tongue Flap from Linkage Mechanism

3.1.2 Manufacturing and Testing: Linkage Driven Silicone Flap

For manufacturing and prototyping, a majority of the parts were rapid-prototyped through a 3D printer - a combination of using the Lultzbot Taz 6, Ultimaker 3, and the Prusa i3 MK3 - using PLA plastic. One of the biggest reasons why 3D additive manufacturing was employed was availability, as the printers in the MQP Lab and Foisie MakerSpace were both readily available for printing.

For larger parts, such as the dentures, the 3D printers had an easy time. Due to the amount of abnormal angles from fillets and chamfers, some sanding was required to create a smoother surface. In Figure 16 below is (starting from the left) the maxillary denture, the bottom of the mandible, and the teeth of the mandibular denture.

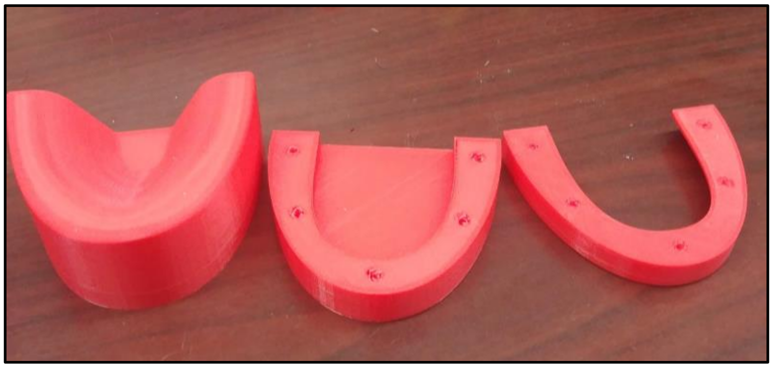

Figure 16: PLA 3D Printed Denture

As seen in Figure 17 below, one of the largest limitations of this design was that it did not resemble a tongue in physical appearance or in practical usage. In addition, the tongue flap is susceptible to damage such as tearing or stretching due to the mechanism, and the one-dimensional design would halt future development. Without access to memory shape alloys, the current design put in place would be infeasible and there are more efficient designs to approach this problem. In addition, a redesign would be required to incorporate modifications for speech in the future, which would defeat the purpose of creating this prosthetic, as other products on the market do a much better job at it.

Figure 17: Prototype for Silicone Sheet Tongue

3.1.3 Pneumatically Driven Tongue - Proof-of-Concept Air Pump

Focus soon turned towards a new idea, which was a soft robotic design. Air or fluid would be pumped into the system and actuate the movement that would be designed into the tongue itself. For initial testing of the pneumatic concept, I collaborated with Masters student Francis Darmont-Araya to create a fixture driven by air pumps controlled by an Arduino toggling solenoids for air to be released into the tongue. Originally, the tongue was actuated manually through large syringes to generate the sufficient pressure as shown in Figure 18 below.

Figure 18: Large Syringe

As shown in Figure 19 below, this prototype is more of a proof-of-concept, and this project's goal is to miniaturize the controls and actuation system and integrate it completely into the dentures themselves. The flow chart for the control system can been seen in Figure 20.

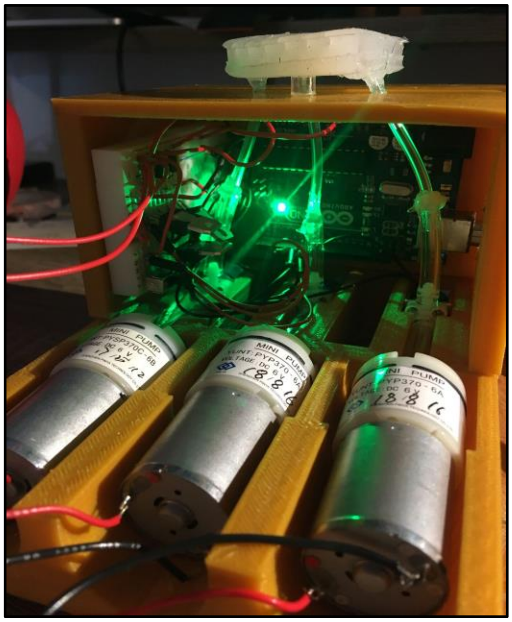

Figure 19: Proof-of-Concept Test Fixture for Pneumatic Tongue

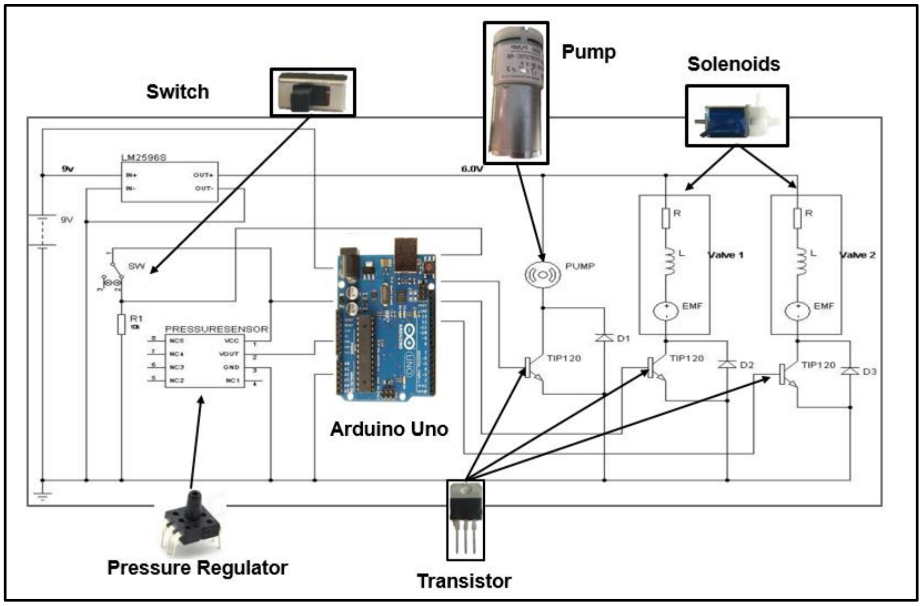

Figure 20: Flow Diagram of Arduino Controlled Pneumatic System

Figure 21 below shows the tongue prosthesis separated into two, the left showing the cavities inside the tongue that would be filled with fluid to be actuated, and the right shows the base. The materials of the two parts are slightly different, although both are made of Ecoflex 00-30 Silicone, the base is more rigid to allow the movement to be generated on the top of the tongue rather than balloon up. As this project started leaning more towards the soft robotic side, my task was updated to miniaturization of a pneumatic system. From here, I started to explore different ideas such as a centrifugal pump and eventually the camshaft design.

Figure 21: Tongue Prosthesis, Body on Left, Base on Right

3.1.4 Design Iteration: Pneumatic Centrifugal Pump Actuator

One of the first ideas for pneumatic actuation miniaturization was a centrifugal pump. A miniaturized centrifugal impeller pump would be extremely compact, and only would require enough clearance for an input of fluid or air. The two variables that were important to the impeller blade were the direction of the blades and the angle of each blade.

First, I explored the importance of the way the impeller blades faced. As seen in Figure 22 below reproduced as is from [13], there are three different types of impeller blade types: forward-facing vanes, radial vanes, and backward-facing vanes. Forward-facing vanes are blades that have their ends facing the way that the impeller is rotating with an angle β of greater than 90 degrees, radial vanes are blades that are perpendicular and straight with an angle β of 90 degrees, and backward-facing vanes are the opposite of forward-facing vanes with an angle β lesser than 90 degrees. Forward-facing vanes are the best for our application as head h decreases as the volume flow Q decreases.

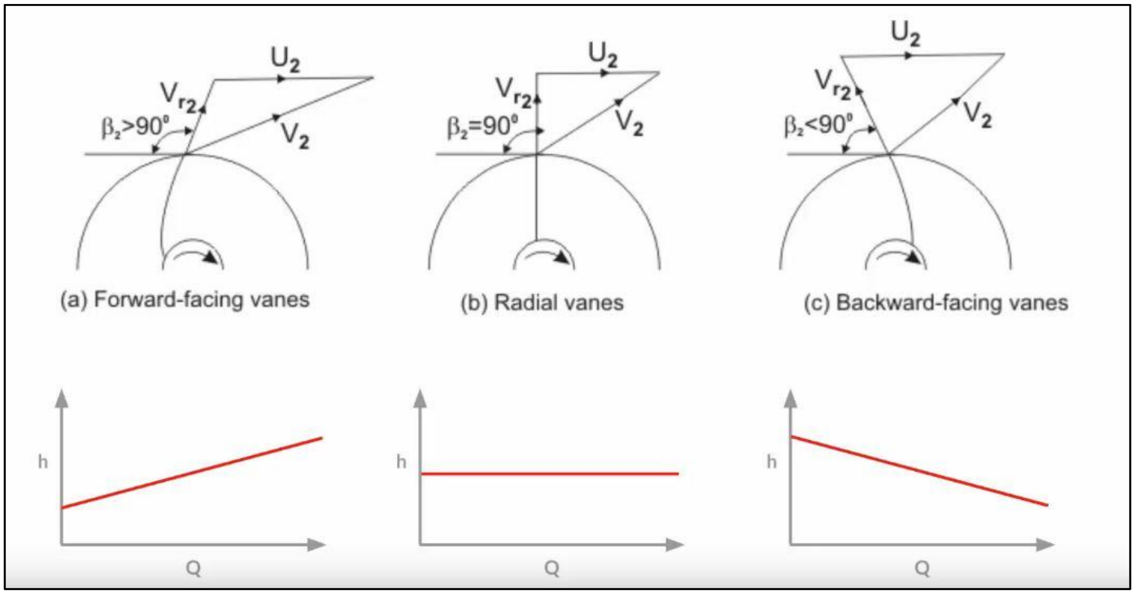

Figure 22: Effect of Outlet Blade Angle on Head and Volume Flow in a Centrifugal Pump. Reproduced as is from [13]

For industrial centrifugal pumps with large volume flow - upwards of hundreds of cubic meters per hour -, the pressure difference is extremely important, as it determines the efficiency of the pump. For such a large pump, the ideal angle β of the impeller blades is around 33 degrees towards the front - 123 degrees to be exact if we are going by Figure 22 above - as it provides a significant pressure difference, something that will be extremely important especially in a miniaturized impeller pump design.

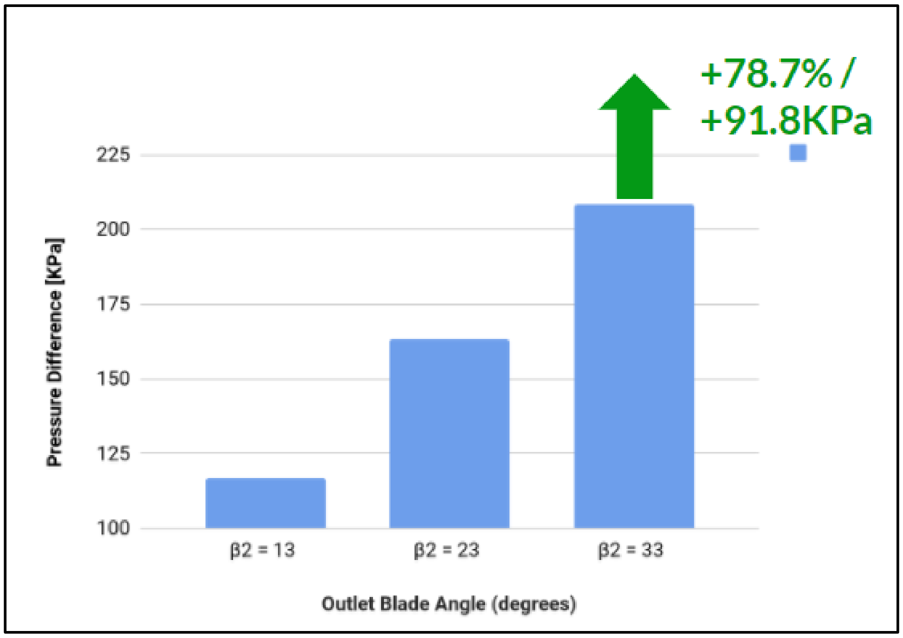

Figure 23: Pressure Difference for Industrial Centrifugal Impeller Pump Blade Angles [2]

One of the initial designs for the impeller blade featured a bottom blade, which was intended to prevent the blades from warping over long usage. Test were intended to be run on impeller blades with different numbers of blades, ranging from 3 up to 8, the maximum possible to be prototyped on such a small impeller. A 6 blade impeller design with forward facing vanes with an angle of 33 degrees is shown below in Figure 24.

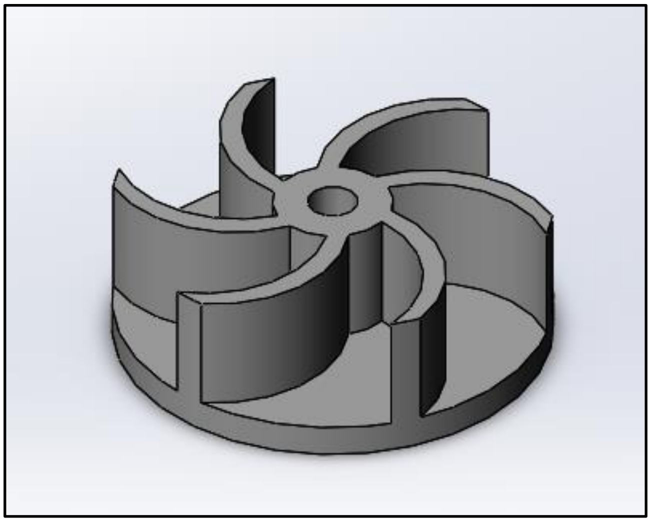

Figure 24: 6 Forward-Facing Blade Impeller with 33 Degree Angle

One problem that came with the air pump centrifugal pump system using these sorts of impeller blades was the introduction of friction and insufficient pressure and volume flow. With the design with a diameter of around 8.5mm and a height of around 3mm, the impeller blades would barely be able to produce any volume without a high RPM motor, which would be extremely uncomfortable to have in a denture. The height and diameter of the impeller blades were minimized due to the need to integrate them into the dentures themselves, and there is very limited space overall. By using the simple equation of volume - where r is the radius and h is the height -

$$r^2 * \pi * h \ = (3.5mm)^2 * \pi * 3mm \ = \ 115.395mm^3$$

we can determine the total volume inside the pump. After accounting for the impeller pump taking up around $77.92mm^3$ of space, there is only around $37.475mm^3$ of volume that can be pushed into the system. Considering the best case scenario of an efficiency of 50% for a small-scale impeller centrifugal pump, around $18.7375mm^3$ of air can be generated and pressed into the system. Realistically, the motor would have to running at over 480 RPM to generate enough volume flow to actuate the tongue, which is over 8 rotations per second. When taking friction into account, the required RPM will only increase, leaving this design for driving a pneumatic system infeasible without even taking into account pressure regardless of whether the pump is driven fluid or air.

3.1.5 Manufacturing and Testing: Pneumatic Centrifugal Pump Actuator

Unfortunately, 3D additive manufacturing is not without its flaws. The prototyping process was extremely slow due to the size of some of the parts, with the impeller blades for the centrifugal pump being the main culprit. Even at 200% of the original size intended for the project, the print still would often come out warped as seen in Figure 25 below.

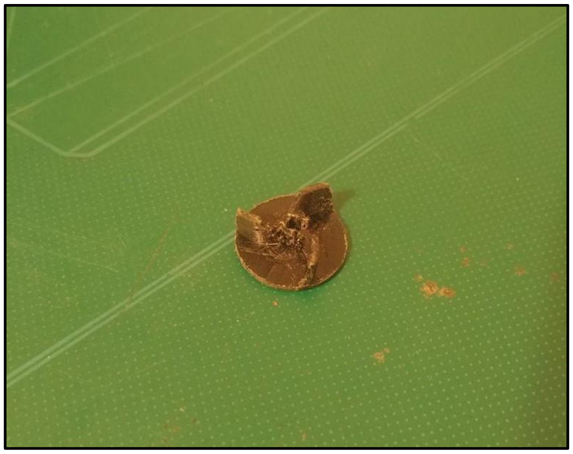

Figure 25: One of the many Failed Prints for the Impeller Blades

Luckily, not all the parts were as difficult to print. The testing apparatus for the impeller pump design were all printed with relative ease and few failed prints. However, when holes are 3D printed, they tended to shrink a little bit, requiring some manually drilling to be done. As seen in Figure 26 below, the print on the right has the hole drilling in the middle to allow for the motor end to reach the impeller blade, which would sit inside the testing apparatus.

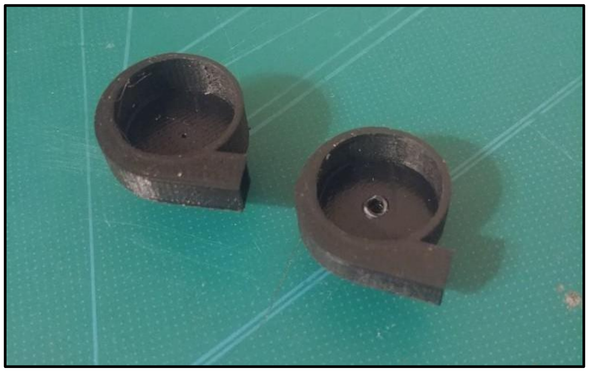

Figure 26: Testing Apparatus for the Impeller Pump (Right with Hole Drilled)

In Figure 27 below is the impeller blade inside the testing apparatus. With this we ran into an obstacle, friction. Due to 3D printers not being exact, the impeller blade and the testing apparatus often featured either too much or too little space between, resulting in no pressure and volume flow being generated or a scraping noise and very little rotational motion from the impeller blades.

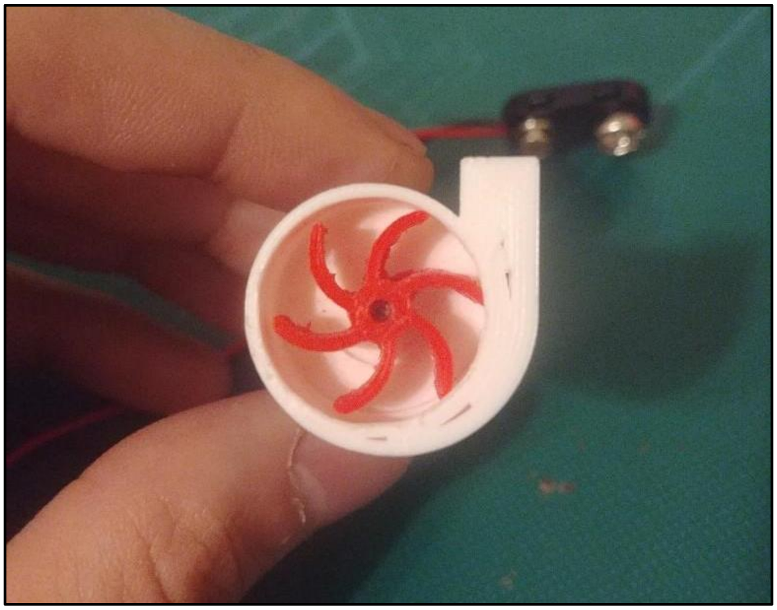

Figure 27: PLA Prototype for 6 Blade Centrifugal Impeller Pump

As manufacturing using 3D printing was posing to be an issue, I turned my attention towards machining. With the help of Thomas Kouttron at the Machine Shop in Higgins, aluminum prototype impeller blade could be manufactured, as shown in Figure 28 below. Unfortunately, one of the biggest issues with aluminum is the weight compared to PLA, and the aluminum impeller blades slipping on the motor being used. Normally, by creating some wedge or indent to connect to the motor would work, but it was incredibly challenging to do on such a small piece.

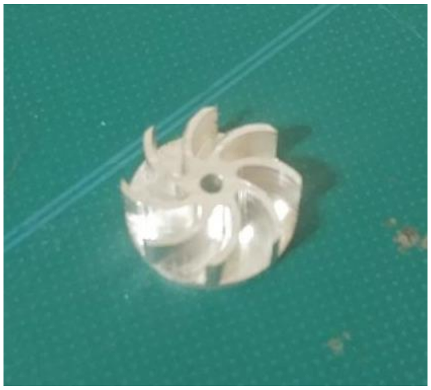

Figure 28: Aluminum Prototype for 8 Blade Centrifugal Impeller Pump

3.2 Fluid Actuation Design

3.2.1 Manual Actuation - Syringe

As mentioned earlier in 3.1.3, Francis originally actuated the tongue prosthesis with the help of syringes. A few of the benefits of using syringes are a consistent volume flow compared to centrifugal pumps, and the ability to calculate the volume flow and pressure extremely easily. Unfortunately, the syringes that Francis originally used were too large, and I turned towards procuring syringes that were much smaller and would be suited for my applications. The 1mL syringes that were procured are shown below in Figure 29.

Figure 29: 1mL Syringes

3.2.1 Design Iteration: Slider Crank

Just having syringes in the actuation mechanism is not enough, as there needs to be some sort of mechanism to drive them. One of the initial designs for actuating the syringes was a slider crank system, a design commonly used in reciprocating piston engines in cars, as shown below in Figure 30. The limitations of a slider crank design is the space required for the mechanism. When the syringe is in its neutral position, the linkage extends upwards, and would be difficult to minimize. In addition, since there are three syringes that would needed to be actuated, having three separate slider-crank mechanisms were not exactly the most efficient design. Taking inspiration from the reciprocating piston engine again, I decided to switch gears and look at camshafts.

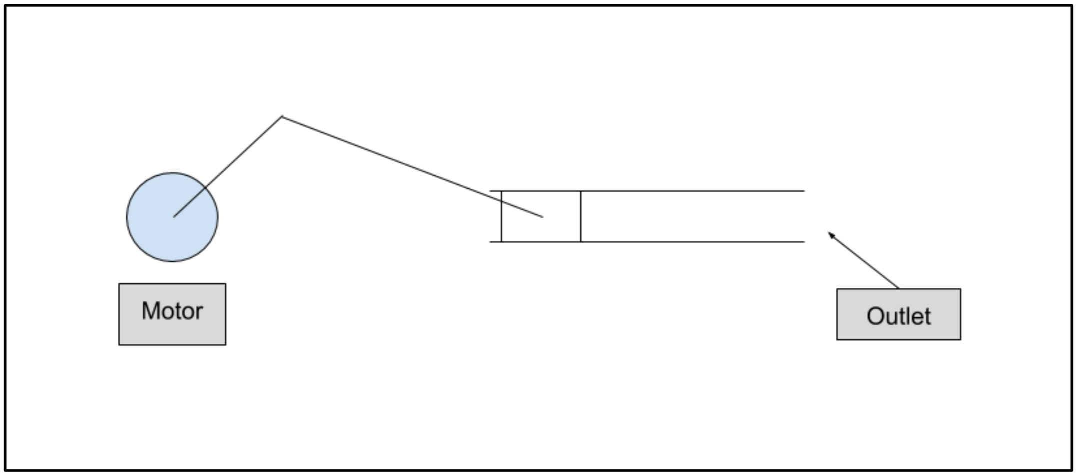

Figure 30: Slider Crank Actuation Design

3.2.3 Design Iteration: Camshaft

A camshaft is a part that is used in piston engines, especially in cars. The camshaft itself consists of two major components, the cylinder and lobes (also known as cams) that push against valves to actuate the piston motion. As the camshaft rotates, the lobes, or little protrusions, provide a smooth and set pressed distance that allows the pistons to move the same distance every time [6].

Figure 31: Section of a Camshaft

This camshaft design is the framework for the design that would satisfy all of our goals. It not only can provide synchronized for the tongue, but also be able to integrate into the denture itself, while providing sufficient pressure and volume to actuate the tongue. The camshaft actuation mechanism consists of a few parts: a camshaft, two bevel gears, two pinions, two motors, and three pistons. The motors (as seen in Figure 32 in black) are attached to the pinion (pink). As the motor spins, the pinion drives the bevel gears (in blue) attached to the camshaft (orange) which press the three pistons (in green) in a set synchronized pattern. As many glossectomy patients require the additional removal of the dentures, the actuation mechanism would be embedded into that space and act as substitute for those dentures, which was custom designed using 3D modeling software as seen below.

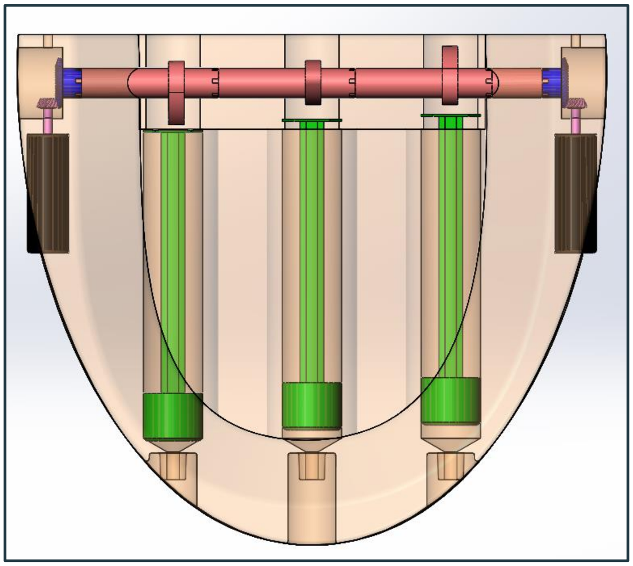

Figure 32: Transparent Top View of Camshaft Based Actuation Mechanism, X-Y Axis

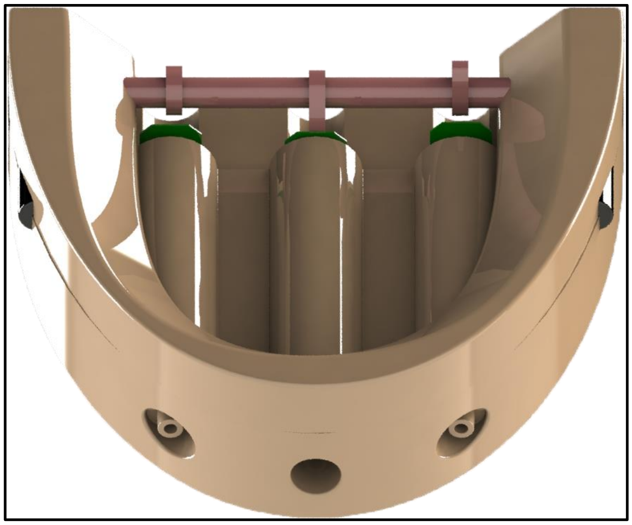

Figure 33: Front View of Rendering of Camshaft Based Actuation Mechanism

Below in Figure 34 is the entire camshaft actuation mechanism without the denture enclosure. The three pistons are in green, the two motors in black, the two pinion gears are in pink, two bevel gears in blue, and the camshaft is an orange-peach color.

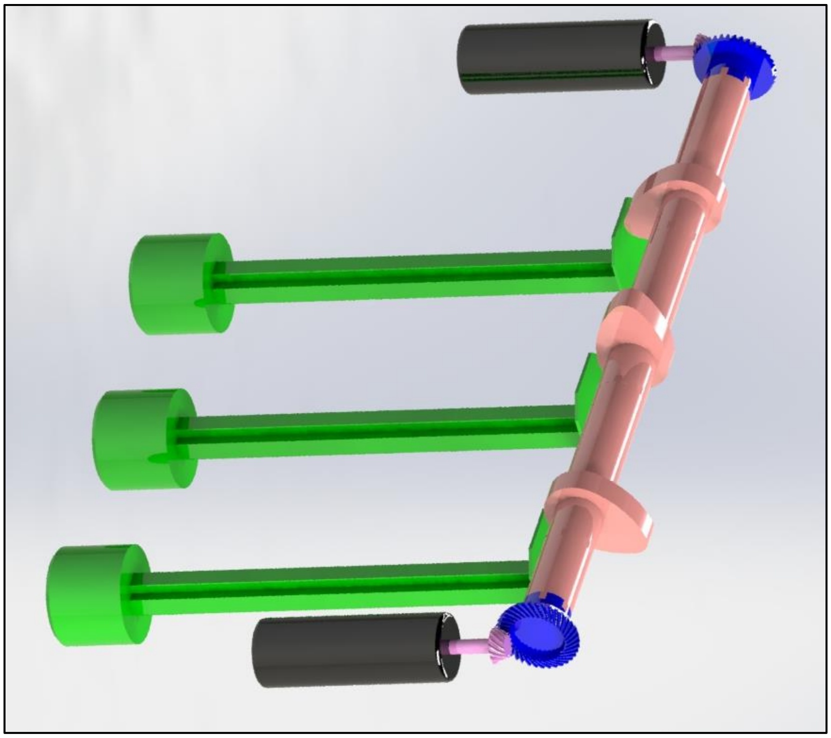

Figure 34: Isometric View of Camshaft Mechanism Without Denture

3.2.4 Manufacturing and Testing: Camshaft

The three pistons each drive fluid from inside the piston chamber through the outlet at the front of the denture that eventually will attach to the pneumatic tongue through flexible tubing. The reason why fluid is used in adverse to air is similar reasoning to why the centrifugal pump would not work, sufficient pressure would not be able to be generated in addition to a much quicker response time. The reasoning for why three pistons were used is due to the soft robotic tongue having three inlets for each of the actuation zones, one at the tip, middle, and root. The dimensioning for the tongue model designed by Francis Darmont-Araya is provided in Figure 35 below.

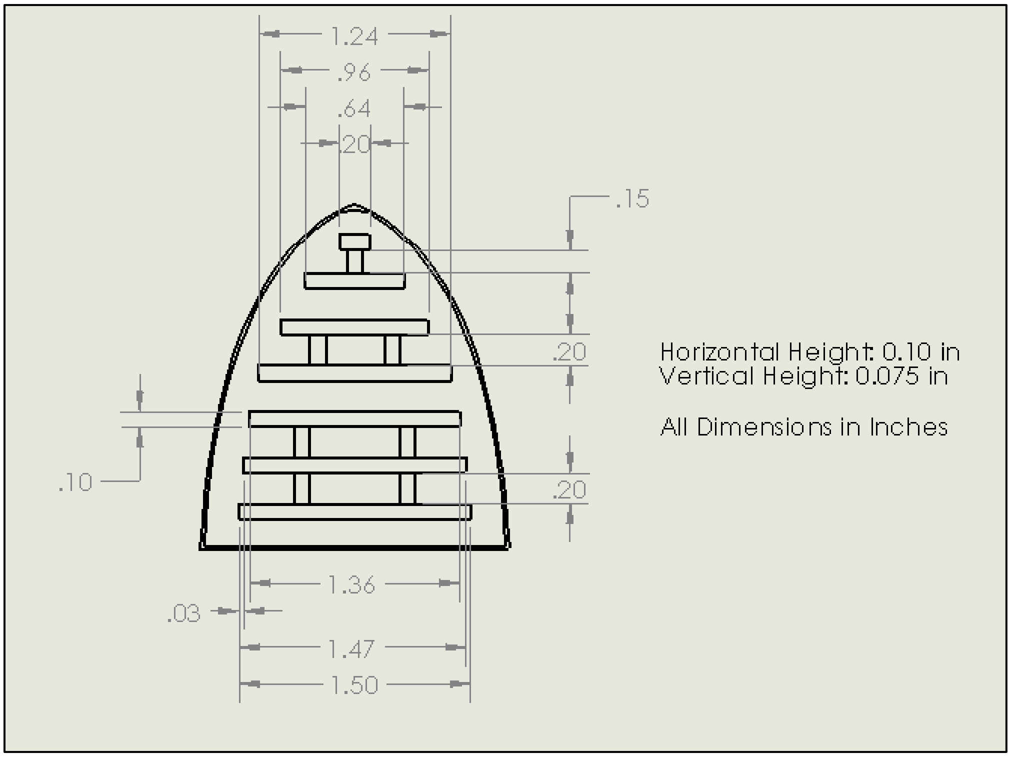

Figure 35: Dimensions for the Inner Cavities of the Pneumatic Tongue

After calculations, we determined that the volumes for each of the sections starting from the tip going down to the root of the tongue were 156.1mm^3, 409.7mm^3 , and 807.9mm^3, respectively. As the piston cylinders were 5 mm in radius, and the camshaft pushes each piston around 14mm from rest to the max extension of the cam, the total volume of fluid driven can be calculated using the equation

$$r^2 * \pi * d = (5mm)^2 * \pi * 14mm^3 = 219.8mm^3$$

Bevel gears were employed in the design to allow the motors to drive the camshaft at a 90 degree angle. The reason why this is so important is to allow the bevel gear and possibly a gearbox in the future to control the rotation of the camshaft. Since the swallowing motion of the tongue is approximately 1 second, and the micro motors, seen below as the second motor in Figure 36, that were selected have a maximum RPM of around 1000, - and a length of 20mm and diameter of 7mm - requiring a microcontroller such as an Arduino or Raspberry Pi to control the speed. Synchronization of the entire linkage must happen such that the entire bolus is moved in 1 sec. The cam rotation of 1 rotation per second might not be sufficient.

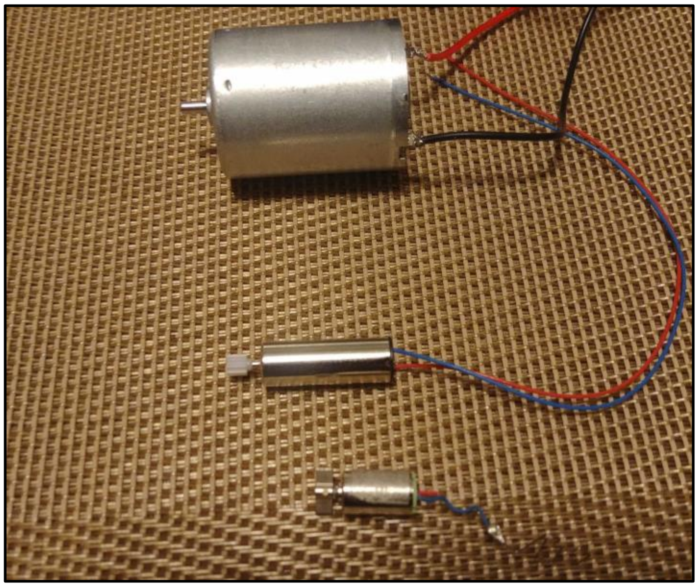

Figure 36: (Top to Bottom) Motor for Air Pump Prototype in Chapter 3.1.3, Motor for Camshaft Design, Vibration Motor Used in HexBug Nano for Scale

Ideally, the gear ratio would be relatively low to prevent a huge size disparity or the gear teeth being too small. Unfortunately, there were not any numbers given for the torque of the motor itself, so some test and calculation will have to be done in the future to determine it, or possibly find another micromotor that comes with those specifications. Figure 37 below shows a close up of the bevel gear assembly.

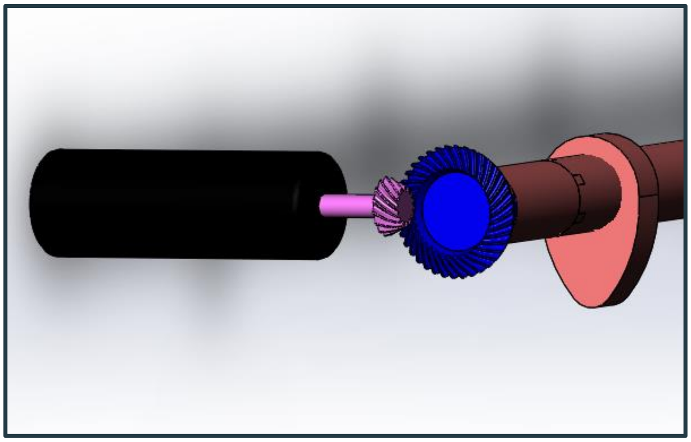

Figure 37: Close up of Motor(Black) Connected to Pinion(Pink) + Bevel Gear(Blue) Assembly Driving the Camshaft(Orange)

3.3 Summary

This chapter walked through my thought process and concept designs that were modeled and manufactured. Section 3.1.1 and 3.1.2 talked about the linkage driven silicone flap, and the limitations it had due to lack of resources and lack of future mobility as a project. Section 3.1.3 talked about Francis' work on a proof-of-concept soft robotic design, changing the project's focus to a pneumatic pump design. Sections 3.1.4 and 3.1.5 go into detail of the centrifugal pump design, and its limitations especially due to size and inability to generate pressure due to friction. Section 3.2 talked about the step by step process of going from a manually syringe driven system to a slider crank, and eventually the camshaft design to generate the movement while maintaining the same movement every time. The next chapter reviews the results from this chapter and examines the difficulties faced throughout the project.

Chapter 4: Results and Discussions

This chapters discusses the results of the concept designs that were explored, in addition to talking about the difficulties of miniaturizing the actuation mechanism and understanding the scope of the project.

4.1 Results

Unfortunately, due to the nature of the project being two separate components, there was not much testing done. For the camshaft design, each piston can press about $219.8mm^3$.The centrifugal impeller pump design is good at first glance, but when you calculate out the RPM required for volume flow needed, it is over 480 RPM or 8 rotations per second, which would create an uncomfortable vibration sensation inside the mouth. This will be sufficient to actuate the tongue and should provide enough pressure for the swallowing motion. In the future, testing will needed to determine the torque of each of the micro motors, in addition to how much pressure the camshaft can drive the fluid. Some tests will need to be run to obtain the total volume of fluid required to be driven into the three tongue actuation points to create the motion, and modifications can be made to the pistons to accommodate that data.

4.2 Difficulties and Obstacles

Throughout this project, I was met with many difficulties, with two of the biggest being understanding how the tongue itself worked and the miniaturization process of the actuation mechanism as a whole. There is very little research and tests done on providing the exact motion of the tongue during swallowing, and all the data available are extremely vague and conceptual. A large part of the project was spent trying to understand the motion and the best way to provide actuation for that movement.

The major issue that came along with miniaturization was prototyping. When it came to prototyping, especially for the impeller blades for the centrifugal pump, it took many different tries and sizing up by 200% before the 3D printers would not fail on the print. Due to the scale of the project and the limited resources available, injection molding - one of the best options for extremely small plastic objects - and SLA resin laser printing were not accessible. Many higher end parts, such as high precision micro motors were also out of the price range that was provided for the project. Regarding the impeller pumps specifically, the miniaturization proved to cause too many issues regarding friction between the parts.

Chapter 5: Conclusion and Future Work

5.1 Conclusion

This project has succeeded in creating a framework for a miniaturized actuation mechanism based on a camshaft design, and explored a few other alternative mechanism including a linkage design with a silicone sheet and a pneumatic centrifugal impeller pump design. The camshaft actuation mechanism was successfully embedded into the mandibular dentures, which was designed using SolidWorks and can be remodeled on a case by case scenario. The camshaft in the mechanism would drive multiple pistons, pushing fluid into the tongue prosthesis to actuate the motion. Results show that the camshaft would allow for a smoother and consistent tongue movement due to the nature of the design, and fluid inside the system creates a much quicker tongue movement from actuation.

5.2 Reflections

Throughout this project, I learned a lot about soft robotics and how tongues worked in general. I also learned how difficult manufacturing some parts can be even if it is possible to model out. Normally throughout projects, I work in a small group of around four members, so working by myself as an undergraduate was difficult but also extremely rewarding as I definitely learned a lot. Working with Francis was a really great learning experience, as he taught me a lot regarding how to approach the problems in this project, and gave overall amazing guidance that I am extremely thankful for. I believe that this project does not commit any glaring ethics violations, and would be extremely beneficial for society. Although it may not affect most people, I believe that this project can help people in the future understand the importance and functions of the tongue, and will definitely help those oral cancer rehabilitation patients' lives significantly.

5.3 Future Work

There are many things that can be done to improve upon this project. One of the more immediate improvements is synchronizing up the motion of the tongue with the camshaft, in addition to calculating the exact amount of fluid that would be required to drive each section of the tongue. For the camshaft design itself, the microcontroller should be integrated somewhere in the design, in addition to adding a compartment for a battery to power the microcontroller. Covering up the camshaft mechanism would also be idea to avoid any of the bolus or other external particles to affect the mechanisms function. Detailed analysis using methods in kinematics and dynamics must be carried out as well to provide some concrete numbers to back up the feasibility of the project.

A few ideas for much more down the line for the project are working on getting the tongue to not only swallowing, but assist with speech, and including some sort of input to tell the mechanism when to act. For increasing the function of the pneumatic tongue to include speech, many more inputs and actuators will be required, in addition to more research required on the movement of the tongue itself. For including an input for when the mechanism will actuate the tongue, two ideas are are connecting a sensor to the extrinsic muscles that help swallow, and including some sort of wireless module like bluetooth in the microcontroller. The wireless module would link up to a button or muscular sensor around the wrist, which would have a preset “swallow” action. There are many different muscular sensors out on the market that could fulfill these requirements, and it would be extremely interesting to see how far this project can go in the future.

Bibliography

[1] “Cancer.” *Wikipedia*, Wikimedia Foundation, 15 Apr. 2019, en.wikipedia.org/wiki/Cancer.

[2] Churazova, Anastasia. “Centrifugal Pump Design Optimization with CFD Simulation.” SimScale, SimScale, 29 Mar. 2019, www.simscale.com/blog/2017/11/centrifugal-pump-design-simulation/.

[3] *Fluid Machinery*, nptel.ac.in/courses/112104117/chapter_8/8_6.html.

[4] “Key Statistics for Oral Cavity and Oropharyngeal Cancers.” *American Cancer Society*, www.cancer.org/cancer/oral-cavity-and-oropharyngeal-cancer/about/key-statistics.html.

[5] “List of Cancer Mortality Rates in the United States.” *Wikipedia*, Wikimedia Foundation, 12 Jan. 2019, en.wikipedia.org/wiki/List_of_cancer_mortality_rates_in_the_United_States.

[6] Lu, Xuanming, Xu, Weiliang & Li, Xiaoning, A Soft Robotic Tongue—Mechatronic Design and Surface Reconstruction. Mechatronics, IEEE/ASME Transactions on, 22(5), pp.2102–2110.

[7] Nice, Karim. “How Camshafts Work.” *HowStuffWorks*, HowStuffWorks, 13 Dec. 2000, auto.howstuffworks.com/camshaft.htm.

[8] OpenStax. *Anatomy and Physiology*, OpenStax, 6 Mar. 2013, opentextbc.ca/anatomyandphysiology/chapter/11-3-axial-muscles-of-the-head-neck-and-back/.

[9] Pravin Bhirangi et al. (n.d.) Technical Considerations in Rehabilitation of an Edentulous Total Glossectomy Patient. *International Journal of Dentistry*. [Online] 2012 (2012), 125036. [online]. Available from: https://doaj.org/article/183fa34888fa46b2a06efe2bbac706da.

[10] “Surgery.” *Glossectomy - Resection - Surgery - Cancer Treatment Services - Cancer Center - Willis-Knighton Health System - Shreveport - Bossier City - Ark-La-Tex*, www.wkhs.com/cancer/cancer-treatment-services/surgery/resection/glossectomy.

[11] University of Wisconsin Hospitals and Clinics Authority. “Stages of Swallowing.” *UW Health*, www.uwhealth.org/voice-swallow/stages-of-swallowing/11463.

[12] Yamakita, T., Obokawa, Y., Eguchi, K., Ishii, H., & Taknishi, A. Retrieved September 21, 2018, from http://www.takanishi.mech.waseda.ac.jp/top/research/index.htm.

[13] Yarramaneni V, Balakrishnan D, Aparna IN, Kapoor S. Prosthetic management of Total Glossectomy Patients, Int J Prosthodont Restor Dent 2016; 6(3):66-68.

[14] "Dysphagia (Difficulty Swallowing)." *DYSPHAGIA (DIFFICULTY SWALLOWING) | New England ENT & Facial Plastic Surgery | N. Andover, Haverhill, Ayer | Salem, NH*, www.newenglandent.com/dysphagia.html.

[15] Fabiane, et al. "Dental Arch Dimensions in the Mixed Dentition: a Study of Brazilian Children from 9 to 12 Years of Age." *Journal of Applied Oral Science*, Faculdade De Odontologia De Bauru - USP, www.scielo.br/scielo.php?script=sci_arttext&pid=S1678-77572011000200014.