A Novel, Bio-Inspired, Soft Robot for Water Pipe Inspection

by

Wade Adams

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

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Graduate Supervisory Committee:

Daniel Aukes, Chair
Thomas Sugar
Wenlong Zhang

ARIZONA STATE UNIVERSITY

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ABSTRACT

This thesis presents the design and testing of a soft robotic device for water utility pipeline inspection. The preliminary findings of this new approach to conventional methods of pipe inspection demonstrate that a soft inflatable robot can successfully traverse the interior space of a range of diameter pipes using pneumatic and without the need to adjust rigid, mechanical components. The robot utilizes inflatable soft actuators with an adjustable radius which, when pressurized, can provide a radial force, effectively anchoring the device in place. Additional soft inflatable actuators translate forces along the center axis of the device which creates forward locomotion when used in conjunction with the radial actuation. Furthermore, a bio-inspired control algorithm for locomotion allows the robot to maneuver through a pipe by mimicking the peristaltic gait of an inchworm. This thesis provides an examination and evaluation of the structure and behavior of the inflatable actuators through computational modeling of the material and design, as well as the experimental data of the forces and displacements generated by the actuators. The theoretical results are contrasted with/against experimental data utilizing a physical prototype of the soft robot. The design is anticipated to enable compliant robots to conform to the space offered to them and overcome occlusions from accumulated solids found in pipes. The intent of the device is to be used for inspecting existing pipelines owned and operated by Salt River Project, a Phoenix-area water and electricity utility provider.

ACKNOWLEDGMENTS

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INTRODUCTION

1.1 Thesis Overview

The organization of this paper is as follows: Chapter I provides an overview to the project and research goals, Chapter II presents the background information of this project, while the proof of concept design and testing and the final design and testing are presented in Chapters III and IV respectively. A conclusion with discussion is included in Chapter V. All of the supporting documentation for design of the device and testing conducted during this project is included in the appendices.

1.1.1 Chapter I

An introduction to the project and the associated project and research goals. Context information that is important to know when considering soft robotic systems will be included in this section, while a more focused analysis of soft robotics is discussed in the following chapter.

1.1.2 Chapter II

1.1.2.1 Soft Robotics

A look at the characteristics of soft robotics being utilized today and the benefits of their use over conventional robotic counter parts.

1.1.2.2 Project Specifications

This section will describe the requirements and constraints that were present in this project when it was conceptualized as a research project. These requirements and constraints were prioritized with help from an engineering contact from Salt River Project.

1.1.3 Chapter III

1.1.3.1 Design

The design of the initial small-scale prototype will be presented in this section. The content in this chapter was the subject of the conference paper that was presented and included in Appendix A.

1.1.3.2 Fabrication

A look at the manufacturing methods and machines that were used and created during the development of this project.

1.1.3.3 Testing

An overview of the testing that was conducted on this device in order to validate its the proof of concept model and ability to meet the design criteria and constraints.

1.1.4 Chapter IV

1.1.4.1 Design

This section will provide information on the design changes that were made when the device was scaled up to accommodate the larger diameter pipelines that will be the environment that device must operate within.

1.1.4.2 Fabrication

Many changes to the process were made when manufacturing the larger scale device. The size of the actuators that were used in the scaled up version required different methods of fabrication, and this topic will explore these options.

1.1.4.3 Testing

The final testing of the device with real environmental conditions will be presented here to prove the efficacy of the full scale device in a realistic setting.

1.1.5 Chapter V

The conclusion will provide a discussion about the results of testing and the potential of future work for this project.

1.2 Motivation

Maintaining a solid infrastructure consisting of freshwater and sewage pipelines is necessary to maintain the health, safety, and technological advancement of any society. Aging infrastructure, especially when it comes to delivering water, is significantly detrimental to the surrounding region and environment Rogers and Hunt (2006); Rajani and Kleiner (2004). Maintenance of these pipes is critical to the safety and well-being of the people in the area since a lapse in maintenance could cause contamination of fresh water or devastating leaks, which can lead to severe damage to the surrounding area. This issue is very prevalent in the city of Flint, Michigan, where the water supply was rerouted through aging lead pipes and lead to the contamination of the water supplied to the residents of the city Riaz *et al.* (2016). This issue is still ongoing and is considered by many as a water supply crisis. The damage that can be caused can be both physically and financially ruining for cities and communities Liu and Kleiner (2013). Therefore, routine maintenance and cleaning of these pipes must be performed in order to have continued functionality and safe utility operation.

Current maintenance methods are not as efficient as they could be because they normally require the pipe supply to be shut off during inspection Hao *et al.* (2012). These inspections can involve humans crawling inside the pipes, exposing themselves to great health risks as the pipes may contain hazardous conditions. This method is time consuming as well as costly. Ultrasonic sensing methods are regularly utilized but require a probe attached to a tether that is strung over great distances. Ultrasonic probes are known to be prone to lateral movement, which leads to inaccurate data during the collection process. Another modern inspection method involves the use of pipe inspection robots which overcome the aforementioned issues but are generally expensive and require regular maintenance in order to guarantee reliability. Some pipe occlusions and obstacles can be tough and sometimes impossible for these traditional robots to overcome such as the mud seen in the bottom of the pipeline that is seen in Fig 1.1. Pipe inspection robots currently on the market are designed using approaches traditional to mechanism design such as using wheels and tires based on rigid metal frames Horodinca *et al.* (2002). A limitation of current pipe inspection robots made with rigid components is the low flexibility that they offer when utilized in dynamic operating environments Wang *et al.* (2013). The cost of more adaptable rigid inspection platforms increases significantly depending on the degrees of freedom in the powertrain. These platforms also require very invasive and frequent maintenance, due to the damage done by the debris in the pipelines, making them less ideal for utility pipe applications, where nearly continuous operation is desired. Zhang and Yan (2007); Elkmann *et al.* (2007). This maintenance is typically for freeing debris from the drive components of the robots such as removing rocks from drive chains

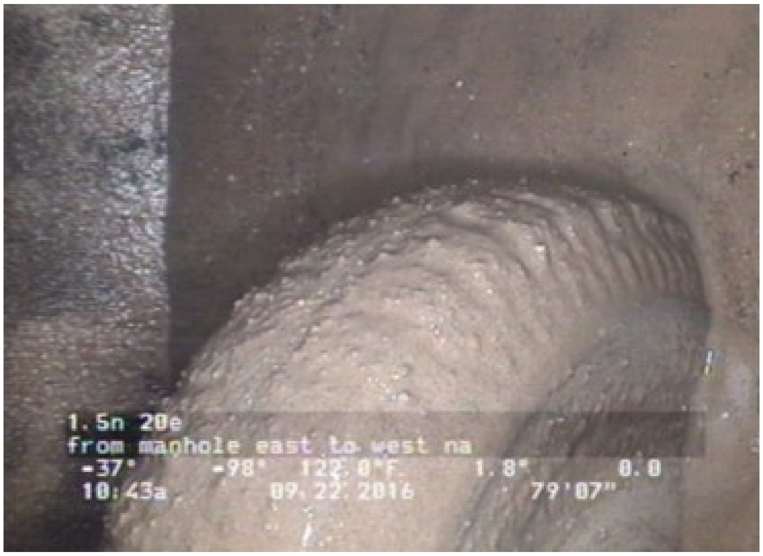


Figure 1.1: This figure depicts the wheel of an inspection platform that has been immobilized by muck buildup in the bottom of a water utility pipeline. This image was taken by SRP in an actual utility pipeline. This device was removed from the pipeline with a tether and the inspection was delayed.

and gears. Besides the limitation of flexibility, the use of rigid robotic solutions for inspection of water-based utility pipes is further hindered by the buildup of debris and muck in the pipes Jones (1978); Lee (2012). An extreme example of this problem is shown in Fig 1.1, where the wheel of a rigid robotics water pipe inspection platform is stuck in the mud buildup in the bottom of a pipeline. Based on these observations, a less expensive, more durable solution that was designed and developed during this thesis will be presented.

The proposed solution is a soft robotic device, which is inherently compliant and inexpensive. Using a design and manufacturing approach derived from soft robotics Polygerinos *et al.* (2017); Sridar *et al.* (2017) for pipe inspection will help overcome the issue of navigation through debris buildup, due to the compliant nature of the materials and flexibility of the design. On the left side of Fig 1.2, a concept rendering of the prototype is shown in a partially occluded pipeline. Previous research into soft robotic pipe navigation does not apply in utility-based applications due to the varying size of, and the extreme conditions present in the pipelines Calderón *et al.* (2016); Verma *et al.* (2017). This thesis discusses the elements of this novel soft platform as well as a proposed locomotion strategy for navigating through water utility pipes using the “inchworm” movement method. This soft robotic device is designed to be more compliant, robust and scalable to accommodate for the conditions present in water utility pipelines as well as to reduce the impact of debris and partial occlusions in the pipe, without driving up the cost exorbitantly.

1.3 Working Knowledge

1.3.1 Prior Art in Soft Robotics

Soft Robotics is a new field of robotics that is still in the research phase, with limited commercial applications. Few companies produce soft robotic components, and most of the new developments are being driven by research universities around the globe. Examples of other research in the field of soft robotics will be discussed in the following section.

1.3.2 Nature of Soft Robotics

When designing devices using soft robotic principles, the components and materials are inherently compliant. This property allows for the creation of several types of systems that are more optimal for interfacing with the human body or performing more delicate tasks, such as grasping objects. The materials used in soft robotic actuators and systems tend to be much less expensive than their conventional counterparts. Unlike working with conventional robotics, complex industrial machines are not needed to manufacture soft robots in small quantities for prototypes. In order to manufacture these actuators in a high volume fashion, industrial manufacturing

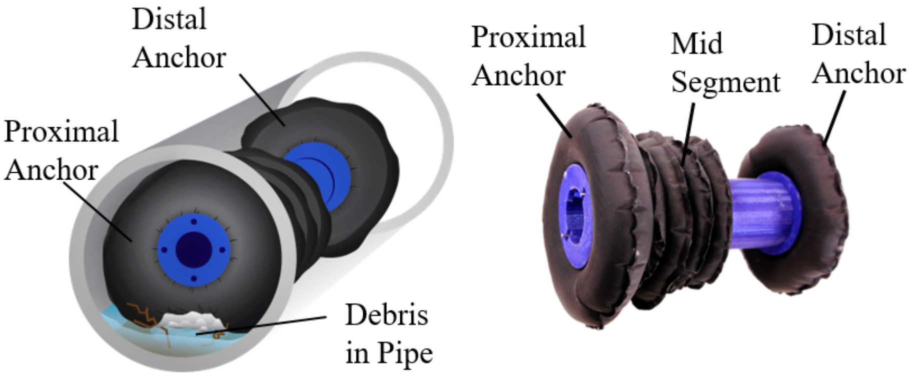


Figure 1.2: Illustration of the pipe inspection robot concept and the robot prototype showing the fully inflated state of each segment.

machines would be necessary. Nearly all of the soft pneumatic actuators used in this project were created with very basic tools such as sewing machines and heat sealers, with the rigid components being made with a small Fused Deposition Modeling 3D Printer (MakerGear M2). One of the greater drawbacks to using inexpensive materials and equipment when making soft pneumatic actuators is that it typically takes a long time to manufacture a single device and there tends to be a lot of waste in the process.

Nearly all soft robotic systems are designed with the full range of motion planned prior to the development of the device. This is commonly referred to as mechanical programming. When the device is created, it typically has a single function, to expand and contract based on internal pressure. The design of the actuator is what characterizes the motion that it will perform when inflated. Some actuators are designed to bend, while others contract or extend in a linear direction. Different methods of constraining or influencing the shape of the actuator when inflated need to be planned prior to the creation of the actuator, as it becomes difficult to adjust a soft pneumatic actuator after it has been manufactured. These actuators provide very simple motions when inflated which must be considered when designing a complete soft robotic system that may incorporate numerous actuators. When compared to a traditional DC motor-based system, which cannot change its shape, the soft robotic actuator requires more design consideration due to its dynamics, as well as because the force exerted on the world is partially determined by the load path from the world, which is not known in full when designing the actuator.

The controls that are required in order to use soft robotic devices are similar to controls used in other pneumatic systems, such as industrial material-moving systemsand and Essert (2007). Systems which work with compressed air typically deal with components such as compressors, electrically actuated pneumatic solenoids and air pressure regulators. Instead of directly controlling the flow of electricity, as in DC-motor based robotic systems, soft robotic control systems must control the pressure and volume of the air or fluid going into the device. These two systems are analogous, however, and share many of the same considerations, such as locations of sensors and lengths of carrier lines.

1.3.2.1 Soft Robotic Actuators

Traditional soft robotic actuators are actuated with a fluid that affects volume change by filling a space in a soft material and creates a deformation in that soft material which then, using elastic stress/strain theory, converts that strain into forces which can be used to perform functions. Traditional soft robotic actuators can be divided into many categories categories but the two main materials used to construct soft actuators are silicone based elastomers and thin film plastics. Fig 1.3 shows two similar soft robotic actuators made from two different materials: silicone based elastomers and thin film fabrics.

Figure 1.3: This image shows two commonly used soft robotic actuators; silicone-based on the left side and fabric-based on the right. Both of these actuators change their radial lengths when inflated.

The most common soft robotic actuator design uses elastomeric silicone rubber materials that are molded and cast into actuator shapes and designs. These devices provide a semi-rigid structure that are compliant when deflated and become more rigid when they are inflated. These devices typically include one or more types of deformable material, such as silicone rubber and other reinforcing materials, such as cotton thread, that provide mechanical constraints along the length of the thread. When these types of actuators are designed, the motion that the actuator will undergo when actuated under ideal loading conditions is determined by the construction the device. If there is any additional or misplaced loading the actuator will deform in an unknown manner. This process occurs when the designer decides where to place certain features such as pockets in the elastic material, where air will collect and expand, or whether the cotton threading will be placed to strategically restrict the motion in a particular direction. The combination of these passages and restrictions allows the designer to create complicated motion patterns out of relatively simple materials that require no power.

Another class of soft robotic actuators is developed using thin film materials that can be heat-sealed in a manner that creates specific and strategic air pockets and restrictions, very similar to the style of the previous actuators. The thin film plastics are much more susceptible to tearing and leaking than elastomeric materials but have fewer design and manufacturing considerations. The cost of thin film plastic is generally much less than that of the elastomeric based products. This project and thesis were based on the creation of a specific actuator shape designed and manufactured out of thin film plastic and therefore will be the main subject for the following sections.

1.3.3 Applications in Industrial Environments

While pneumatics have long been used in numerous heavy industries, soft robotic systems are just now being implemented for the first time. Soft systems are not as robust and are harder to control using traditional approaches than a traditional robotic system, making it challenging to implement these systems in an industrial setting. Besides the difficulty of implementation, the materials being used in soft robotic systems are typically more delicate, susceptible to hazardous environments, and have a shorter lifespan than conventional robotic systems. Thin plastic films and silicone-based rubbers are used extensively in the manufacture of soft robotic devices; these materials are excellent candidates because of their natural compliance and soft nature, but they generally fatigue more quickly than rigid components for the stress and forces that they could be exposed to in an industrial environment. The actuators created using these materials are also more limited in the amount of force that is able to be generated than traditional robotic systems. Explorations into the use of different materials and methods of manufacturing soft pneumatic actuators can greatly increase the ability and applicability to use these systems in an industrial setting. A lack of commercial availability of soft robotic systems also limits the amount innovation that can be implemented into industrial environments.

One of the most common soft robotic systems that is used in industrial applications is soft grippers. Soft grippers can robustly grasp a wide variety of shapes without the controls and processing required of traditional grippers. This makes them ideal for grasping unknown shapes; such as those shown in Fig 1.4 Brown *et al.* (2010). Soft graspers such as these allow for the autonomous interfacing of more delicate or intricately shaped objects that typically would require a human operator to work with. There are plenty of opportunities for soft robotic systems to be implemented in

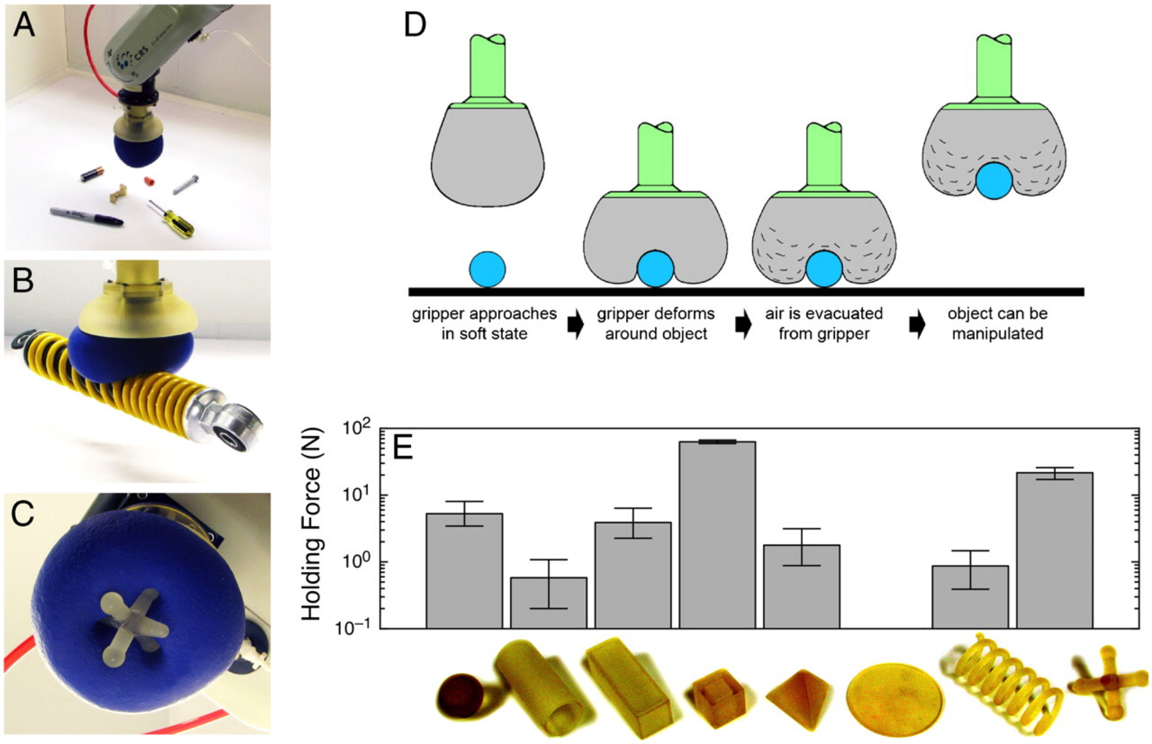


Figure 1.4: This diagram from Brown *et al.* (2010) shows an example of a soft robotic grasper that can be used in an industrial environment to pick up objects of varying size and complexity.

industrial environments, however fundamental challenges of strength and durability still remain.

1.3.4 Challenges Faced in Soft Robotics

Numerous challenges remain unsolved in the field of soft robotics on the topics of controls, manufacturing and evaluation. These primary tasks are a fundamental part of the development of any soft robotic system; Numerous groups are working on solving these and many other challenges, as summarized by Iida and Laschi (2011).

Controlling soft robotic systems can be extremely challenging because most systems have numerous parameters that are either dynamic or non-linear in nature. When controlling systems like these, the design of the system's feedback and controller is extremely important. If there are any imperfections with the feedback loop, then it can be difficult to have a functional control system. This is especially true because the state of the pressure and volume of air in the actuators is not precisely known and any error can cause failures in the devices. One of the most common issues that was encountered when developing a control scheme is the location of the air pressure sensor and whether the supply line was open during the measurement, which can greatly impact the accuracy of the pressure feedback loop. If an air pressure sensor is placed in line with the pneumatic supply line too far away from the intended measurement location, this can lead to an inaccurate pressure information due to surges in pressure caused by the fluid dynamics of air, which results in different fluid pressures at different locations in the length of restrictive tubing that the compressed air is flowing through. Depending on the proximity of the sensor to the actuator, the measurement becomes sensitive to the pressure drop in the length of supply line, similar to a resistor in an electrical circuit. A similar issue that leads to inaccurate pressure information is the timing of when measurements are taken. The pressure sensor is sensitive to the inertial properties of the moving air and if there is not enough time for the supply line to settle, the measurement will not be valid. Inaccurate measurements do not necessarily pose an immediate safety concern in most soft robotics projects, due to the nature of the robustness of soft robotic actuators, however compounding pressure measurement inaccuracy, which is caused when the actual actuator air pressure and volume does not match the measurements from the controller, can lead to instability and failure in a feedback-based control system.

Many different processes and materials can be used to make soft robots. Most soft robotic systems that are made in the Bio-Inspired Mechatronics Lab are made with silicone based elastomers, or thin film plastics. The process for making the silicone based actuators requires the use of molds, ovens, and vacuum chambers in order to create a viable actuator. This process requires much more time and is susceptible to more issues than the thin plastic film based actuators, due to the number of manual steps which require precision, training, and experience. A number of issues can occur during the silicone curing process, such as air bubbles in the cast that will result in failures during the first full pressure inflation. Issues sealing the inflation interface between hardware and the soft actuator can cause leaking and ruptures if not sealed appropriately. Although thin film plastic actuators do not require a curing process, the difficulty with manufacturing these types of actuators centers around the heat sealing process used to create the actuator. Too little or to much heat will cause separation, delamination, and even burn through spots in the seal which can result in failures in the actuators. There are generally more steps required to manufacture thin film plastic actuators, which which can result in more human error, even though the total time for the creation of an actuator is significantly lower than the silicone based actuators.

Finally, evaluation is a challenge faced in soft robotics. Existing software for conducting computer based FEM analysis on models is not ideal for use with hyper-elastic actuators. Non fixed volume models have not been properly implemented into most FEM Analysis tools, which provide inconclusive results when conducting measurements on soft pneumatic actuators. Most of the dimensions of models are fixed when conducting a standard FEM Analysis and having high elasticity properties in the model typically causes errors in the rendering of the computations. Most evaluations done on soft air actuators are typically conducted in a programming environment such as MATLAB (Mathworks) which is much more time intensive and does not provide the graphical user interface that is seen by most FEM Analysis Tools.

There are a plethora of issues when it comes to working with soft robotic systems, which provides many areas of applicable research. Throughout this thesis, all of the issues listed above will be discussed in more detail as they relate to this project. The methods of solving the issues are specific to this device and design and only the overarching concepts of how the problems were solved can be applied to other soft robotic systems.

1.3.4.1 Peristaltic or "Inchworm" Locomotion

This device utilizes a method of locomotion that mimics the biology of an inchworm. The locomotion strategy involves anchoring the rear end in place, extending the center section and then anchoring the front end in place. At this point the inchworm has completed one half of the locomotion cycle, the forward reaching movement. The distance that it has traveled is given by the length of the extended center segment minus its contracted length. The next step is to reset the rear end in order to allow another forward extension. The rear end releases its anchor, and the center contracts. The rear end can now anchor and the inchworm can start the next cycle. The cycle allows the inchworm to constantly have one end providing an anchoring force keeping it stationary, while the other is in motion van Griethuijsen and Trimmer (2014). This principle is heavily used in the operation of the device that was designed in this project. In order to move along the pipeline the device is effectively locked in place with at least one toroidal actuator at any one time, which helps the device to maintain concentricity with the pipeline at all times, allowing for effective and efficient operation. The locomotion cycle that was implemented on the proof of concept design is shown in Fig 1.5.

1.3.5 Conference Paper Preparation and Presentation

During the course of this project, a research conference paper was produced, accepted and presented at the IEEE International Conference on Soft Robotics re-

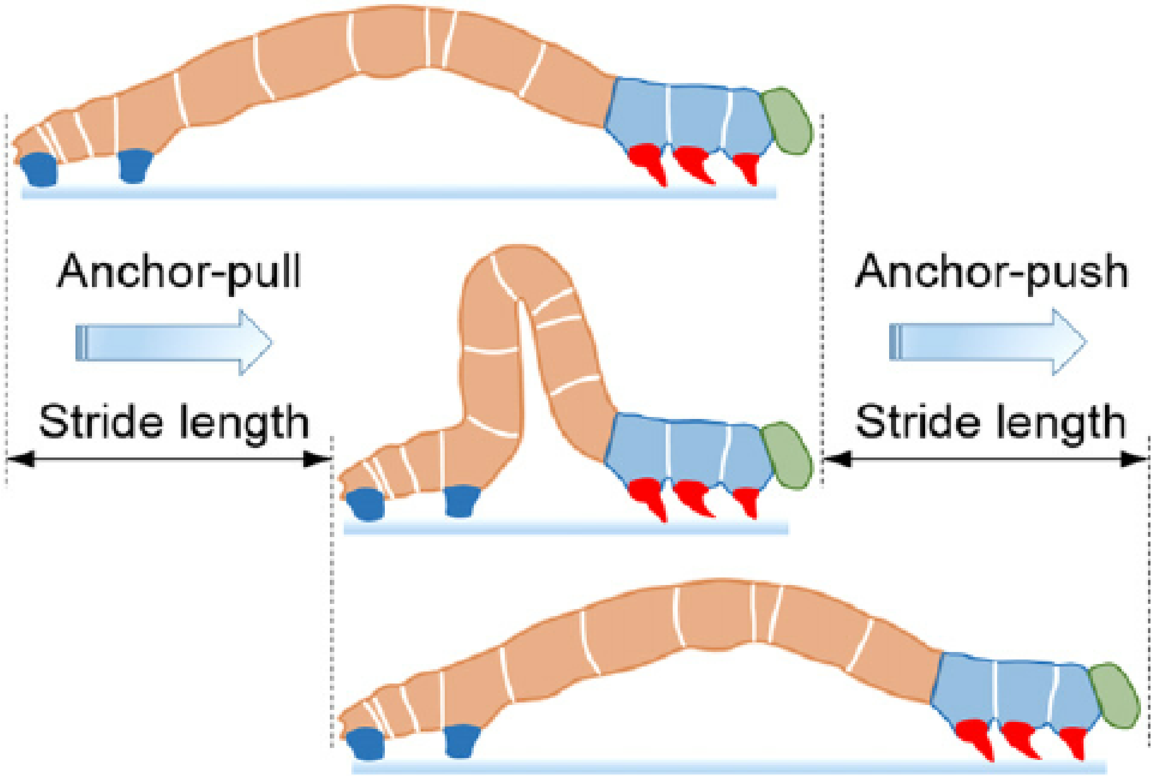


Figure 1.5: This diagram from Wang *et al.* (2014) shows an example of the locomotion of an inchworm.

garding the Proof of Concept Design, which is covered in Chapter III of this thesis. The presentation at the conference generated interest in the project from soft robotics professionals from many different research universities and provided the project with appreciated feedback and opportunities for further work and design improvement.

1.4 Project Specifications

The initial purpose of the research was to develop a soft robotic device in coordination with SRP that would negate the challenges that are faced by rigid robotic devices when operators are inspecting pipelines for damage. The end goal of the project was to deliver a device that is capable of being used to inspect damages in an actual underground pipeline that is operated by SRP. The following four functional requirements guided the design of the device from the start of the first phase of the project. Over the course of two project phases, different device specifications and constraints were ratified in order to better meet needs of the engineers at SRP. These overarching requirements and specifications still remain.

1.4.1 Functional Requirements

- Must be capable of navigating a pipeline
- Must provide a stable platform for pipeline inspection equipment
- Must be controlled by user to investigate problems at will
- Must not be affected by occlusions in the pipeline

1.4.1.1 Specifications

- Use soft air actuators to provide anchoring force in the pipeline
- Use soft air actuators to provide linear, telescopic extension
- Incorporate a pan/tilt camera mechanism into design
- Design a device controller for the operator

Chapter 2

TOROIDAL SOFT PNEUMATIC ACTUATOR

2.1 Actuator Design

The actuators created for use in the water pipe inspection device are toroidal in shape which allows them to occupy the entire volume of pipeline and apply anchoring force circumferentially to the inner surface of the pipe across the section width of the actuator. In Fig 2.1 the device with two actuators is shown fully inflated, while applying force to the pipeline.

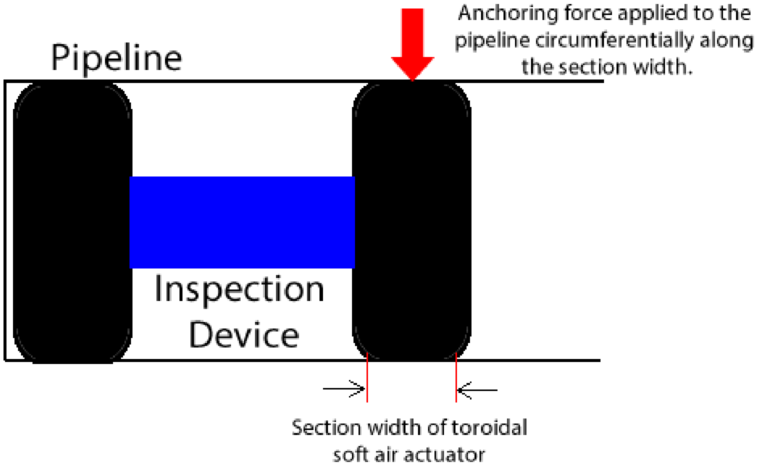


Figure 2.1: The above graphic shows how the actuator sits in the pipeline and distributes the anchoring force on the pipeline along the section width of the actuator

2.1.1 Geometry of Toroidal Actuator

The toroidal shape of the actuator allows for the application of anchoring force along the outer surface in the radial direction of the actuators. The contact area between the actuator and the pipeline is where the anchoring force is being applied and is based on the design of the actuator. There are two different styles of actuators, extensible and inextensible which both have different methods of determining contact area. The contact area is the most critical part of the actuator as it along with the internal pressure of the actuator, determines how much force is being applied to the pipeline.

Another important design aspect of the toroidal shape is that when manufactured with thin film materials, upon inflation the actuator increases in thickness while decreasing in outer diameter. This means that the deflated actuator has a diameter that is larger than when it is inflated. The thickness of the deflated actuator is smaller than when it is inflated. The gain in thickness allows for other applications of this actuator, instead of only being able to apply anchoring force to the pipeline. The increase in thickness is determined by the design of the actuator and is guided by the following equation, where OD is the outer diameter of the inflated torus, ID is the inner diameter of the cutout section and t is the thickness when inflated: $t = (OD - ID)/2$

When the actuator is fixed in place and inflated the gain in thickness provides a linear motion along with the decrease in outer diameter. Both outcomes of the inflation of a toroidal actuator are show in Fig 2.2, where the red lines represent the greatest dimensions of the actuator in any state. These two force and size change properties can be utilized in the design of the water pipe inspection device for anchoring and linear locomotion.

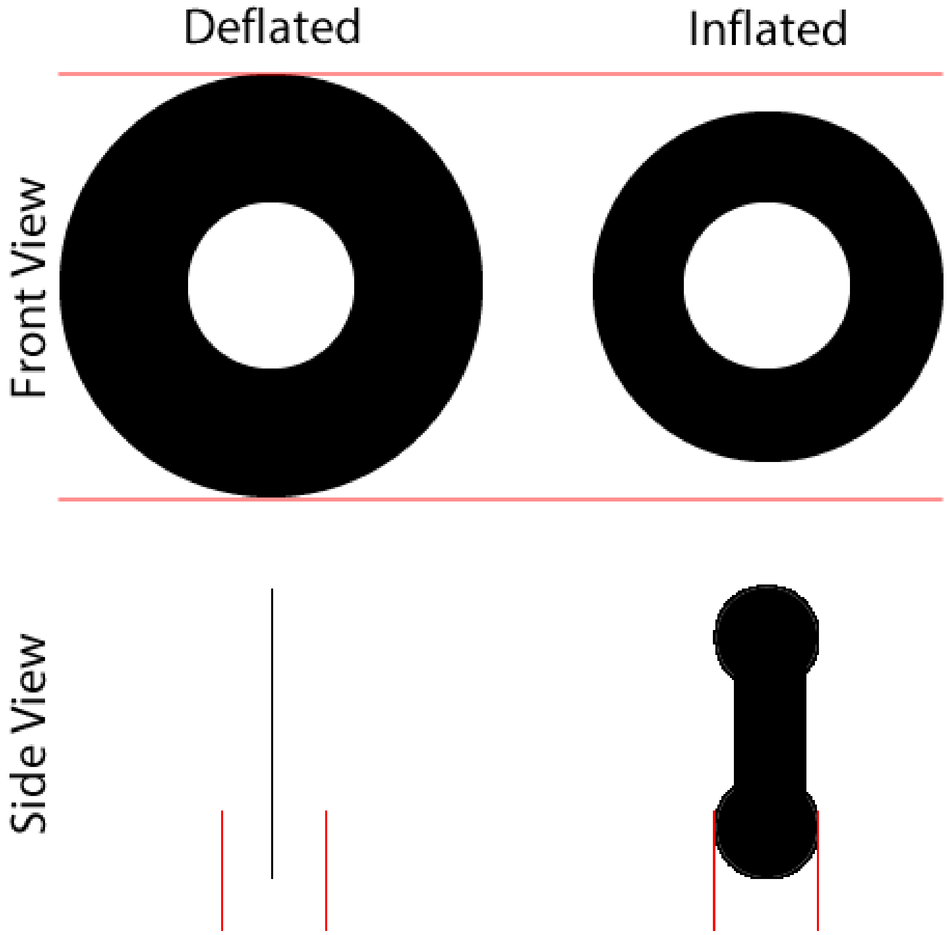


Figure 2.2: The above graphic shows the difference between the diameter and thickness of the actuator between its inflated and deflated states. This figure only shows the principle of the size delta between the states, this is not to scale and does not represent the correct proportion of size change.

When the toroidal actuators are used to distribute anchoring force onto a pipeline the shape of the actuator will be deformed in some places. Assuming the actuator is strictly vertical in the pipeline and is inflated to the anchoring state, the top of the actuator will be deformed and the surface area that is in contact with the pipeline will be a set amount depending on the design of the actuator. If the inner diameter of the pipeline is 24" and the actuator is 25" in outer diameter when fully inflated, there is a total change of diameter of 1". This change in diameter impacts the entire toroidal soft actuator equally and so the contact area between the actuator and the pipe is consistent all the way around the circumference of the actuator. In order to mathematically find the contact area between the actuator and the pipeline, the difference between the diameters of the fully inflated actuator and the pipeline need to be known. Using chord theorem and the equation for surface area of a rectangle the following equations will demonstrate how to find the contact area. H will be the difference in diameters between the actuator when fully inflated and the pipeline. r will be the inner radius of the torus cross section. c will be the chord length found by the chord theorem and used to find the contact area with C which is the outer circumference of the torus. Fig 2.3 shows the different parameters as they relate to the toroidal soft actuators.

$$c = H/2 * (2 * r - (H/2)$$

$$ContactArea = c * C$$

The evenly distributed anchoring force applied to the pipeline is a function of the internal pressure of the actuator and the contact area that was found based on the size differences between the actuator and the pipeline. These calculations are ideal and should be used for reference, as there can be variances in the fabrication of the actuator that can cause differences between the actual and ideal anchoring force. It is also important to note that these equations can only be used for inextensible actuators with a fixed volume. If the volume changes while the actuator is inflating such as with an extensible actuator, the contact area will increase as the pressure increases.

2.1.2 Inextensible Actuators

Inextensible toroidal actuators are a type of actuator that has a fixed volume when inflated fully. A mechanical constraint is needed to restrict the actuator from extending into elastic region of the material strength properties of the actuator. The design requires that the stress is handled by the mechanical constraint rather than the soft actuator, whether it is made out of thin film materials or silicon elastomers. This is beneficial for use in the pipe inspection device because it allows a fixed volume of air to actuate the device. The rest of the system can be designed around this volume in order to decrease the inflation and deflation times and improve the speed of locomotion. The fixed volume of the actuator allows for an established amount of force to be placed on a constant inner diameter pipeline, if there was variability in the diameter of the pipeline, or if the mechanical constraint was not present, the force being applied would not be constant, as is the case with extensible actuators.

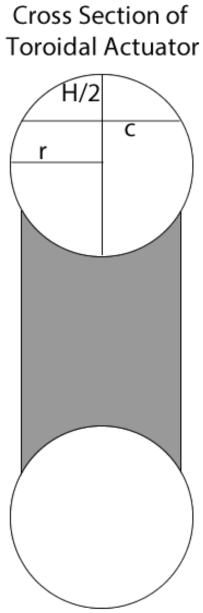


Figure 2.3: The above graphic shows the parameters necessary for finding the contact area between the actuator and the pipe.

2.1.3 Extensible Actuators

Extensible actuators differ from inextensible actuators because they do not contain a mechanical constraint to create a fixed volume. Instead, the extensible actuators rely on the mechanical properties of the actuator fabrication material such as thin film materials or silicone-based elastomers. Some of the materials used in this application are known as hyper elastic materials which are able to strain over large distances with little material stress. This property has its benefits for testing, however it is not ideal for use with the inspection platform where fixed volumes of air are required for efficient operation. This style of actuator will reach a certain internal pressure which starts to strain the material and the rate of material stretching becomes faster than the increase in internal air pressure. What is observed in testing is an increase in volume by hundreds of cubic inches of air with slight increases in air pressure. A visual comparison of the two styles of actuators can be seen in Fig 2.4.

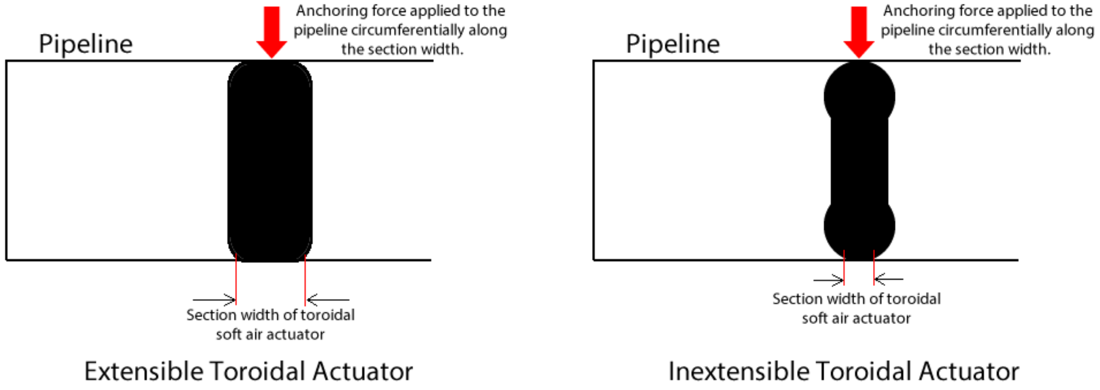


Figure 2.4: The above graphic shows the differences in section width and contact surface area between the two styles of actuators that are used for this project.

2.2 Actuator Stress on Pipeline

In order to determine the impact that these actuators will have on the pipelines that they will be used in, it is important to understand how the pipelines react to the anchoring force. Hoop or cylinder stress is a term used to categorize the the internal stress of a cylinder that is being subject to a circumferential force along the inner diameter of the cylinder. This principle can also be expressed as the stress along the cross section of the cylinder wall. For cylinder applications with a radius to wall thickness ratio of 10 or greater, the thin-walled cylinder stress equation is used. The common application of this equation is for pressure vessels with a consistent pressure throughout the entire system. The force being applied to the pipeline by the actuators is pressure at the contact area and so it can be assumed that the parameter P is the internal pressure of the soft air actuator rather than the internal pressure of a pressure vessel. The other parameters in this equation are r which is the radius of the cylinder with reference to the outer diameter and t which is the wall thickness of the cylinder. This equation will give the stress in the cylinder walls from contact with the actuators.

$$Cylinder\ Wall\ Stress = (P * r)/t$$

The stress in the pipeline walls is affected by the style of actuator that is used. For extensible actuators, the stress will not vary greatly with pressure. As the volume and overall force are increasing the actual stress will remain low due to the increase in contact area. With the inextensible actuators the contact area stays the same, so as the internal actuator pressure increases, so does the cylinder wall stress.

Chapter 3

SMALL SCALE DEVICE: DESIGN AND TESTING

3.1 Proof of Concept Phase

A proof of concept device was developed that is capable of accommodating a six inch inner diameter pipeline. A small-scaled version of the device allows for faster testing and less resource intensive design changes. By creating a small device before the large scale device, the control system was able to be simulated using a soft robotics analysis platform that has been built in the Bio-Inspired Mechatronics Lab at Arizona State University. In addition to easier testing, using smaller scale actuators and rigid cores allows for more rapid prototyping and design changes using readily available tools, such as fused deposition modeling (FDM) 3d printers and a custom CNC heat sealing machine. The proposed proof of concept design was created with two major considerations; scalability and modularity. The intent of scalability in the design was to ensure that no major considerations were needed in order to accommodate larger outer diameter pipelines. In essence, the same device could be manufactured with a simple increase in scale without changing the master design of the components or methods of locomotion. By using modular components in this system, if there is ever any damage to the device, or if a design change is necessary the entire device does not need to be replaced. These two design themes remain as major requirements for the device and are present throughout the design process that is presented during in this thesis. Fig 3.1 shows the final version of the small scale device design with all of the parts labeled.

3.1.1 Small Scale Device Design and Fabrication

The design of the proof of concept device combined novel toroidal soft air actuators with a telescoping rigid core. The toroidal soft air actuators are designed to remain flat while deflated and decrease in overall diameter as well as increase in stiffness when being inflated with air. These actuators provide two different types if force that are managed by the geometry of the toroidal shape. From their flat shapes, the toroidal soft air actuators apply force along the front face and along the outer most edge of the curved surface. The actuators are shown in both a deflated and inflated state in Fig 3.2. The rigid core acts as a base that the soft air actuators and pipeline inspection equipment are able to attach to. The telescopic feature of the core in conjunction with the stacking of several toroidal soft air actuators is what

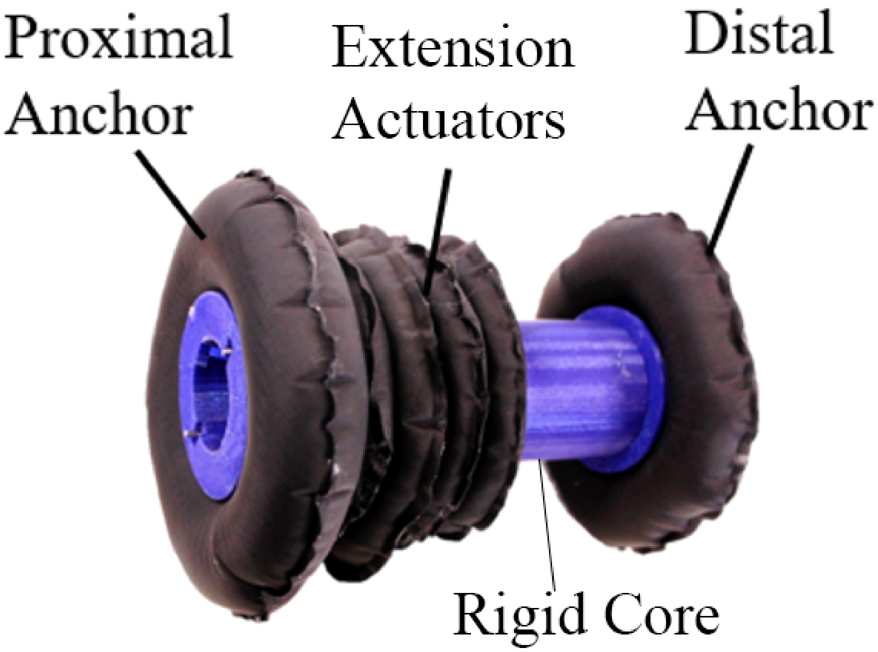


Figure 3.1: The Small Scale Device shown in both an inflated state, with all of the parts shown.

enables the device to extend, while elastic bands provide the retraction force when the center stack of actuators is deflated. This device had to be fabricated in many different parts. The rigid core was 3D printed, while the actuators were fabricated by hand with the development of new tools speeding up the process significantly. Most of these manufacturing methods are only viable for creating a small scale device such as the one that is used in laboratory testing. In order to create larger scale devices, new designs and methods of manufacturing had to be implemented, which will be further discussed in chapter four.

3.1.1.1 Small Scale Rigid Core Design

The rigid core of the small scale robot is comprised of multiple components that are made using a commercial 3D printer (Makergear M2) with polylactic acid plastic filament as the printing material. The core is designed with telescopic rigid cylinders which slide over each other to elongate or shorten in order to permit translational motion. There are four main 3D printed components; the outer sleeve, inner sleeve and two actuator caps. The outer and inner sleeves provide the telescoping; the outer

Figure 3.2: The first set of toroidal soft air actuators are shown in both a deflated and inflated state, from left to right respectively.

and inner sleeve dimensions are specified with tolerances that permit sliding while minimizing radial backlash. These parts are held together with elastic bands that provide the force needed to retract the device when the center actuators are deflated. The outer sleeve has a flat surface that extends beyond the wall thickness of the sleeve and provides a surface for the center actuators to apply force to. The inner sleeve is slightly longer than the outer sleeve, causing a gap between the outer sleeves back-plate and the conic end of the inner sleeve. This gap between the two flat surfaces, which is designed to be adjustable, determines how many toroidal soft air actuators can be used as center actuators, in order to provide the extension force needed for locomotion. If the gap is larger, more actuators can be used and the total stroke length of the robot can be increased. All of these features can be seen in Fig 3.3.

In order for the full stroke length to be achieved, however, the length of the sleeves will also need to be increased, according to the inflated actuator thickness equation in Chapter Two. The design of this device takes advantage of this geometric principle and uses multiple actuators stacked, that when deflated are flat sheets and when inflated provide extension. The addition of same sized actuators provides a linear increase in the maximum stroke length of the device as each actuator provides a consistent increase in thickness. The total adjustments that need to be made are

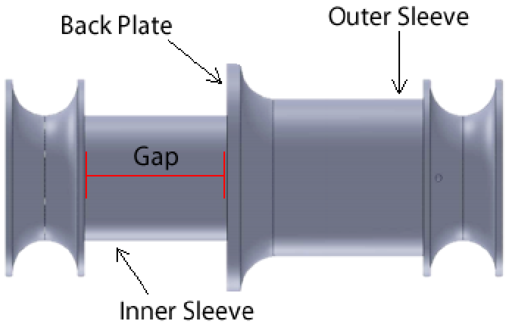
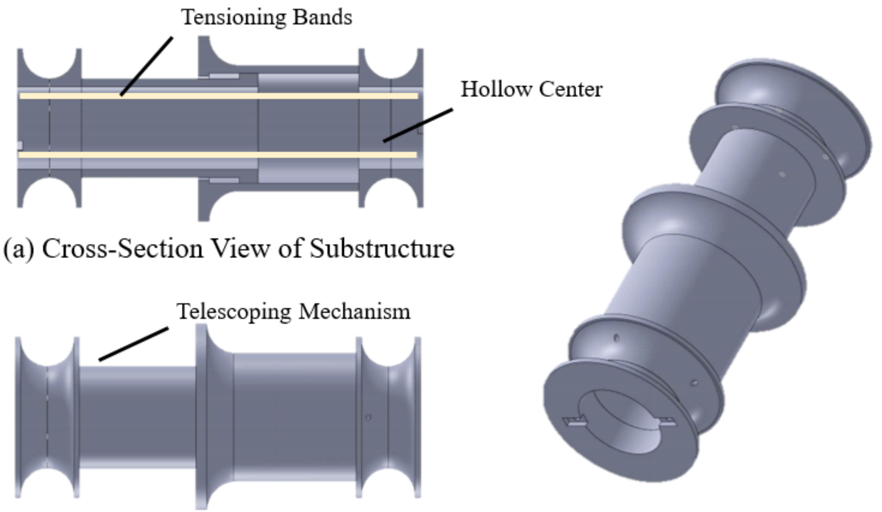


Figure 3.3: The following figure shows different features of the rigid core for the small-scale proof of concept device in its extended state.

dependent on the number and outer diameter of the toroidal soft air actuators that will be used to provide the extension force on the robot. An experimentally determined margin of safety to prevent binding is to provide a gap length of at least 150 percent of the total length of the stacked soft air actuators. More than 150 percent of the length is in excess and less than that can cause issues with binding during the retraction cycle.

The non-interfacing ends of the outer and inner sleeves have a conic shape that interface with the conic shape of the actuator cap. The two conic shapes are joined to create a hemispherical shape around the diameter of the rigid core. The shape that is made between the actuator cap and the non telescopic end of the sleeves is roughly the same shape of the toroidal soft air actuators. This is important because the interface locks the actuators in place as well as transmitting the force outwards from the core and into the pipeline. The rigid core can be seen in Fig 3.4 without any actuators integrated onto the device.



(a) Cross-Section View of Substructure

(b) Side View of Substructure

(c) Isometric View of Substructure

Figure 3.4: The following figure shows different views of the rigid core for the small-scale proof of concept device in the extended state.

3.1.1.2 Fabrication of Small Scale Rigid Core

The rigid core of the small scale laboratory testing device was manufactured using a standard, consumer grade, 3D printing machine (Makergear M2). The core is a telescopic device which means that the two halves of the device need to have tight tolerances wherever there is interfacing between the two parts. This 3D printer is capable of printing geometries within the required tolerances without having to process the parts further after their initial printing. In other words the parts are ready for assembly when they are done printing. Since only a couple of parts actually needed to be manufactured it was logical to develop these parts with a 3D printer oriented design in mind. For a production quantity of parts the design could be modified slightly in order to better suit a high volume manufacturing process, such as injection-molding. This might require more steps to actually finish the parts, but would take less time to complete than the 3D printing process and be far more cost effective. The rigid core is printed in 6 different parts and assembled using stainless steel pins for alignment and adhesive glue that binds the parts together.

Once the telescopic parts of the core are fit together, the toroidal soft air actuators that will be used for linear extension are secured in place between end cap and the flat side of the larger telescopic part. The end caps are friction fit onto the telescopic core in order to allow for the easy removal and replacement of the linear extension actuators. For a more permanent connection the end caps must be secured better in order to ensure continued operation and prevent damage to the device. The toroidal soft air actuators are held in place by the two halves of the core end caps which are shaped to contain the actuator when it is inflated. These end caps are held together with stainless steel pins that are friction fit into the part in order to allow for the easy removal and replacement of the soft air actuators. This feature is only necessary for laboratory testing. For realistic setting testing, the end caps would be secured using strong adhesive or bolts, as discussed in Chapter Four.

Elastic bands that span the length of the device are used to supply the contraction force that is a necessary part of the locomotion cycle. During assembly these elastic bands were put into place and secured around stainless steel pins protruding from the ends of the core. The addition of these elastic bands is the last step of the main body assembly as this contraction force also assists the with the friction fit force that is holding the end caps in place. Once these elastic bands are put into place, the last step of assembly is to hook up the pneumatic supply lines to all of the actuators.

3.1.1.3 Design of Small Toroidal Soft Air Actuators

The novelty of this project is attributed to the design of the actuators that are used to provide the anchoring force to the inside of the pipelines. These actuators have been designed and fabricated for this project and have gone through several iterations in order to deliver the proper amount of force. When the actuators are inflated from their initial flat-sheet shape, the overall diameter decreases, but the thickness of the actuator increases as is discussed in Chapter Two. The increase in thickness in the actuators is used for generating linear motion in the small scale design. The actuators that are to be used solely for forward locomotion are not designed to operate in the elastic stress portion of their mechanical properties, unlike the anchoring actuators. These extension actuators are encased in an inextensible fabric sleeve that will ensure that they do not reach the elastic region of stress. Instead, any excess force or increase in internal pressure will be applied to the fabric sleeve rather than the actuator.

By design, the outer diameter of the actuator is larger than the inner diameter of the pipeline when it is deflated. A slight inflation of the actuator will effectively prime it and reduce the outer diameter so that it is more easily fit into the pipeline.

The actuator will then be inflated fully until it is anchored into the pipeline. There are two options for effectively anchoring into the pipeline; the elastic region actuators or the non elastic actuators.

For the elastic actuators, the outer diameter is designed to match the inner diameter of the pipeline. When the actuator is fully inflated a very small surface area will be in contact with the pipeline; this leads to problems with the actuators slipping out of place and preventing proper operation of the device. At this point, there is very little stress in the plastic film of the actuators. When the air pressure is increased, the stress in the film increases and the actuator starts expanding until more surface area is in contact with the pipeline. The biggest issue with developing this type of actuator is that it fatigues much more quickly than the non-elastic toroidal actuators. However, this style of actuator is less prone over-pressurization because it does not have a fixed volume. The thermoplastic polyurethane film that is used to create this style of actuator is considered a hyper elastic material because it can withstand very large stress and strain before it reaches its yield point. The modulous of elasticity for the material used was found experimentally, to be 32.5 KSI (224MPa).

Non-elastic actuators exhibit higher longevity but require thicker materials and can be less robust than elastic actuators in some aspects such as accommodation of occlusions. The actuator is designed with a larger outer diameter than the inner diameter of the pipeline and is encased in a inextensible fabric sleeve that shares the same outer diameter as the actuator. The manner in which the inextensible actuator inflates is identical to the linear actuators that are used for forward locomotion, even though the device takes advantage of the radial force along the outside edge of this actuator to anchor into the pipeline rather than utilizing the increase in actuator thickness for extension of the rigid core. This style of actuator is considered to have a fixed volume when fully inflated, and because the outer diameter of the robot's toroidal actuators is greater than the inner diameter of the pipeline, there is more surface area in contact with the pipeline without encroaching into the elastic stress region of the plastic film. Because these actuators are considered inextensible, once the maximum pressure is achieved inside the plastic bladder, the rest of the force is translated into the inextensible fabric sleeve. These actuators can deliver more force into the pipeline than the elastic actuators because they have a fixed volume and so once filled, any extra volume is translated into higher air pressure as shown by the Ideal Gas Law: $PV = nRT$ where P is the pressure of the actuator, V is volume and nRT is a constant. The elastic actuators grow in volume as the pressure increases and so there is a greater contact area and less cylinder wall stress.

3.1.1.4 Fabrication of Small Scale Toroidal Soft Air Actuators

Throughout this project, numerous methods for fabricating toroidal soft air actuators were explored. The materials used to create these devices were also scrupulously selected through a process of literature review and trial and error. Many of the processes that can be used to manufacture other soft air actuators were not feasible in the creation of these toroidal soft air actuators due to the geometrical requirements of the toriod shape when it is in its flattened state. In essence, the creation of these toroidal soft air actuators is done in two dimensions with only mathematical consideration for the third dimension. It is up to the designer to predict how the actuator will change its shape or motion when it is inflated, as is the case with most soft pneumatic actuators. Imperfections in the creation of the flat state toroidal actuators resulted in rupture points when the device was inflated for the first time. The amount of error that was seen in the by-hand manufacturing method of these actuators led to the creation of a machine that could create these actuators with a much higher success rate. In order to create a toroidal soft air actuator that would not rupture when it was inflated, both the outer and inner seal of the actuator need to be concentric circles free of any major deviations. The more perfect the circular seam, the less chance it will rupture during inflation. If there are any imperfections in the seal or deviations from the ideal circular shape, those imperfect areas will become points of concentrated stress and will tear either the seal or the material.

A device that was created in order to more precisely manufacture these actuators will be discussed in a following section, however this device is effectively a CNC heat sealer. This allows the user to design the shape of the actuator that they want to seal on the computer and then seal the shapes with the machine, which has a significantly higher degree of precision than sealing by hand. For the creation of elastic soft air actuators, once the actuator is sealed, a connector is locked into a single layer of the TPU film and the actuator is ready for use. This connector allows the actuator to be connected to a pneumatic supply line that will transport the high pressure air in and out of the actuator. When non-elastic actuators are required for the device, a sleeve of inextensible nylon is encased and sewn in place around the soft air actuator. The sewing of this sleeve finishes the manufacturing process of the actuator and adds features that are not seen in the elastic actuators, such as adding a seam that can be used to anchor the actuator.

3.1.1.5 Design of Small Scale Control System

In order to effectively control this device, numerous mechanical pneumatic components are necessary. Firstly the correct inlet air pressure must be achieved by regulating it with a mechanical air pressure regulator. Electro-pneumatic valves are utilized in line after the regulators to control where the air flow is going. There are three states that the actuator can be in while being used in this system; inflating, deflating and a hold state. Each one of these states has it's own valve configuration. By electronically actuating the valves, the state of the bags can be changed very quickly and autonomously. Finally air pressure sensors that are put inline are implemented in order to measure the air pressure inside the actuators. A control algorithm is created utilizing these components in order to create a locomotion cycle that will allow the robot to navigate down the pipeline. When the device is used in the pipelines operated by SRP, a microcontroller-based control system would be able to perform all of the functions necessary to operate the device. A simple validation testbench was developed in order to characterize the feasibility of the design and more easily characterize the soft air actuators. The test bench utilizes the LabView programming environment (National Instruments, USA) that interfaces with all of the pneumatic control components, such as the valves, regulators and air pressure sensors. The control system becomes a constant and ideal source of air pressure for the device during testing. The proof of concept design was able to be validated successfully and the actuators were proven effective for their purpose of anchoring the device in the pipeline. With this current method of control, as shown in Fig 3.5 the device was strictly limited to operation in the test pipeline that is affixed to the test bench. In order to achieve operation in the intended operating environment, a system that can be implemented on board the device was developed during the second phase of the project, which is discussed in chapter four.

3.1.1.6 Custom Machining and Manufacturing Methods

Many experiments were conducted in order to create a method of manufacturing these soft toroidal air actuators, but none had the precision in heat sealing as the CNC heat sealer as seen in Fig 3.6. What was found when attempting to improve the sealing process for these actuators is that it is necessary to control the force being applied at the seal, the heat of the sealing surface and the motion that the sealer is performing. This eliminated hand sealing the actuators with hot iron type tools, as the control of force and motion needed to manufacture perfect actuators requires too much time and precision to be done correctly. The CNC heat sealer produced accurate and repeatable circular seals, which allowed for the process of fine tuning the necessary sealing temperature and the force applied to the seal. The process for tuning the temperature was found experimentally; using a thin Teflon sheet between the tip of the hot iron and the layers of TPU prevented any issues with sticking and also allowed for more even distribution of heat in the seal itself. In order to achieve the proper amount of force being applied to the seal, many different designs were considered, including a spring loaded device to prevent the over-exertion of force into the material. In the end it was discovered that by adding a 5mm thick silicone rubber sheet underneath the TPU, the seals would not rip during sealing.

The same problem with concentric circle sealing was noticed when creating the inextensible sleeves for the non-elastic actuators, and so another machine was introduced to cut out the material with high precision. A desktop laser cutter, (GlowForge)

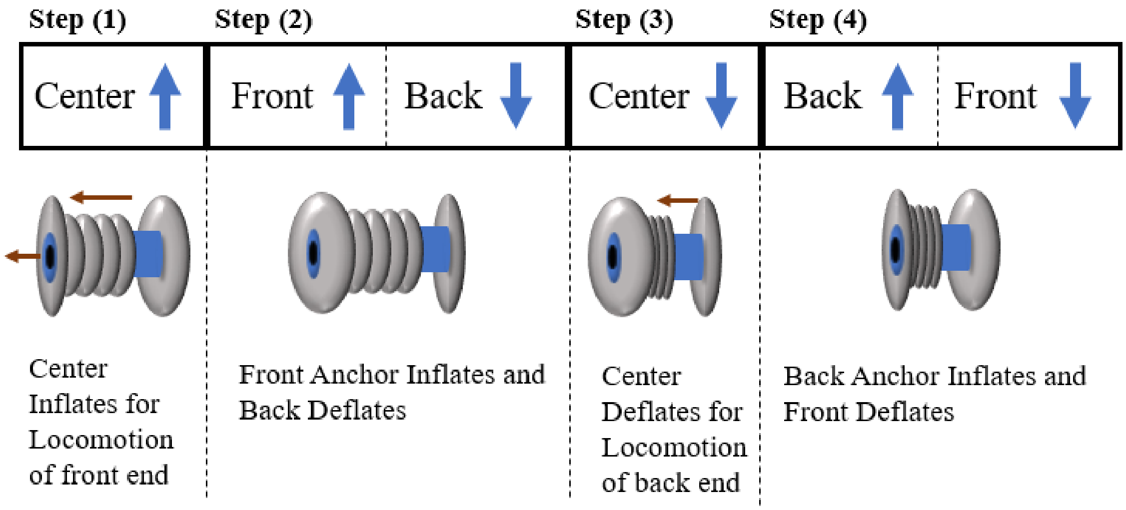


Figure 3.5: A diagram of the locomotion cycle utilized by the small scale proof of concept design that is discussed in Chapter 3.

was used to cut out the material into almost perfect circles before they were sewn together, encasing the soft air actuators. By ensuring that there were as few eccentricity errors as possible when creating these actuators, the number of inflation cycles that the actuators could undergo was greatly increased before they deteriorated to an unusable state.

3.1.2 Evaluation of Small Scale Device

The evaluation of this device was conducted in two different manners. There were no requirements or specifications for the amount of force generated by any of the actuators that were designed and fabricated. The main validation of the device was focused on whether or not the device could navigate the pipeline. While individual actuator testing would be required to understand the interplay between pressure, force, and locomotion, our experimental testing focused on validating the system holistically.

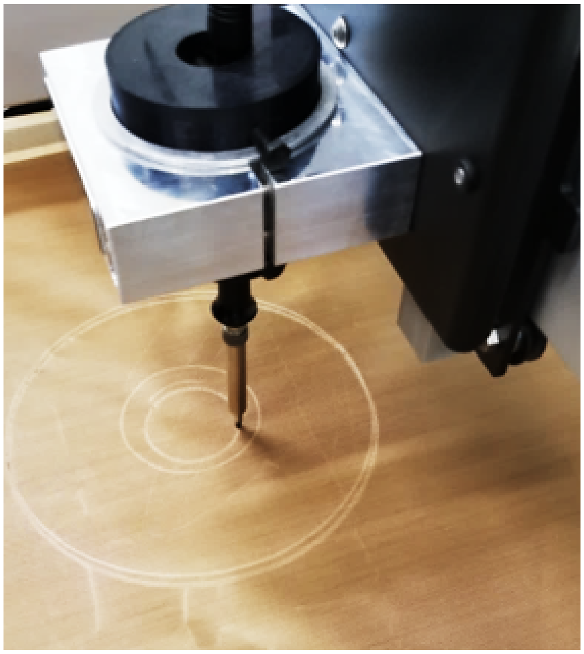


Figure 3.6: This custom cnc heat sealer system was made to precisely fabricate small soft robotic acutators.

For the scope of the project, one metric that required attention was the speed at which the device would navigate the pipeline. For the small-scale proof of concept, the speed did not need to meet any requirement, however the locomotion cycle of the device could be optimized using such small volumes of air. For the large scale device, the speed consideration was much heavier, which will be discussed in chapter four. For the sake of characterizing the toroidal actuators, two majors evaluations were made. A force test was conducted on the toroidal soft air actuators in order to identify the amount of force that could be generated when anchoring in the pipeline. The second test determined the amount of linear force generated by the stack of actuators in the robot's rigid center. Both evaluations were conducted on the small scale, non-elastic, (fixed volume) actuators. It has been observed that depending on the style of actuator, elastic vs. non-elastic, the volumes can vary greatly and the force that the actuators can exert will also vary significantly. In order to ensure that the pipelines would not rupture under maximum pressure, a force test was conducted by measuring the force generated at lower pressures. A testing rig was set up in a universal testing machine (Instron Model 5943) which could measure the force being applied to the pipe. This testing setup, consisting of a section of pipe mounted to the Instron, allowed for the measurement of force while locking the rig in place to replicate the real environment in which the device would be used. We assumed that the toroidal actuators provided constant radial pressure around the circumference of the pipe in our calculations. Fig 3.7 shows the radial force being measured by the test rig and the air pressure being fed into the actuator. It can be seen that the actuator is capable of generating force at well over the planned operational pressures. The error bars demonstrate a large deviation in the amount of force being generated and this is believed to be due to actuator tilt in the test setup.

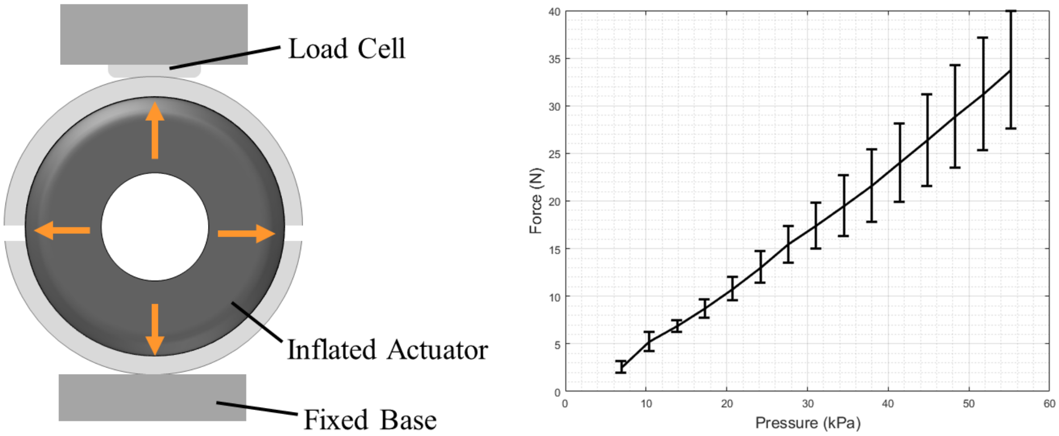


Figure 3.7: The test platform used to test the soft pneumatic actuators.

One metric related to the amount of anchoring force being generated by the toroidal soft air actuators is the tilt of the device when it is extended before the actuator at the opposite end is anchored. If the actuator does not generate enough force to effectively anchor the device in place when it is subjected to this cantilever position, the center actuators can sometimes drive or drag one end of the robot against the bottom of the pipeline. While this is not necessarily dangerous for the device, it does present a situation where the device could lose some of its efficiency or functionality due to debris and muck in the bottom of the pipelines.

The second force test was conducted in a similar manner using the same universal testing machine (Instron Model 5943), to measure the force of the extension actuators used in the rigid telescoping center portion of the robot. The actuators were tested while still affixed to the device to provide the most realistic measurement of force being generated by the device. While this testing setup does not truly characterize the actuators themselves, it provides a very good sense of force generation by the device, during the linear extension cycle. The test was conducted with different numbers of stacked actuators to measure the impact on the force generated by stacking multiple actuators in series. Based on the results in Fig 3.8 it is shown that there is a

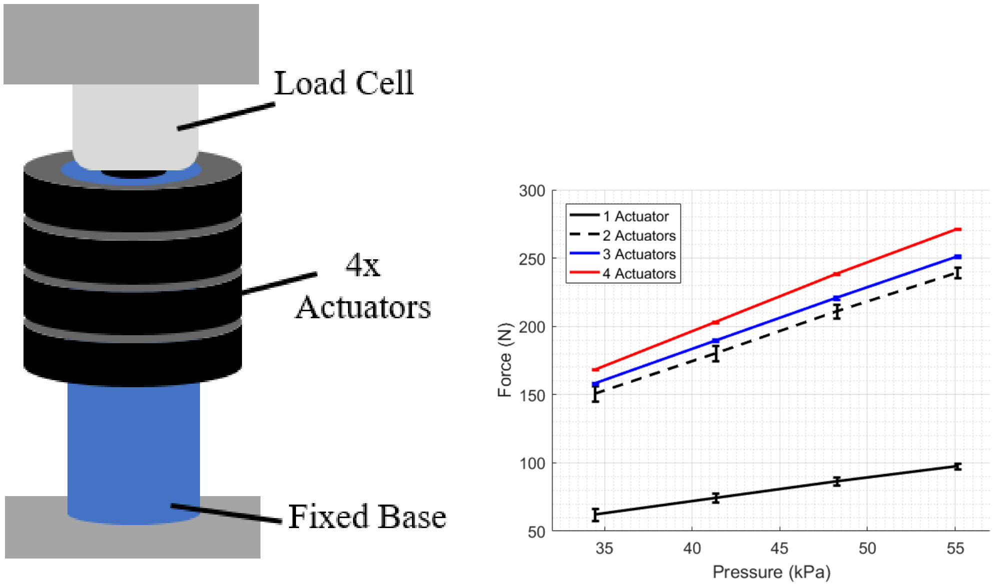


Figure 3.8: The above graphic shows the test setup and the results of the stacked actuators force testing.

linear correlation between the amount of force generated and the air pressure of the actuator. This was an expected principle of the non-elastic actuator design and the results validate that there was no unintentional elasticity in the device.

The second insight gained from this test was that the output force increases when multiple actuators are stacked in series because deformation in the actuators leads to more contact area with the rigid core. This force does not increase linearly as each actuator is incrementally added, but is a result of differing pressures due to changing contact areas between the actuators and the rigid core. The test was conducted with a maximum number of four actuators, because that is what this iteration of the device was designed to utilize. As the rigid core is extended and retracted the actuators will have non-constant contact areas between each of the actuators and core, resulting in different applied forces throughout the locomotion cycle.

These force tests provided the insight required to understand the characteristics of the force generation by these toroidal soft air actuators. Other tests were conducted that provided more additional information about the actuator, including pneumatic hysteresis and insights into the orientation of the actuator in the pipe and its effective force on the pipeline, though this information was not used in the design of the robot.

3.2 Proof of Concept Testing

System-level testing validated that the device was capable of successfully locomoting through a 6 inch inner-diameter pipe. The testing was conducted at the device level to ensure that the device successfully navigated down the pipeline and an effective rate of speed. This testing time was also key in developing and optimizing an effective locomotion cycle. This included numerous iterations of logic development and the implementation of numerous pneumatic control theories, such as constant-pressure time-based controls, system pressure based controls, the idea of flow control and the use of a vacuum pump to ensure that the proper volume of air was evacuated out of the toroidal actuators to release the anchoring force. There was one noticeable rocking issue in the small scale device that caused inconsistencies and improper timing in the cycle. These initial rounds of testing also provided plentiful insight on the airflow dynamics and the effect of long distance pneumatic supply lines and sensing. All of the testing was conducted on the test platform seen in Fig 3.9. Overall this testing period ensured that when the next size robot was developed, a lot of design changes and considerations were made in order to improve the cycling of the device.

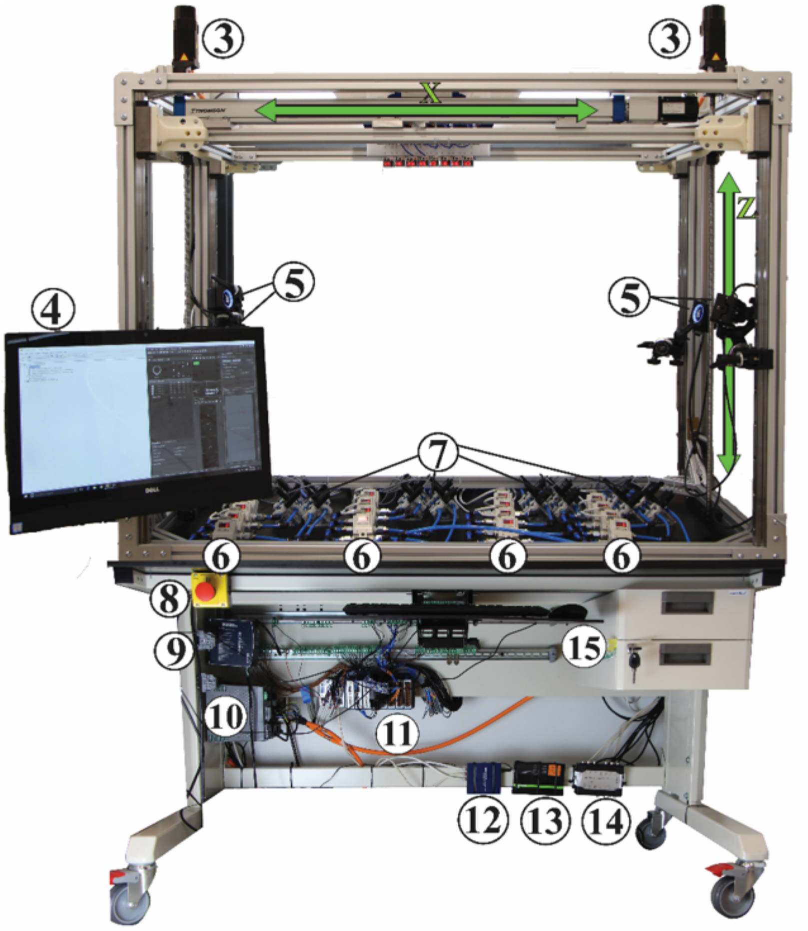


Figure 3.9: The test platform used to test the soft pneumatic actuators.

When striving to create an effective control system for this robot, there were numerous strategies that could be followed; standard time control, pressure based control and what was finally used, a combination of those two schemes. Time-based control is an open-loop control scheme where the valves are opened for a fixed amount of time to allow the high pressure air into the actuators. When strictly using time based control it was found that the amount of air being forced into the actuators would eventually accumulate and the time that it took to evacuate the actuator would increase and the efficiency of the locomotion would decrease. A pressure-based control scheme incorporates feedback from the inline air-pressure sensor to allow the actuator to inflate to a specified internal pressure. With the pressure measurement system, it was found that the non-elastic actuators lost a small amount of volume and most of the pressure and so the anchoring force would again not be disengaged. In order to achieve the accurate anchoring force during inflation and the proper disengagement of the actuators during deflation, a hybrid control method was developed that utilized a pressure-based inflation sequence with a constant volume based deflation, using a vacuum pump to speed up the cycle time. This scheme was found to be the most effective in ensuring that no pressure accumulated over extended periods of time and the timing of inflation and deflation was not exaggerated.

In order to better understand the rocking problem that was seen during the locomotion cycle of the robot, an infrared motion capture test was conducted to visualize the problem numerically. It was found that for every inflation cycle there was a slight backwards motion that seemed to be caused by the way that the actuator was affixed to the device. When the center section was extended, it would push the core backward due to a loose connection between the actuator and the core. Although the problem couldn't be completely eliminated, it was drastically improved by more securely fixing the actuators to the core.

The main focus of the testing conducted on the small-scale device was done so to experiment with control schemes and validate the device as an operation proof of concept. A more complex control system was developed and problems that arose during the initial testing were able to be resolved and accommodated for in the next design, which would be much larger in scale.

Chapter 4

LARGE SCALE DEVICE: DESIGN AND TESTING

4.1 Scaled Up Device Phase

The final design accommodates pipelines 24 inches in inner diameter. In scaling the device we have found that there are other design concerns and issues that were not seen in the smaller scale devices. These issues have led to the use and development of other styles of linear extension, including the use of a metallic pneumatic cylinder, as well as the development of an on-board controller. These modifications were all done in an effort to increase the speed and robustness of the device. The following section delves into the design decisions and modifications to the design and in fabrication and testing, that were made when building and evaluating this large version of the device.

Figure 4.1: This design works in a pipeline with an inner diameter of 24 inches.

4.1.1 Large Scale Device Design and Fabrication

The design of the large scale device varies from the small scale in a number of different ways. The most important difference is the use of a pneumatic cylinder actuator rather than a stack of smaller toroidal actuators. The integration of electronics means that the device is no longer limited to the test bench. Finally, an optical camera system was designed in order to allow the operators of the device to more closely investigate the pipeline while operating the inspection platform. All of these design changes raised issues with the mechanics of the device and so a discussion about those issues takes place in this section. While the device remains a scaled-up version of the first iteration, there are significant changes that ultimately required further consideration for the operation of the device. The integration process for the large scale device was less intensive than the smaller device, because most of the large components such as the inner-tubes and rigid core components were purchased rather than fabricated in the lab. Developing a thorough CAD model of the device also made 3D printing specialty components such as the bushings and end caps much easier than trying to source them from a vendor. Thus our tasks integrating the final device focused more on assembly than fabrication.

4.1.1.1 Design and Fabrication of Large Scale Rigid Core

The rigid core changed significantly from the small scale device, both out of necessity and the desire to optimize the design in terms of materials and cost. The large scale rigid core is made out of different diameters of Schedule 40 PVC pipe that is generally used for plumbing. The large side of the telescoping component is size 6 PVC pipe (6” inner diameter) while the small side is made out of size 4 PVC pipe (4” inner diameter). In order to close the gap between these two pipes, bushings were

3D Printed with a 0.007” tolerance from the outside edge of the bushing to the inside edge of the large diameter pipe. Two bushings spaced approximately two inches apart were used in order to prevent the center section from bending while the device is in an extended state. 3D printed mounting plates connect the pneumatic cylinder to each of the pipes to complete the telescopic mechanism. All of the customized components in the rigid core were 3D printed with PLA filament, due to the ease of printing. The 3D printed parts were secured to the pipes with both friction fittings and stainless steel hardware.

The ends of the rigid core are flat plates with concentric rings that clamp down the sleeve of the toroidal actuators in order to secure them to the core. The process of mounting the actuators involves lining up holes in the sleeves of the toroidal actuators with holes in the clamp rings and end-caps which are then secured using bolts. This design varies from the small scale design because the plates no longer provide a channel to hold the actuator. Instead, the only interface between the actuators and the rigid core is the clamping of the sleeve. The end caps fit into the ends of each pipe and are secured into place with a friction fit and alignment bolts. Through the center of each end cap there is a hole that can be used to mount sensory equipment, such as the optical camera or to run a tether through. The camera system is mounted on a platform that shares the same curve as the inside of the end cap hole, this allows the camera to be sitting centered and leveled in the device. This platform is secured to the end cap with a bolt and can be easily removed or replaced with another device. The last accessory for the end cap is a clear acrylic hemisphere that attaches to the mounting ring of the toroidal actuators and provides transparent protection for the equipment mounted inside the end cap. Fig 4.2 shows the 3D CAD model in an exploded view with each part labeled.

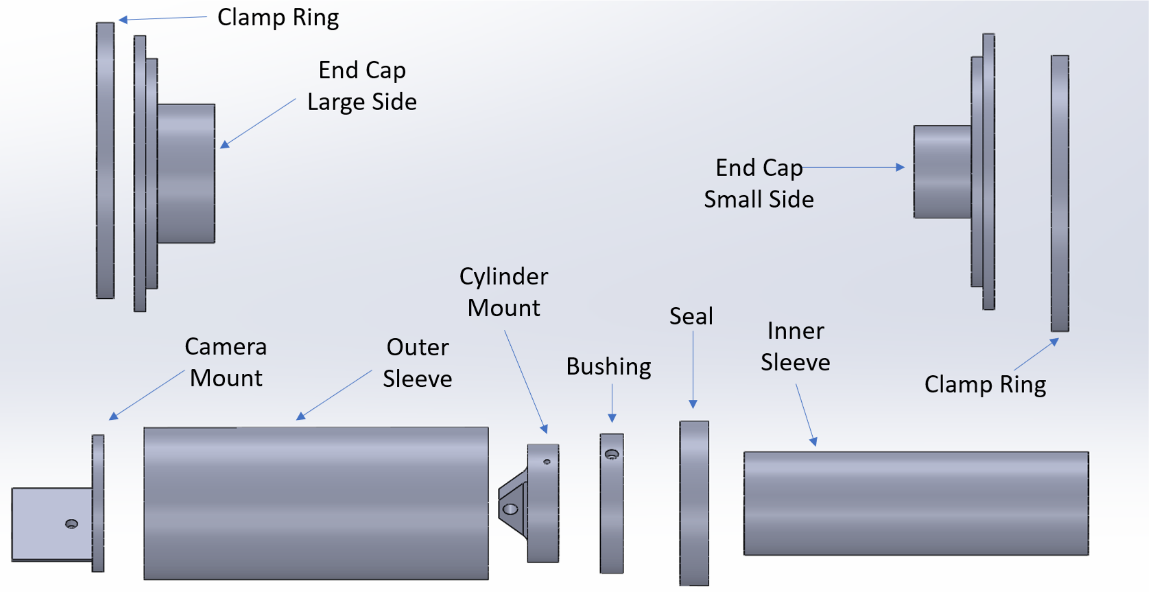


Figure 4.2: This figure shows all of the parts in an exploded view with part labels.

4.1.1.2 Design of Large Scale Toroidal Actuators

The soft toroidal actuators for this large scale version of the inspection platform were so large they could not be reasonably manufactured by the methods previously described to manufacture the scaled down prototype. In order to develop these large actuators, rubber inner-tubes used for the wheels on an all-terrain vehicle were sewn into an extensible sleeve that was attached to the end caps of the rigid core. These inner-tubes matched the exact size that was needed in order to anchor the inspection platform to the pipeline. These inner tubes and were commercially manufactured out of a rubber which provides more extension and mechanical strength than the actuators that are manufactured using TPU in-house. This eliminated nearly all of the trial and error steps to fix leaks that are typically used when manufacturing actuators in-house. The inner-tubes were manufactured with a single air inlet port that contained a Schrader valve. This valve was removed in order to allow the free passage of air into and out of the tube. Removal of the valve ensured that only the only flow restrictions were from the control system and not the actuators themselves.

For the purposes of testing the actuator in the laboratory environment, the inner-tubes were encased in a fabric sleeve made of elastic or extensible material. This allowed for actuator robustness while developing the control system. The choice to use an extensible material is only practical in a controlled testing environment where there are no occlusions in the pipeline, as the elastic material will not assist in preventing the inner tube to rupture if it is bound or exposed to sharp objects and surfaces. In the pipe a sleeve made out of non-extensible ripstop nylon could be used in order to help reduce wear on the actuator as well as convert the actautor into a inextensible actuator. Besides acting as a thin layer of protection for the inner tubes, the sleeve limits how much air the actuator is able to hold during inflation. With the extensible sleeve, the actuator is able to inflate to a volume far beyond what is actually needed to anchor the device into the pipeline. The benefit of the extensible sleeve for the purposes of testing is that it will not rip if the actuator is exposed to too high of a pressure. When testing the control system with the actuators attached, if the pressure and volume became too great the actuator would simply keep increasing in volume. If a sleeve made out of non-extensible ripstop nylon was used during testing, the fixed volume feature of the material would cause the actuator sleeve to rupture, rendering it ineffective if the pressure got too high. The drawback to having an extensible sleeve containing the inner-tube is that the actuator is prone to rotating and rocking around the end-cap. Since the sleeve provides the mounting interface to the end-caps, any extensibility in the mounting points allows for the flexion and misalignment of the actuator in the pipeline.

4.1.1.3 Fabrication of Large Scale Toroidal Actuators

The toroidal actuators that are used in the large scale pipeline are much easier to manufacture than the small scale version of the device, mostly because the air tight component has already been professionally manufactured. When the inner tubes are purchased they already have the air inlet port pre-installed, reducing the likelihood of damage to the actuator during development, but the sleeve still needs to be sewn into place around the inner tube. Two large pieces of fabric are stacked around the inner tube, with one being below and the other being above the inner-tube. The pieces of fabric are sewn together as close to the inner tube as possible without poking holes in it. The center radius hole was sewn first in order to decrease the difficulty of sewing the outer seam. Once the seams are sewn, the excess fabric is cut away, leaving enough room for the seam to attach to the end caps of the device. The inner-tube valve, that allows for the inflation and deflation of the actuator, needs to be exposed outside of the sleeve. A hole is cut out of the sleeve in order to allow the valve to pass through. Once the inner-tube is fully encased in the sleeve, the actuator is mounted to the end caps and and hooked up to the pneumatic supply line.

4.1.1.4 Design of Pneumatic Cylinder

The pneumatic cylinder was used in the large scale device because of the need for reliable and rapid extension and retraction. While not considered a soft air actuator, it is still a pneumatic component that converts pressurized air into mechanical movement. A single soft air actuator was initially used for extension while elastic bands were used for retraction, but this concept was abandoned because the soft air actuator needed to overcome the tension in the elastic bands in addition to the extension force required to propel the device down the pipe. This initial concept caused numerous issues, including the need for higher pressures which caused the elastic bands to rapidly fatigue, lasting only a few dozen cycles before they fatigued to the point of yielding. In order to combat this issue, we proposed two options: the development of a double acting soft air actuator or the use of a dual-acting pneumatic cylinder. Our rationale for this design change is that a dual-acting design would permit both extension and retraction rather than relying on an elastic tensile force to retract the device. In order to increase the reliability of the device, we selected the pneumatic cylinder option.

The selected pneumatic cylinder is a double-action all metal cylinder with a maximum pressure input of 150PSI. With a bore diameter of 2.5" the cylinder can exert forces up to 735lbs or 1370N of force, which is much more than what is needed for either the extension or retraction of the device. The actuator's stroke length is eight inches, it is directly mounted between the two telescopic pipes, the full eight inches of actuator stroke can be used when integrated into the device. With this fixed stroke length, any improvements in overall device speed would require increasing the velocity of the pneumatic actuators.

4.1.1.5 Design of Integrated Electronics and Control System

The test platform that was used to characterize the small scaled device is comprised of electro-pneumatic devices that allowed for the precise control of the direction and pressure of the air flow. This system has air flow limitations because the lengths of the pneumatic supply tubes are very long. This system was designed to be used with relatively low-volume actuators, which limited the small-scale prototype's overall speed and size. When the large scale device was controlled by the test platform, the restricted air flow of our pneumatic control system made it nearly impossible to fully exhaust the toroidal actuators in order to release the anchors and create a uniform and repeatable locomotion cycle. The test bench provides a well-characterized and repeatable control environment consisting of an electro-pneumatic control system with GUI-based, drag and drop programming to quickly and easily implement new steps or loops into the locomotion cycle. Due to the large, non-fixed volume of the actuators, the test bench was not able to supply the volume of air required to operate the large prototype.

The on-board pneumatic control system implemented in the final device consists of six electro-pneumatic valves, a mechanical regulator, three air pressure sensors and an arduino mega 2560 microcontroller. Two valves are required per actuator, and one sensor is required per actuator or chamber. In order to amplify the control signal to each of the solenoid air valves from the microcontroller, six MOSFETs were used at the output pins in order to selectively switch the air. The air pressure sensors are differential sensors that compare the applied air pressure from the pneumatic supply line to the ambient pressure in the form of a 0-5V linear analog voltage which provides scaled readings from 0 to 150 PSI. Two pulse-width modulation output channels were used to control the camera's pan-tilt servos. The arduino mega 2560 was selected for the ample number of digital I/O pins, its zero to five-volt operating range which was compatible with the other hardware, such as the MOSFETs, air pressure sensors and servo motors.

4.1.1.6 Fabrication of Integrated Electronics and Control System

The control electronics used during this project were assembled from various evaluation boards and kits in order to make it easier to replace any components that burned out during testing. During testing this issue occurred frequently, as the MOSFET evaluation kits were very susceptible to static electrical shock, resulting in the channels burning out after only a short time. All of the connections made between the evaluation kits were made with jumper wires and female headers, rather than soldering any connections together. Encountering wire disconnections was preferred over the difficulty of repeatedly re-soldering connections. The evaluation kits were fixed to the exposed face of the end cap with hot melt adhesive. This was done in order to have easy access to control electronics during the prototyping and early testing phase of this project, but would not be ideal when the device is run in a more realistic environment such as an SRP pipeline. The best way to fabricate the electronic control system would to manufacture custom PCBs that have all of the required electrical components, as well as static discharge protection circuitry on-board. This solution would require more time in the design phase, but would free up more space on the device, and is a necessary step when moving towards water proofing the device for further environment testing.

4.1.1.7 Design of Camera System

An analog output optical camera attached to a 9-gram, servo driven, pan-tilt mechanism was integrated into the system to provide the end user with live video feed from the front of the robot during locomotion, and are controlled by the same atmega microcontroller. The camera signal is sent to a screen held by the operator via a separate hand-held controller. This controller has a joystick that can be used to control the pan-tilt servos, so it also needs to interface with the control arduino, which will allow it to start and stop the device in order to inspect potential issues more precisely when they arise. The interface between the system and the controller is a wired connection utilizing a thin cable with shielding.

The pan-tilt mechanism is a plastic housing that holds the camera and two micro servo motors. Each servo is capable of turning 180 from left to right and approximately 130 from bottom to top. The movement range from bottom to top is limited due to mechanical restrictions in the mechanism design. Nevertheless, the camera is capable of capturing the necessary pipeline area in front of the device. The servos are powered by the five volt regulator on the Arduino development board; the current consumption for each servo falls is nominal due to the light loading conditions that the servos are subjected to. In order to control the servos, the Arduino converts the analog input from the joystick on the hand-held controller and maps it to the specified pulse width range required by the servos. This allows for fast and precise control of the camera's orientation. The camera operates on 12 volts DC and is thus connected directly to the valve power supply. The camera, which is sold for use in remote controlled aircraft, outputs in the commonly-used analog NTSC signal. A noticeable amount of parasitic effects were observed, possibly due to the long length of cabling that is used to send the signal to the controller. A shielded ethernet cable was selected to minimize external interference from affecting the signal, but did not completely mitigate the signal loss over the long cable length. Improvements could include amplifying the signal voltage before it is sent or converting it to a digital signal and transmit with very minimal amounts of current, similar to the protocol used in computer networking practices. Both of these options would have required additional circuitry and were not implemented on the prototype.

4.1.1.8 Design of User Interface Controller

The hand-held controller is the primary interface between the operator and remote device. It was designed around a seven inch LCD screen that is powered by a portable battery pack and can receive an NTSC video signal display real time images. Viewing live images on the controller is the main method that the operator uses to inspect the pipeline for cracks, using the camera pan-tilt features to narrow in on potential problem areas. Therefore, it is necessary for the controller to have start and stop control for the device, along with the directional control of the camera all while watching the camera output as a live video feed on the screen. Due to the long length of cable that will be used between the cable and the controller, analog sensor signals will have serious issues retaining their fidelity throughout the cable run. In order to increase the signal-to-noise ratio while maintaining low latency, most of the signals that are generated by the controller were digitized in the hand-held controller by the on-board arduino pro micro and sent to the arduino mega on-board the device via the UART protocol, and decoded for interpretation by the robot. This allows for quick and high fidelity signals to be communicated between the device and the controller. Digitizing the signals on the controller is not an intensive task, the buttons that control the motion of the robot are attached to digital I/O pins on the arduino and pulled high.

The best way to digitize this signal is to use an integrated circuit system that can encode the analog signal directly from the camera and then using the same model of IC, decode it in the controller and output it to the screen. Using this method of signal transmission, there are numerous options for controlling speed and signal fidelity, even going as far as as to transmit the video using different error correcting protocols such as differential signaling. There are other methods to effectively transmitting video data from the device to the controller including using wireless video feeds, however, because there is already a tether going to the device, to supply it with power and air pressure, better video quality will be attainable if the signal is transmitted over a wire.

4.1.1.9 Fabrication of User Interface Controller

The handheld controller used by the operator to control the device was designed to allow for the incorporation of additional controls to accommodate any different sensors used during the pipeline inspections. There is room on the controller to add in additional switches and physical controls if additional features are added to the device. The controller is 3D printed with PLA filament, and provides a sturdy and accessible shell for the seven inch screen that displays the live video feed. The top half of the controller contains all of the cutouts and holes for the buttons and screen while the bottom half provides a mounting surface for the controller electronics, including the power supply and arduino pro micro. Assembly of the controller involves attaching the electronics to the bottom of the frame with hot melt adhesive, proceeded by wiring all of the electronics together and plugging in and placing the screen in its designated mounting surface. The controller's shells are secured together using bolts, which keeps the controller sturdy but allows for rapid disassembly when needed.

4.1.1.10 Design and Manufacturing Challenges when Scaling Size

There were numerous challenges with the design when choosing to scale it up four times in size to accommodate a 24" inner-diameter pipeline. For the full-scale prototype, the tubing, connectors, and solenoid-driven pneumatic valves were resized to allow for the nearly 1600 cubic inches of air that are needed to inflate the actuators and to provide a much faster inflation rate. Due to the large amount of air being handled by this device, the filling and discharge time for each sequence was also greatly impacted. In the acrylic laboratory pipeline, the internal actuator pressure reached only about two to three PSI, resulting in extremely slow actuation speeds. Even with a 20PSI pneumatic supply, it still took over ten seconds to fully inflate the actuator. Because the cycle doesn't require each actuator to be fully deflated before moving to the next step, there can be a time savings after completion of the first full cycle. Even with this savings, the device still moved far too slow to be effective for long-run pipeline inspections. In order to mitigate the issue of speed in the device, further options will need to be explored, such as adding a constant flow rate vacuum pump line to the exhaust ports of the valves, in order to speed up the deflation of the actuators. Another potential solution could involve adding a second connection to the actuator to act as a dedicated exhaust port with shorter pneumatic tubing runs which exhaust straight to the atmosphere. Increasing the tubing diameter will allow more air to flow to the system, increasing the efficiency of the locomotion. Each of these improvements would help to increase the effective pressure change inside the actuator in order to reduce the time it takes to complete a single locomotive cycle.

A lot of the components that were necessary for the design of the large scale device design were too large to be built in the laboratory. The sheer size of the actuators require more expensive and larger equipment than what could reasonably fit in a lab space. Instead, alternative methods and items had to be implemented, such as using inner tubes as actuator components rather than creating our own. The solutions to overcoming some of these scaling issues do pose issues with further prototyping and testing since most of the materials used for the actuators have changed.

4.2 Testing of Large Scale Device: Lab

The testing of this device has been limited to the laboratory with parameters that don't accurately reflect the conditions that will be seen during environmental testing. The laboratory test scenario is primarily focused on verifying operation and measuring the speed of the locomotion. Though locomotion speed is the only quantitative measurement taken in the lab, qualitative observations can be made. Such observations may include rocking, actuator tilt in the pipeline and over inflation, but, these observations do not need metrics to determine the severity of the problem. The very existence of such issues is detrimental so defining the extent of the problem quantitatively is less important, especially as there are no quantitative specifications defined for the current project.

The test pipeline that was used is a five foot long section of 24" inner diameter transparent acrylic pipe with a wall thickness of 0.125 inches. This represents the target pipe size identified by our funding partner, SRP, and provides enough linear space for the device to move several stroke lengths from one end to the other. In order to test in this pipeline, extensible actuators had to be used in order to prevent over stressing the pipeline itself. When testing the control scheme, if the air pressure in the actuator exceeds the desired testing limit with the extensible actuators, they will just grow in size. With non-extensible actuators, however, if the pressure increases beyond a specified limit, the fixed volume attribute of the actuators can cause extremely high air pressures inside the actuator, matching the incoming air pressure from the pneumatic supply line. In this scenario, the actuator will most likely rupture and may exert a significant amount of force on the acrylic pipeline, which it is not rated or designed to withstand. In order to preserve the testing environment, extensible actuators were used exclusively when working inside the acrylic pipeline. There are known issues with using extensible actuators, such as actuator tilt and the lack of a fixed volume, but these issues are likely to be solved once the non-extensible actuators are installed for later testing in a more robust testing environment.

Chapter 5

CONCLUSION

5.1 Results Discussion

The main contribution of this project to the field of Soft Robotics is the ability of the device to be used in an industrial environment such as a hazardous pipeline. This device takes a novel approach to moving through a pipeline while overcoming occlusions and debris. The primary contributions of this thesis are to consider whether this type of locomotion using soft techniques is feasible and to determine the design considerations that are necessary for locomotion in the pipelines. The main method for proving functionality is the qualitative approach of testing and verifying that there are no issues with the locomotion cycle. The main metrics that describe the general performance of the device are the size of the pipe that the device can operate in and the speed at which it operates. These two metrics provide enough information to make assumptions about the progress and performance increases that are brought about by design improvements and modifications to the control scheme.

5.1.1 Validity of Research

The main research goal of this project has been to expand the applicability of soft robotics to heavier industrial tasks and devices. By creating this device and proving its efficacy as a locomotive inspection platform, soft pneumatic actuators have the opportunity to perform work in the same environment that was once even off limits to traditional rigid robotics. As the project continues and this device is improved and tuned for operating in industrial conditions, the speed and ability to overcome large obstacles will also be improved. This will help expand the potential uses of soft robotics from mainly medical devices into much larger and more hazardous industrial environments. When the concept for the toroidal soft air actuators was first conceptualized, a method of evaluating the actuators was needed in order to prevent the wasting of materials and time. A 3D CAD parametric model was developed to provide an FEM analysis for the actuators before they were made out of fabric and TPU. While this model is not yet able to measure the forces exerted by the actuator onto different surfaces, it is capable of qualitatively displaying the displacement that occurs when the actuator is inflated at different air pressures. This model will be further developed in order to better estimate the parameters for each size of actuator that is developed. Along with new material testing, this model will allow for experimentation of using different materials in actuator construction, and being able to determine which materials are appropriate for different applications, ultimately helping to improve future versions of these and other soft robotic actuators.

5.1.2 Device Validation

The device itself was designed to meet the needs of an inspection team, who are currently using rigid robots to navigate the pipelines. The qualitative metric set for the validation of this device is whether or not it is successfully able to navigate in a pipeline. All of the quantitative metrics; such as speed, are intentionally secondary to the ability of the device to complete its locomotion cycle and move forwards in the pipes. Using the standard that we have succeeded, the device is able to move down the pipeline while carrying sensor packages for operators to use during the inspections. The device has been proven to be qualitatively effective and when the work on developing this project continues, improving its performance against quantitative metrics will be a priority, as there will already be a device proven to work.

5.2 Soft Robotics in Industrial Applications: Contributions

The most significant contribution that this work has created is the applicability of soft robotic systems, which are generally not seen in heavy duty use cases, to industrial applications. This bridging of these two fields allows for further expansion into the industrial applications with the desire to increase the integration of robotics and humans working together. Everything from the materials used to the methods of manufacturing these actuators can be applied to other soft robotic systems that are going to be installed in industrial environments.

5.3 Lessons Learned and Design Intuitions

The following list lays out the most important lessons learned during the design and testing portion of this project and thesis. These lessons can be translated to other soft robotic systems, especially those that utilize a large volume of air or are being implemented in an industrial environment.

5.3.1 Summary of Insights

- It is easiest to achieve linear peristaltic motion or extension and retraction with a dual acting pneumatic actuator.
- Extensible actuators should be controlled using more advanced control techniques such as flow control.
- Inextensible actuators must have mechanical constraints that can sustain the force generated by the actuators internal pressure across the entire surface area of the actuator.
- Too much friction between the actuator and the pipeline will cause issues with the device rocking or getting stuck in the pipeline.
- Too little friction prevents the actuator from anchoring into place and prevents the device from locomoting.
- The interface between the actuator and the rigid core needs to be inextensible or misalignment can occur and poor anchoring to the pipeline will result.
- Air exhaust lines or ports should be as short and as close to the actuators as possible in order to reduce the negative impact of flow dynamics in the system.
- Using pressure control for the inflation cycle will allow a higher volume and pressure of air into the actuator, decreasing the inflation time and increasing the speed of the device.
- Pressure based deflation will leave a significant volume of atmospheric-pressure air in the actuator which will still cause friction issues while locomoting. Vacuum powered, time-based deflation will provide the quickest controlled air evacuation.

- Air pressure sensors should not measure pressure when connected to the main actuator air inlet. This can cause inaccurate readings of air pressure and lead to nonfunctional control schemes.

5.4 Future Work

There are several areas in the design that can be modified in order to improve the overall performance of the device, to make it easier and more efficient for the operators to use. The key areas include modifications to the design; improving the pneumatic supply line system and changing out the current pneumatic cylinder to one with a longer stroke length, consolidating the control electronics onto a single PCB, and conducting more testing to continue looking for areas to improve in the system.

5.4.1 Design Modifications

The biggest design modification that can be made in order to increase the effective speed of this device is to increase the stroke length of the pneumatic cylinder. The stroke length has a direct effect on the amount of distance that the device extends and retracts per cycle, with very little impact on the volume of high pressure air that the device utilizes. A pneumatic cylinder with a longer stroke length should be installed into the device in order to increase the effective speed of the device, if that is the desired parameter to improve. Another item that has a large impact on the speed performance of this device is the configuration of the electro-pneumatic components that control the flow of air. In order to allow for faster exhaust times for the toroidal soft air actuators, the distance that the air has to travel to be released to the atmosphere needs to be as short as possible. Relocating the valves closer to the the actuators will allow them to deflate much faster, thus reducing the cycle time of the device. Another modification to the actuators that would have a similar affect would be adding a designated exhaust port on the actuator itself, rather than sharing a single port for inflation and deflation. This setup would also allow for the more optimized placement of the air pressure sensor. The placement of the air pressure sensor on port that is not directly connected to the air pressure supply line would allow for more precise measurements of air pressure and would allow the inflation segment of the locomotion cycle to be continuous while concurrently measuring the actuator internal pressure. This would replace the method of measurement that is currently in place which requires that the high pressure air supply be turned off momentarily in order to measure the internal actuator pressure. While this new measurement method may not save as much time as the exhaust time reduction, it will allow for more precise inflation of the actuators.

5.4.2 Consolidated Controls System

Designing a PCB that contains all of the necessary control electronics in one place will allow for a tidier device that allows for easier disassembly and maintenance. Developing this PCB will not intentionally decrease the cycle time of the device, however, but would be necessary for the next step of development which will require proper water-proofing of the inside of the device. This control system PCB would not only be applicable to this device but would be a practical control system platform for most pneumatic robotic systems, especially if the design could be scaled to accommodate more valves. Having all of the inputs and outputs on a single PCB would eliminate numerous physical connections that have the possibility of becoming unplugged during operation, and will allow for the use of custom plugs on the wires that do need to be run to different components. Overall the consolidated control electronics system will be very effective at making the device easier to operate and maintain, and even though it doesn't directly affect the cycle time, this step is a critical step to accomplish in the future.

5.4.3 Further Testing of Large Scale Device

In order to really flesh out the issues with this device, further testing in the intended environment, such as inside an SRP water pipeline, will be necessary and will provide useful feedback on the design and operation of the device. This testing should be conducted in stages, with an assessment conducted to document the speed of the device and a qualitative analysis of the compliance of the actuators around occlusions in the pipeline. The SRP testing pipeline will more accurately represent the conditions in the intended target pipelines, most notably, the friction force between the actuator sleeves and the pipeline, which plays a major roll in the successful locomotion of the device. This data will drive decisions that might change the design for certain applications, such as tougher or softer sleeve materials for certain pipelines. This testing will also start to incorporate the feedback of the end customers, who will be most impacted by any design decisions that are made, and so it is an opportunity to consider and possibly incorporate further features into the device design.

5.5 Recommendations

The development cycle for this soft robotic platform for pipeline inspections has occurred for just over 20 months and the device is now ready for further use-case testing. This device however is not recommended or ready for for use in a situation that might have detriment to the stakeholders business or assets. The device needs to have the proper modifications, listed earlier in this chapter, made and they need to be validated in a situation that more accurately reflects the end use-case environment. Without further modification and testing it is unknown whether the device will be able to perform optimally with adverse conditions that are not seen in the laboratory setting. Upon the completion of successful testing in a more realistic use-case environment this device has great potential to be put into service inspecting water pipelines.

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APPENDIX A

MECHANICAL DRAWINGS

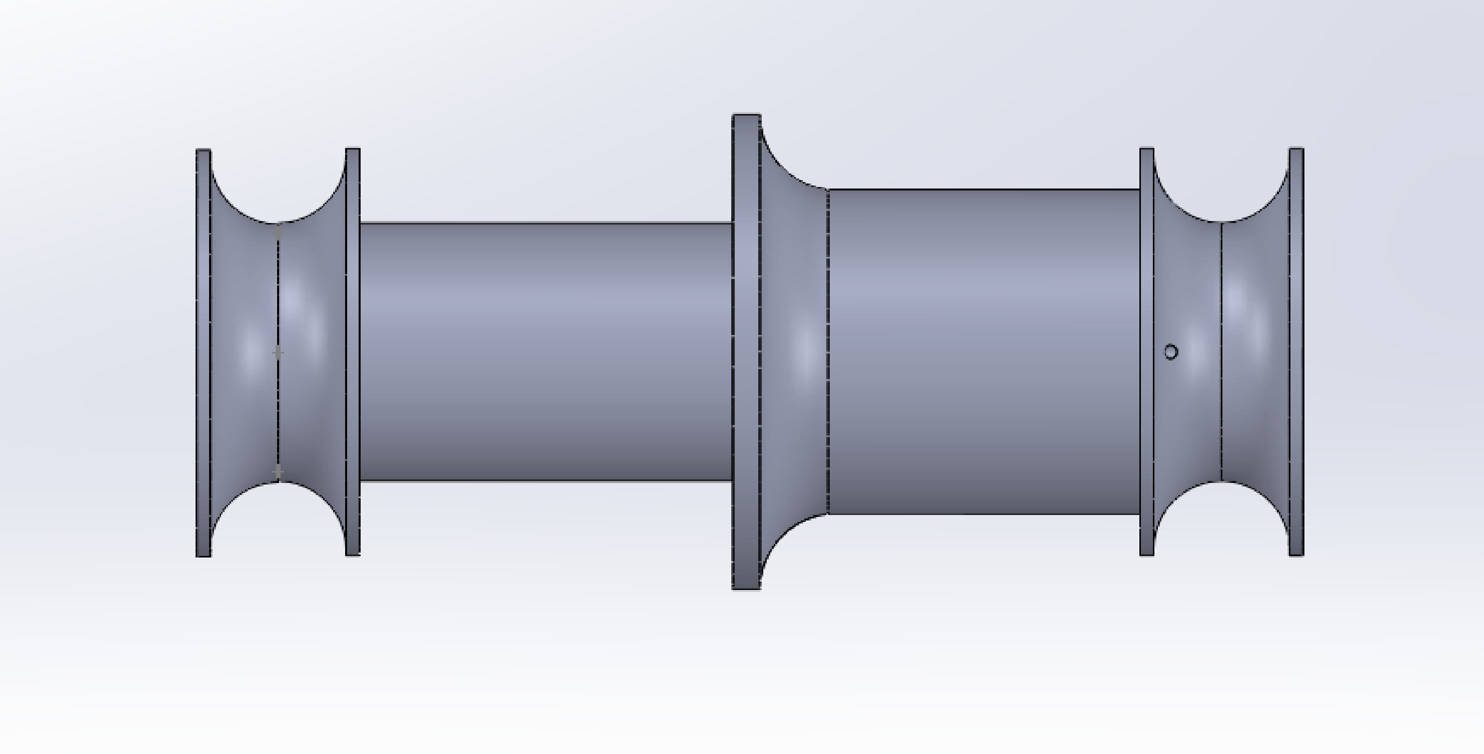

Figure A.1: Side view of the small scale assembly

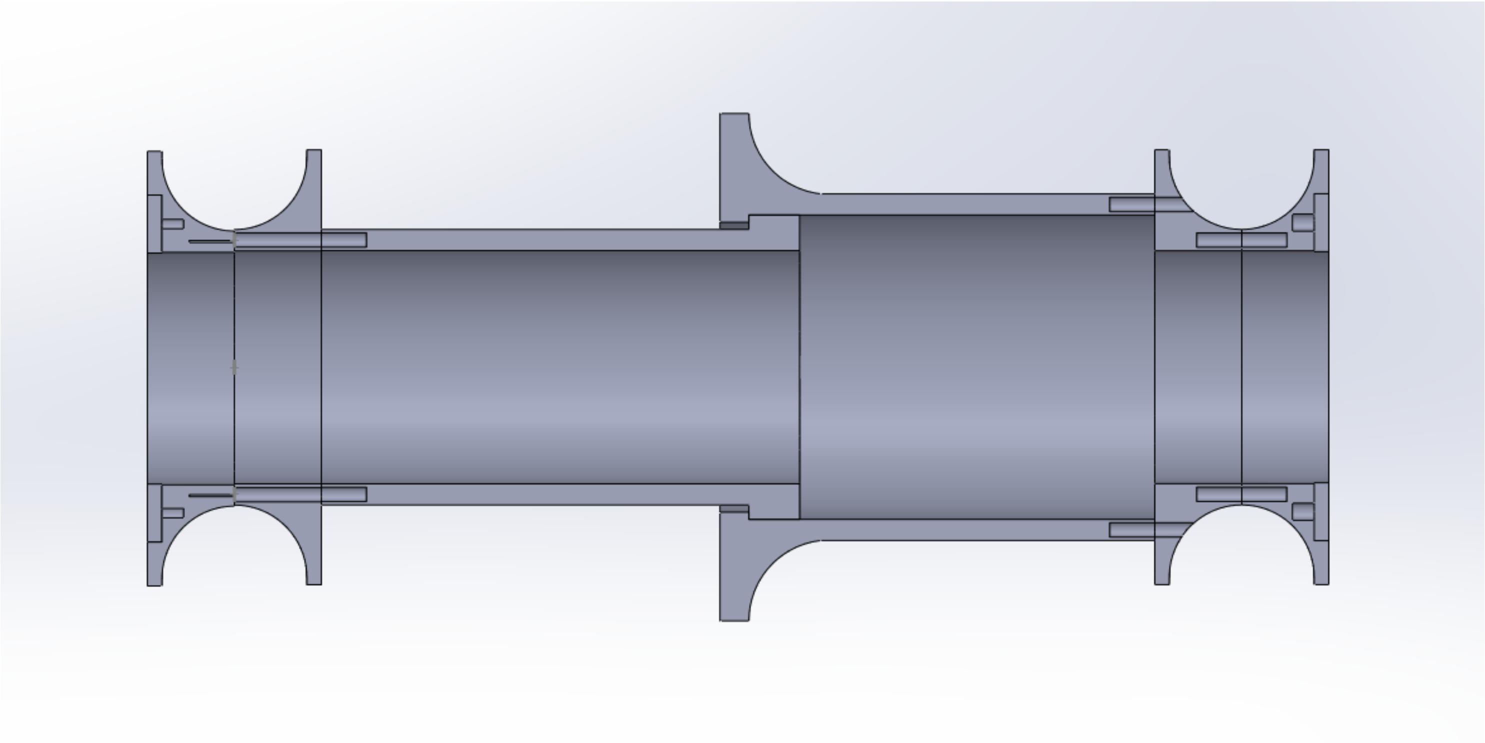

Figure A.2: Cross sectional view of the small scale assembly

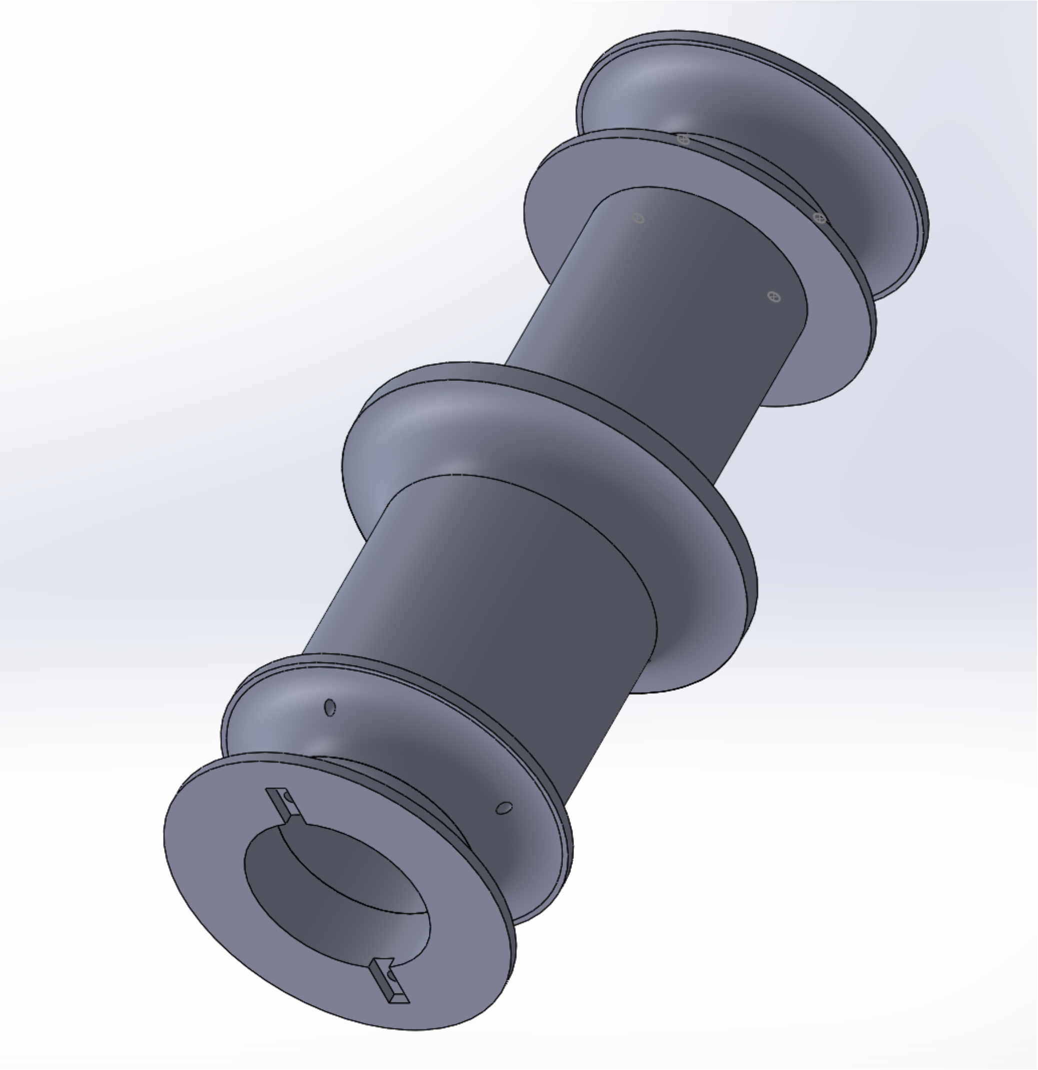

Figure A.3: Isometric view of the small scale assembly

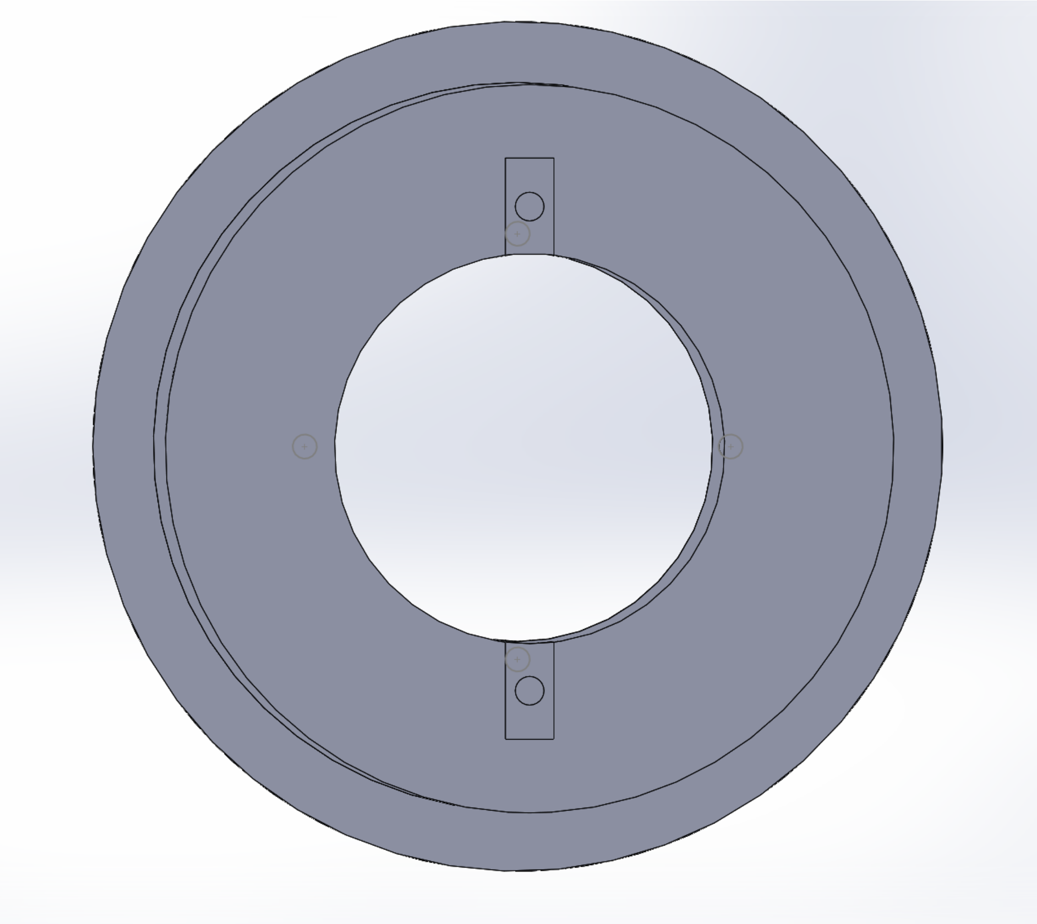

Figure A.4: Front view of the small scale assembly

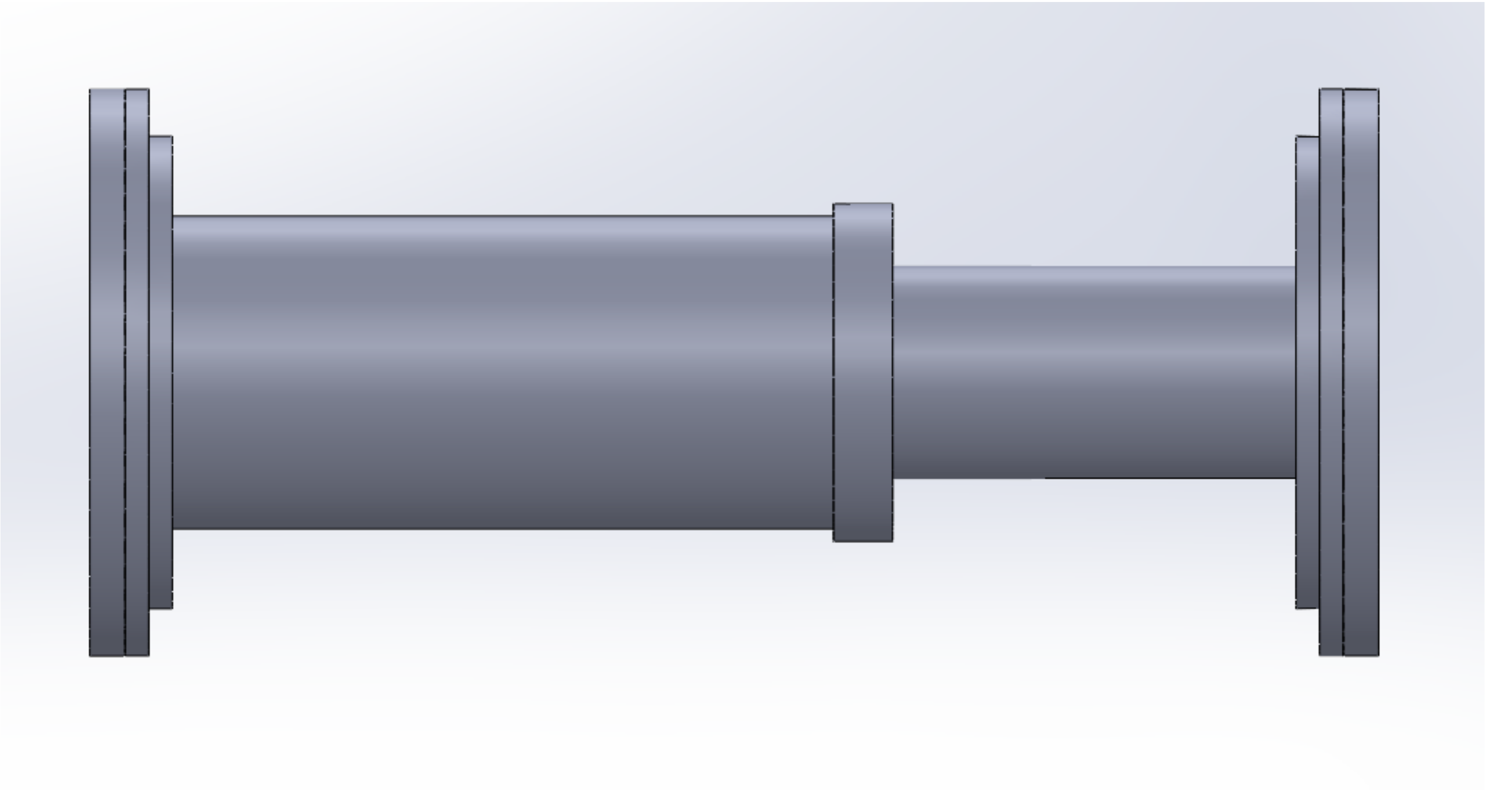

Figure A.5: Side view of the large scale assembly

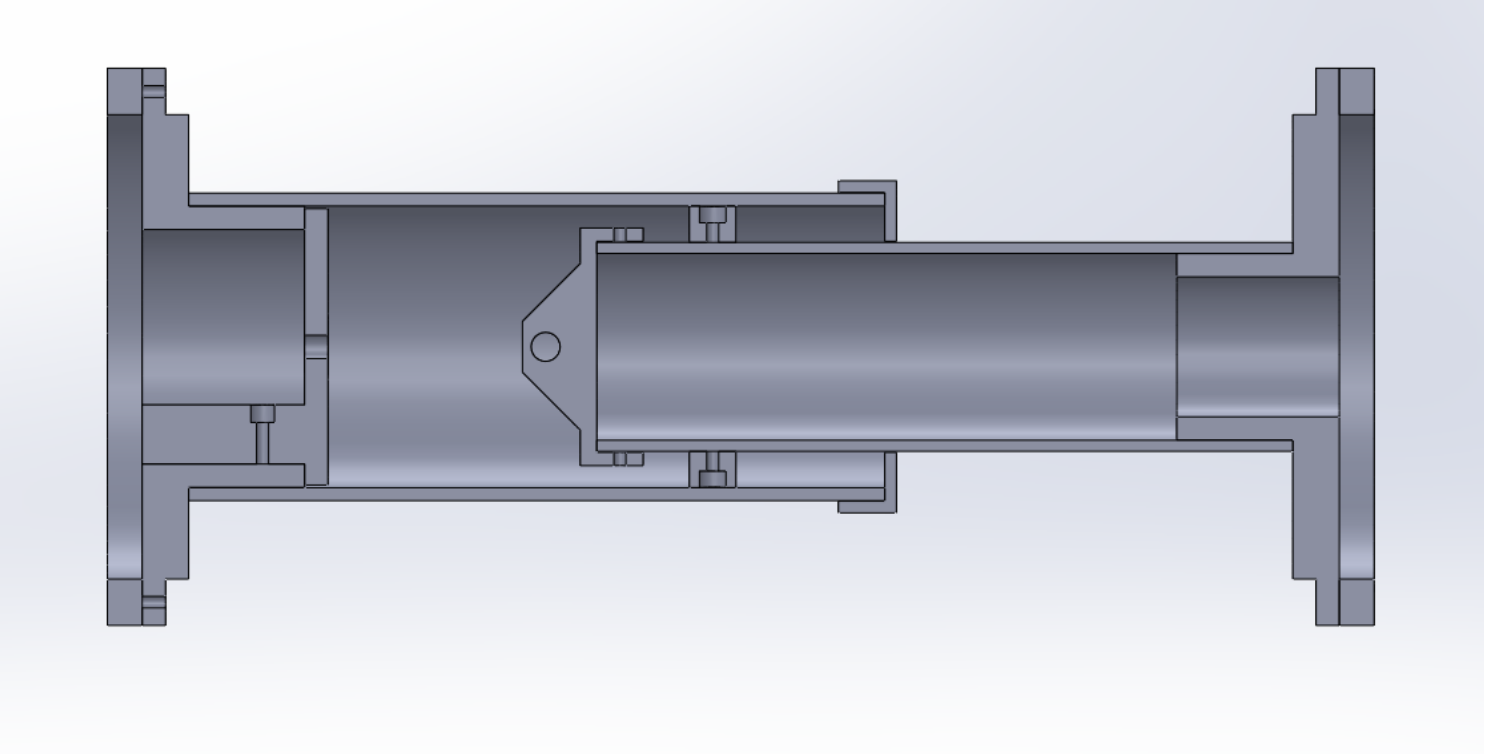

Figure A.6: Cross sectional view of the large scale assembly

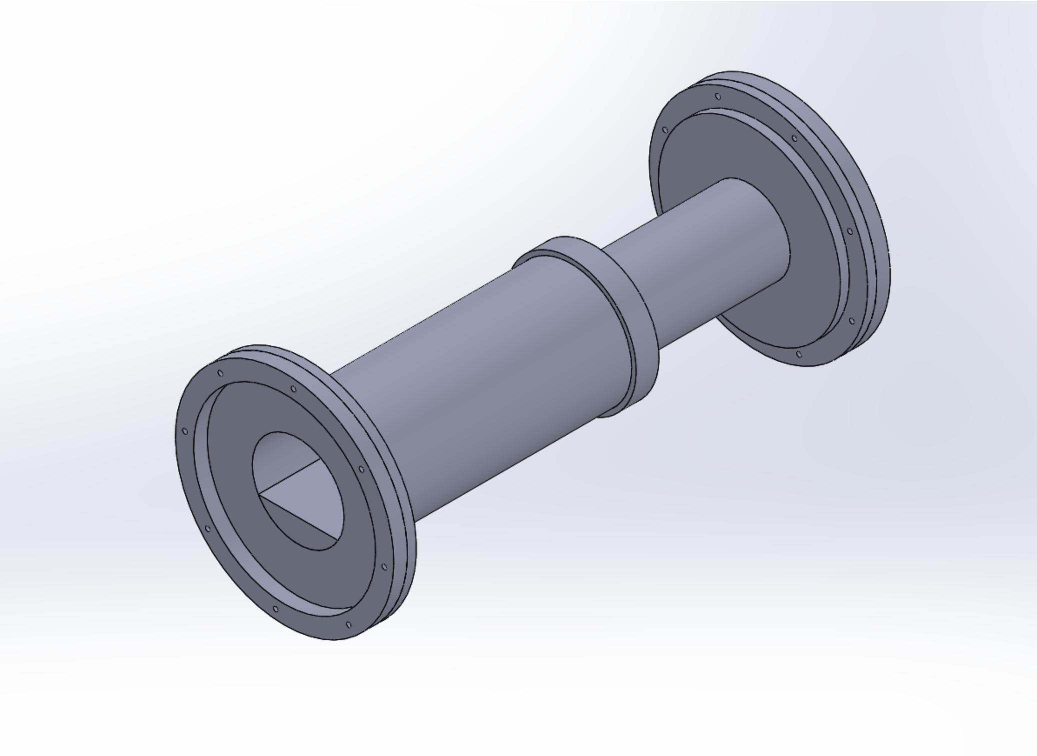

Figure A.7: Isometric view of the large scale assembly

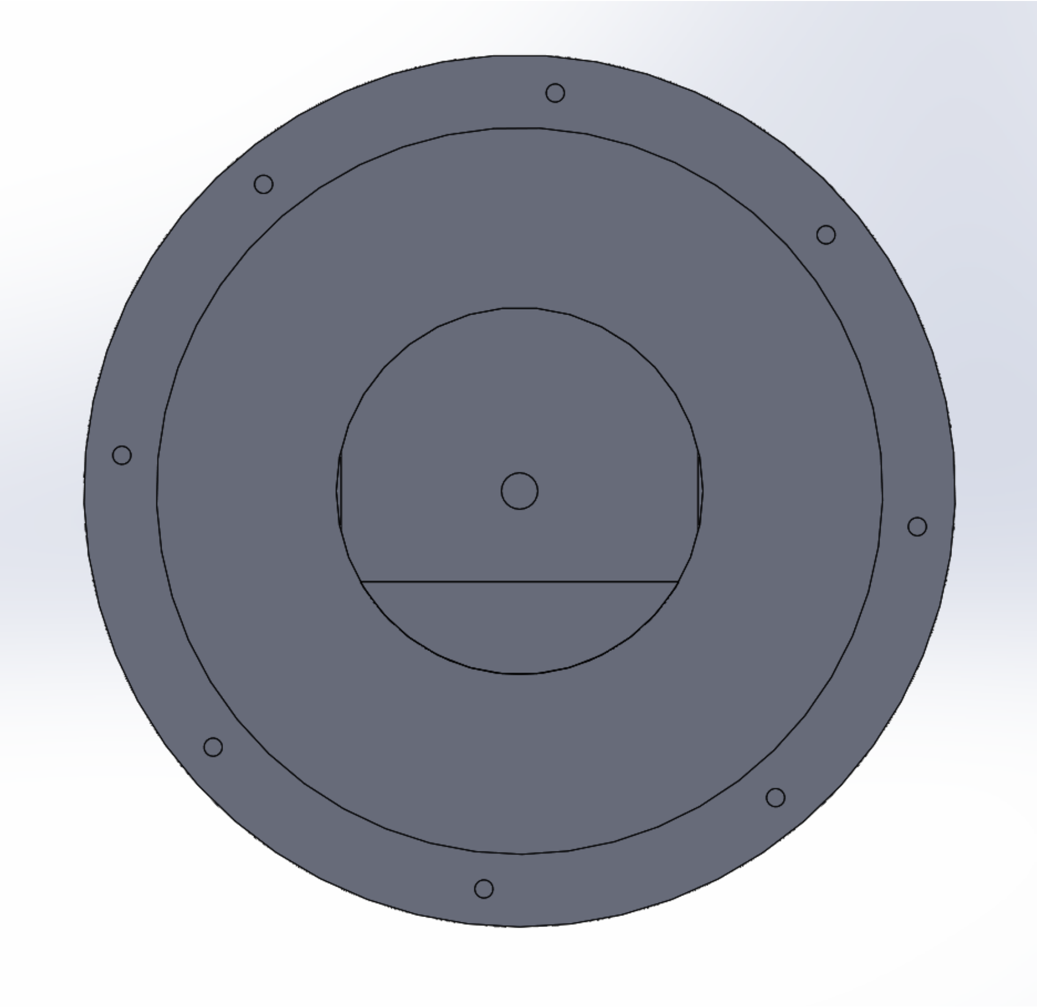

Figure A.8: front view of the large scale assembly