A ROBUST SOFT AND VACUUM HYBRID END-EFFECTOR AND COMPLIANT ARM FOR PICKING IN CLUTTER

by

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ABSTRACT OF THE THESIS

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Robotic grasping has been an active area of research since the dawn of robotics. With recent advancements in artificial intelligence, vision, planning and machine learning, robots are beginning to enter unstructured and unknown environments, such as warehouses.

Warehouse automation and, in particular, picking, is an increasingly popular application domain due to its significance in logistics operations. It usually involves a robot picking a list of items from a shelf, often in parallel with human workers. Different items are usually packed close together in bins and require an end-effector that is small and versatile. Due to the constrained and unstructured nature of the corresponding workspace, sometimes collisions with the environment are not easily avoidable.

This thesis outlines the design and fabrication of a hybrid end-effector that uses both suction and mechanical grasping courtesy of soft-robotics inspired fingers mounted on a flexible arm extension, both of which very robust and capable of sustaining multiple collisions without failure, which could otherwise be expensive and time-consuming. Furthermore, the combination of suction, grasping and soft robotics is a novel idea and offers additional benefits such as low weight and inexpensive components.

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Chapter 1

Introduction

1.1 Motivation

Robots have become commonplace in industrial settings, performing an enormous variety of tasks. Robots are perfect for automating repetitive tasks as they can easily handle heavy loads and offer great precision and repeatability. Robots are also perfect for missions in environments, which would be life-threatening or detrimental to human health. The environments which robots operate can be divided into two main categories - structured and unstructured. The majority of manufacturing environments are highly structured with few surprises. All objects are known and there is little to no uncertainty as far as their position and orientation. In those cases, all robot actions can be easily preprogrammed and then executed as necessary. This results in increased productivity and high-quality goods with very tight tolerances. On the other hand, unstructured environments such as rescue missions, disaster recovery, remote surgery, warehouse picking and others have too many variables and unknowns. This makes such tasks still very challenging to automate and are often accomplished by having a human control the robot using teleoperation. In recent years, however, researchers have been steadily pushing the boundaries, developing new manufacturing technology, sensors, machine learning, vision and planning algorithms. As a result, we are starting to see robots operating independently in unstructured and unknown environments, such as marine robots, self-driving cars, delivery and reconnaissance drones, disaster relief robots and more.

Another area of robotics growing very quickly is warehouse automation. It is a challenging problem to solve due to the inherently unstructured environment, with a large variety of items to be handled by a limited number of end-effectors. A big driving force of innovation in this area over the past 3 years was the Amazon Picking Challenge (APC) in 2015 and

2016, renamed to the Amazon Robotics Challenge (ARC) in 2017. The APC/ARC posed a hard problem to solve because it combined working in a semi-structured environment with grasping in clutter. Participating in the APC 2015 and 2016, as part of the Rutgers ARM team provided first-hand experience with picking in space-constrained cluttered environments and the problems associated with that.

One of the main difficulties is successfully grasping objects of various shapes, sizes, weights and surface textures with just one or two grippers. This problem is further complicated by the limited workspace (e.g. a narrow shelf bin), so an ideal end-effector has to not only be able to handle all objects but also be very compact. As a result of the limited workspace, the probability of collisions between the robot and the environment is high especially on a development system where vision and planning algorithms are constantly being refined and inevitably sometimes contain bugs. With such small clearances between the robot and its environment, even a minimal error in shelf or object detection, pose estimation or planning could result in a collision. Despite the availability of E-Stops and built-in compliance of some end-effectors (e.g. the RightHand Robotics ReFlex Hand [40]) and robots (e.g. Baxter from Rethink Robotics [39]), such collisions often result in serious damage of the end-effector, shelf or both.

The APC prompted a lot of research on grasping and end effectors [16], [18] [15], including our own evaluation and comparison of vacuum gripper vs. a robotic hand [30]. Results suggested that vacuum-based end-effectors are very reliable, effective and compact, however, there were objects, which could not be picked using suction and required a mechanical gripper. In addition, there are reasons to believe that grasps, using taking advantage of both suction and a mechanical grasp, are going to be more stable than grasps which only use either or.

The goal of this work is to develop a novel type of hybrid end-effector, which combines suction and mechanical grasping and can handle collisions with minimal or no damage. The solution outlined in the following chapters was inspired by the rapidly growing field of soft robotics and exploring it was a rewarding and enlightening experience.

The following chapters will define the problem in more detail, briefly cover several alternative solutions which were attempted and provide an overview of soft robotics. Then each component of our solution will be described, followed by an outline of the experimental process, the data gathered and what it revealed.

1.2 Problem Definition

As mentioned above, this thesis aims to alleviate the consequences of the inevitable collisions between robotic end-effector and the environment when picking in clutter and tight spaces, similar to the setting of the APC. Depending on the type of end-effector and its construction the damage may be limited to the shelf, the end effector or both. Some robotic hands, such as the ReFlex Hand, try to improve the reliability and robustness of the hand by using flexible materials for its passive joints. This, however, is apparently not sufficient and we have suffered from broken fingers multiple times. This problem is further exacerbated by the fact that most of the robotic hands available today are just too big for picking objects in clutter. Parallel-jaw grippers are generally more robust and smaller than fingered hands, but in many cases, they fail to reliably grasp certain types of objects. The APC also taught us that vacuum-based solutions can be very compact, simple, effective and reliable but also not perfect as they struggle with porous and heavy objects which require a mechanical gripper.

Most of the available grippers today are built from rigid materials which means they can easily get broken or bent or cause damage to their environment.

The ideal solution to this problem would be a hybrid end-effector, which combines suction and mechanical grip, is long and compact in order to easily reach into narrow spaces and is made of materials which are flexible enough deform during a collision but resilient enough to return back to its original shape. It should also be able to maintain its shape while grasping an object of up to 500g (our heaviest test object weighs 400g). The work outlined here has accomplished all of these objectives.

Chapter 2

Background

2.1 Previous Work on Hybrid End-Effectors

While there has been a limited amount of work on hybrid end-effectors, specifically combining suction and mechanical grasping ([34] [10]) multiple teams participating in the APC hand developed such hybrid grippers.

In 2015 (see Fig. 2.1) Team MIT (2nd place) used a parallel gripper with long spatula-like fingers and a suction cup mounted on the back of one of the fingers and Team Nanyang (9th place) featured a gripper with 2 parallel fingers and a retractable mount with 2 suction cups - parallel and perpendicular to the fingers.

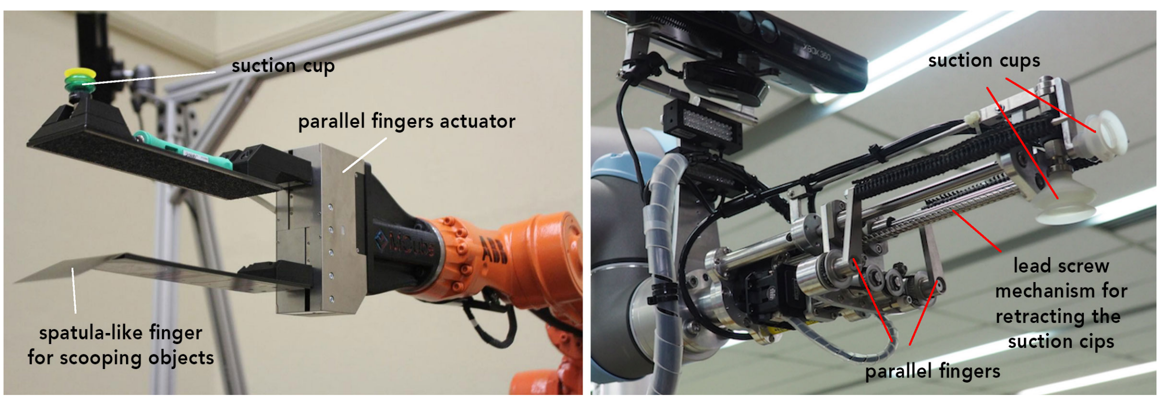

Figure 2.1: Hybrid Grippers used in the Amazon Picking Challenge 2015: Team MIT (left), Team Nanyang (right)

In 2016 (Fig. 2.2) Team Delft (1st place in both Stowing and Picking tasks) [24], participated with a single-armed robot and a gripper comprised of a long and narrow tube terminated by a suction cup which could be rotated 90 degrees. It also featured a retractable pinch mechanism, which acted as an opposable thumb, holding objects by pressing them against the air tube. The gripper used by Team MIT (3rd place in Stowing; 4th place

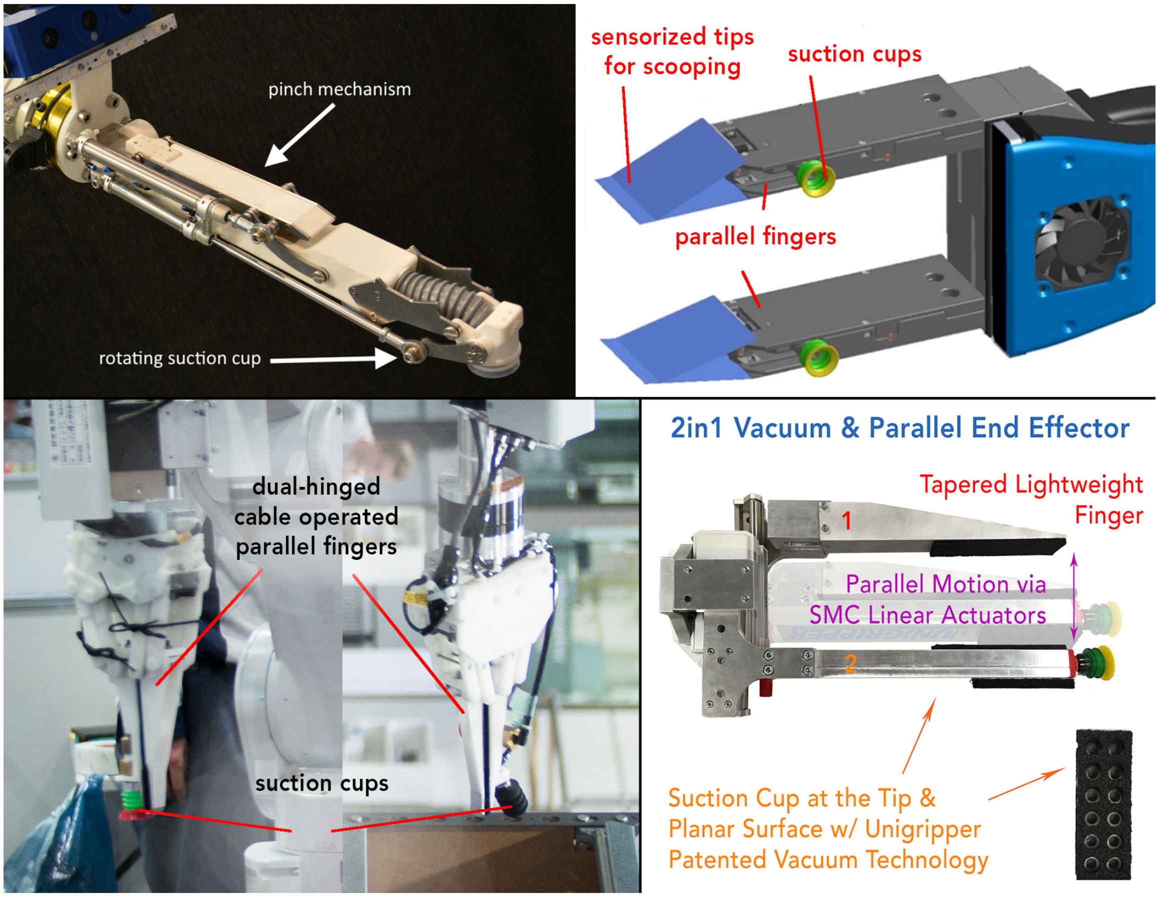

Figure 2.2: Hybrid Grippers used in the Amazon Picking Challenge 2016: (clockwise from top-left) Team Delft, Team MIT, Team Rutgers ARM, Team C^2M)

Picking) was similar to their design from 2015 but featured shorter fingers and suction cups mounted on the side of the parallel fingers. Team C^2M (11th place overall) used two robotic arms and two almost identical grippers. Their design featured long and narrow parallel fingers and one of their grippers had a suction cup mounted at the tip of on one of the fingers and the other had 2 suction cups mounted on one of the fingers - perpendicular to the fingers and at a 45-degree angle. Our team, the Rutgers ARM also developed a hybrid gripper in 2016, however, we were forced to withdraw due to system malfunction. The Rutgers hybrid gripper was designed in collaboration with Unigripper [5]. It featured a parallel mechanism with 2 long and sturdy fingers. One of the fingers was tapered and intended for scooping items, while the other had a suction cup at the tip as well as UniGripper's patented vacuum technology and vacuum foam on the outside. Unfortunately, the gripper was too bulky, due to the large aluminum components and actuators. It was also quite heavy, thus reducing the effective payload of the robot. Eventually, the idea was abandoned and the design was never improved further.

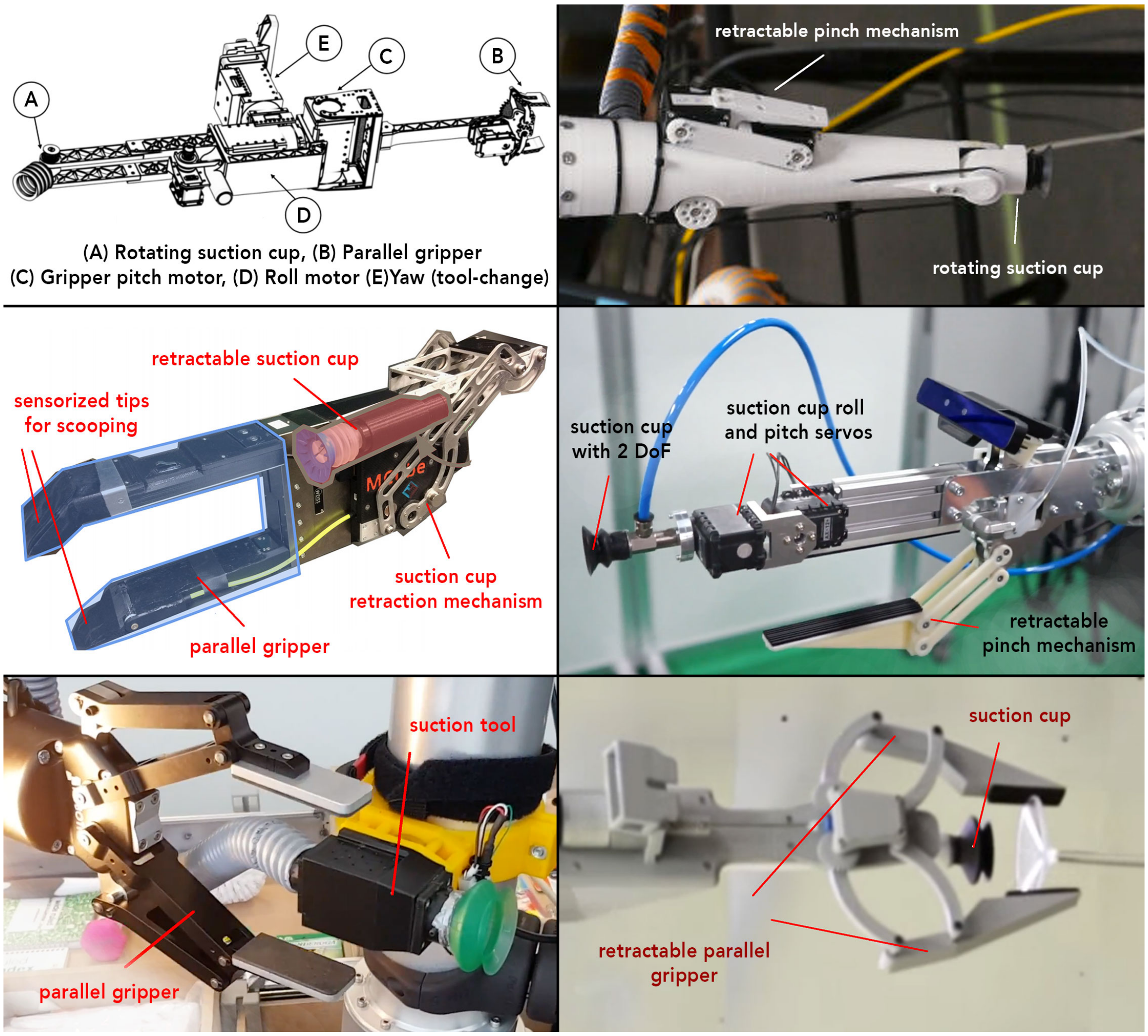

Figure 2.3: Hybrid Grippers used in the Amazon Robotics Challenge 2017: (clockwise from top-left) Team ACVR, Team NimbRo, Team NAIST-Panasonic, Team Duke, Team IFL PiRo, Team MIT-Princeton

In ARC 2017 (Fig. 2.3) the number of hybrid grippers used had doubled. The challenge was won by Team ACVR who used a custom-built cartesian robot with a dual-ended end-effector featuring a suction cup on one end and a small parallel gripper on the other. Team NimbRo (2nd place) employed 2 arms with identical end-effectors consisting of a long tube terminated by a suction cup, which could be rotated 90 degrees and a retractable pinch mechanism similar to the one used by Team Delft in 2016. For Team MIT-Princeton (5th place) the design remained similar as the year before, however, the suction cup was now mounted on a retractable arm and featured a single, larger cup presumably to allow for higher air flow. Team NAIST-Panasonic (6th place) had a suction cup with 2 DoF mounted at the tip of a long arm and a retractable finger. An unusual spin on the hybrid gripper idea was demonstrated by Team IFL PiRo (7th place) who used a Robotiq 2-Finger parallel gripper with a suction cup mounted on the body of the robot and used as a tool whenever needed. Finally, the students from Team Duke also had a hybrid which, like many of the others, featured a suction cup mounted at the tip of a long slender arm, but unlike Delft and NimbRo, their design had 2 interconnected retractable fingers.

Despite the variety of different grippers most of them use suction as their primary means of picking and featured one or more "fingers" to assist with difficult objects. Additionally, none of them used suction and grasping at the same time. These problematic objects can be divided into 2 categories - too heavy for suction or too porous. As it is easy to see suction is a powerful tool when used correctly and any system not making use of it would be at a disadvantage.

It is important to mention that while all of the hybrids listed above use suction, they do not all use the same kind of suction. Depending on the air-flow and vacuum strength achieved by the system there are 2 types of suction: high vacuum/low airflow and low vacuum/high airflow. Both are commonly used and depending on the application one may be better than the other (See Fig. 2.4 for a detailed comparison).

High Vacuum/Low Flow suction is usually generated using pneumatic generators called "air ejectors". Air ejectors are driven by an air compressor and employ the Venturi Effect. This method achieves very strong vacuum (approx. -700mbar or more), which is often used in combination with bellowed suction cups to lift heavy objects. Unfortunately, the amount of air this setup can evacuate is limited, so even small leaks can break the suction. This makes it useful with surfaces which are airtight and smooth. When choosing suction cups for such an application, smaller is better due to the reduced chance of leaks.

Low Vacuum/High Flow suction, on the other hand, makes use of electro-mechanical generators such as vacuum pumps or more commonly "side channel blowers", such as vacuum cleaners. They usually deliver much weaker vacuum (-300bar or less) but are able to move massive quantities of air. Household and industrial vacuum cleaners were indeed

High Vacuum (< -700mbar), Low Flow	Low Vacuum (~ -100-300mbar), High Flow

Pros:
• High vacuum strong suction/lifting force, great for heavy objects (good seal and no leaks assumed, i.e. smooth continuous surfaces)
• Allows for smaller suction cups (good in tight spaces)
	Pros:
	• Inexpensive vacuum source (e.g., vacuum cleaner)
	• Good tolerance for vacuum leaks
	  • Works on uneven surfaces as well as porous materials (e.g., fabrics)
	  • Precise positioning not as important (easier planning)

Cons:
• Expensive (air ejectors, air compressor, etc.)
• Even small leaks can affect grasp robustness
  • Not good for uneven surfaces
  • Requires precise placement if smooth surfaces are limited
  • Will not work on porous materials
	Cons:
	• Weaker suction/lifting force, can be problematic for heavy objects
	• Requires larger vacuum opening (e.g. suction cup) and air tubes to accommodate the high air flow;

Air Compressor Feeding Air Ejector

6hp Dry/Wet Shop Vac

Figure 2.4: Comparison of Low and High Vacuum

some of the most popular suction sources in the APC and proved to be incredibly effective. Vacuum cleaner-based vacuum grippers were the only non-mechanical solutions which were able to successfully pick up porous and fabric-based items. The reason is that they can move so much air that even large leaks are ok. Surely everyone has seen a piece of clothing or curtain getting stuck to the end of a working vacuum cleaner. The downside of this type of suction is that larger diameter air tubes are required in order to maintain the high flow.

The relatively light weights of the items and the ability to also pick porous items made vacuum-cleaner based end-effectors immensely popular amongst APC/ARC participants. This was especially true after APC 2015, where Team RBO demonstrated how powerful such an end-effector can be by being able to pick most items with ease and eventually winning the competition. Their simple and elegant solution used a fixed suction cup, however during the next challenges it was shown that giving the suction cup a degree of freedom was beneficial.

As mentioned previously we have been using the ReFlex Hand in our lab. While it is an excellent hand, we often commented that it would be even better with a suction cup in the middle of the palm. RightHand Robotics seem to have listened as they recently released a commercial solution, similar to the ReFlex hand, with a suction cup in the middle of the palm (Fig. 2.5 on page 9) [41]. Even though the hand is as bulky as most other commercially-available 3-finger hands, they get around the issue by mounting the suction cup on a long tube which extends past the tips of the fingers. Once an object is securely attached to the suction cup, the tube is gently retracted into the palm at which point the fingers close around the object, further improving the grasp and securing the item. This is a very clever approach to picking in clutter and was an inspiration to our own solution.

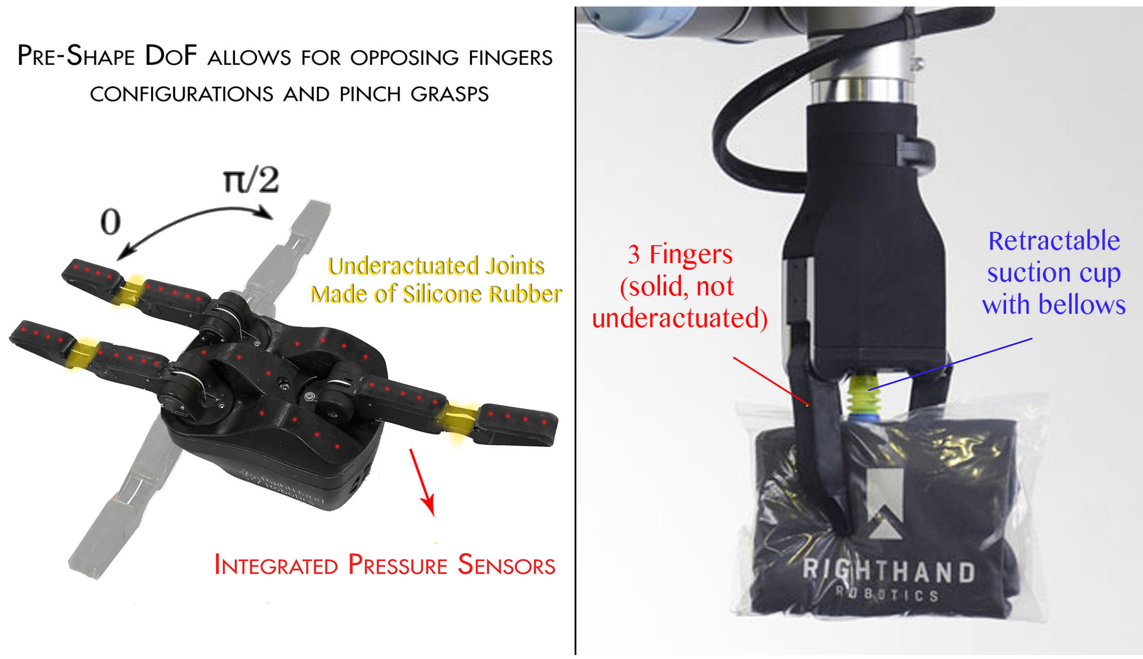

Figure 2.5: RightHand Robotics Grippers: ReFlex Hand (left), Commercial Hybrid Gripper (right)

In relation to the discussion on suction, it is worth briefly mentioning that I designed and built a prototype for a low vacuum high flow suction end-effector was as well. This is not surprising given the many benefits of this type of suction. The design featured a long arm constructed from laser-cut plywood, a 3D printed base for connecting the arm to the robot's wrist, a 3D printed tip to facilitate actuation of the suction cup and an electric linear actuator. The suction cup was designed and cast in-house using silicone rubber and featured asymmetric design (longer lip on top) to prevent cylindrical objects from breaking suction due to rolling. The air source was a 6hp dry/wet shop-vac. Since the vacuum levels achieved for successful "grasps" were really low, a vacuum sensor could not be used for grasp validation. An inexpensive mass air-flow (MAF) sensor from a 1990's Nissan Sentra, paired with an Arduino UNO was adapted and shown to work reliably.

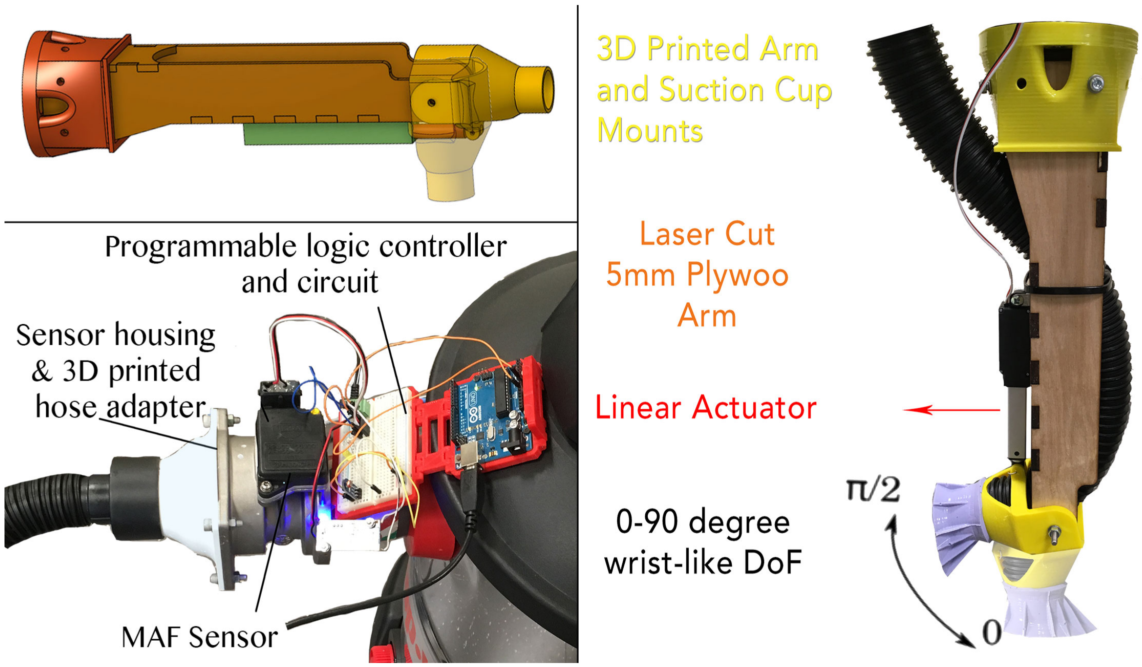

Figure 2.6: Rutgers High Flow Vacuum Gripper: (clockwise) Original CAD design, Prototype gripper, MAF Sensor-based Grasp Validation Unit

Even though the end-effector performed well, the prototype was a bit bulky. The design could be optimized to be more compact and stronger (plywood was chosen for its ease of use), however, the focus was shifted towards compliant grippers, so the project was abandoned.

It is easy to see that even though very effective all of the solutions listed above are constructed from rigid materials, so in the unfortunate case of a collision, there could be serious damage to the end-effector, robot, and even the shelf. The lack of a hybrid end-effector that could also handle collisions with the environment is the main motivation behind this work and is what makes it unique.

2.2 Overview of Soft Robotics

2.2.1 What is Soft Robotics?

The word "robot" tends to invoke similar images in most people's minds - usually a humanoid or industrial robot that makes whirling sounds and moves with precise but discontinuous and somewhat jerky motions. Regardless of the specific type of robot, they are usually made of rigid links connected together by passive or active joints driven by motors, gears, and cables. In most cases the joints of these robots are actuated by non-backdrivable motors, making the entire assembly very inflexible. It is this rigidity that allows the controller to calculate the position of each link with very certainty and achieve high levels of precision. Unfortunately in certain scenarios, such as trying to mimic the motion of living organisms, the properties which make robots useful become a limitation. It is this unyielding nature that also what makes robots unsafe to be around.

Soft robotics is a relatively new research field which focuses on the design, fabrication, and control of robots that are made of or incorporate flexible materials. Successful applications of soft robotics require knowledge of mechanical engineering, material science, computer science, electrical engineering and more, making it a truly interdisciplinary field. The term "soft" is misleading since it is used to describe any robotic system that uses compliant materials in a way that is vital to its operation.

Even though generally less precise than their rigid cousins, the flexible nature of soft robots gives them a long list of advantages. Durability is usually towards the top of that list since soft robots can usually withstand serious deformations without damage. They are also much better at mimicking fluid and complicated motions exhibited by living organisms. Most of them are actuated pneumatically or using tendons which often results in much lighter robots since the power source is external to the robot. The majority of soft robots' functionality is a direct result of their design and physical properties (morphology), so they are often made of very simple components. The built-in compliance also makes them inherently safer to interact with.

The materials used in soft robotics are easy to work with and even though some specialty equipment is required, it is usually much less advanced and expensive than what is needed to fabricate "rigid" robots.

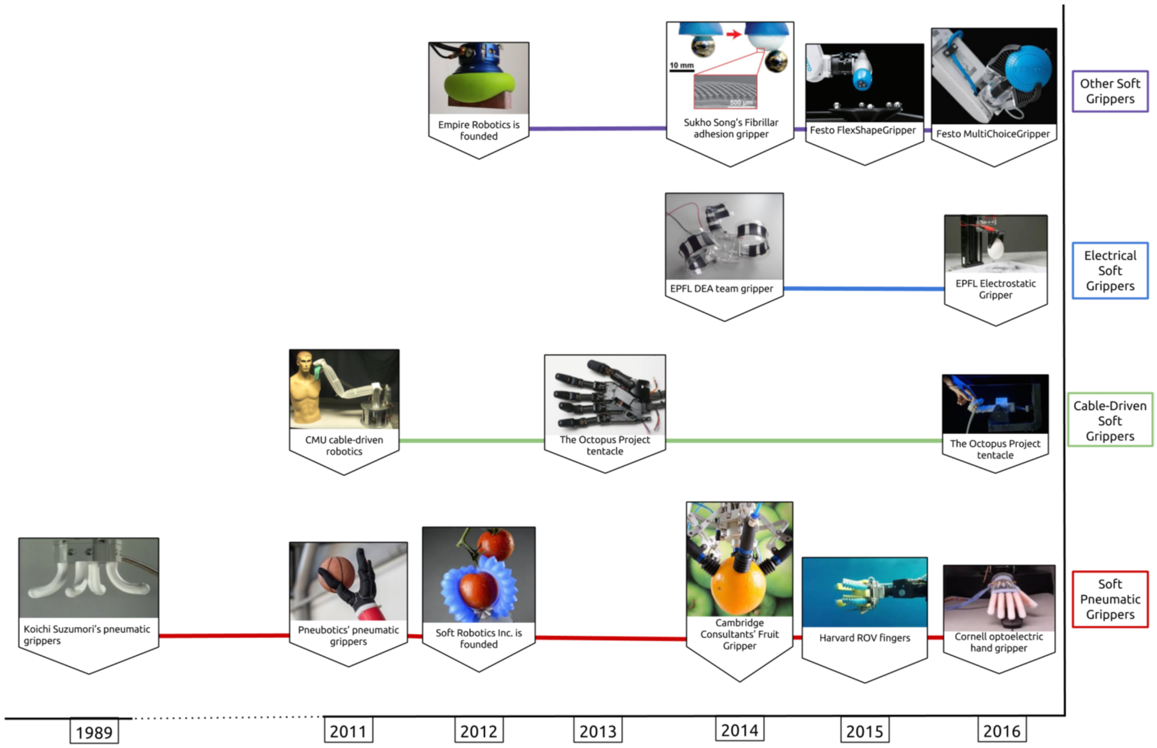

Figure 2.7: Soft Robotics History (Copyright Aidan Leitch)

It is hard to determine when exactly soft robotics emerged. An interesting graph attempting to summarize the history of soft robotics was recently posted on the SuperReleaser.com website (Fig. 2.7). Pneumatically Actuated Muscles (PAM), also known as McKibben Muscles named after their creator Joseph L. McKibben, were created in the 1950s, however, according to many, soft robotics emerged as a field in the late 1980's from the work on flexible microactuators by Suzimori [50]. The field didn't receive a lot of attention for several decades until 2010 when it quickly started gaining popularity. Advancements in manufacturing technology (especially 3D printing) and materials science have made it much easier to fabricate and test different designs and have been the major contributors to the establishment of Soft Robotics as a field. The creation of the Soft Robotics Toolkit (SRT) website [51], [25] in 2014 was instrumental to popularizing soft robotics by offering detailed instructions on how to design, model, construct and actuate a wide variety of soft actuators.

2.2.2 Soft Actuators 101

As mentioned above the term “Soft Robotics” encompasses all robots that incorporate flexible materials at the functional level. The main area of research in soft robotics has been the design and fabrication of soft actuators. These are robotic components that are responsible for moving or controlling the robot and like other actuators usually need a power source and control signal.

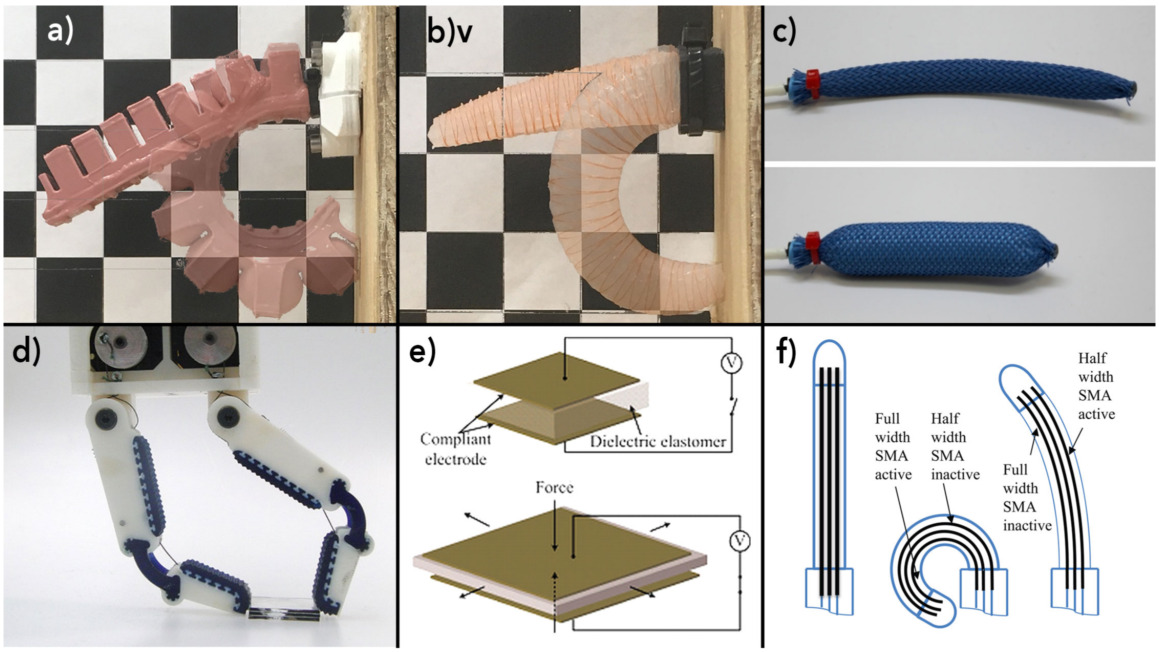

Figure 2.8: Most popular types of soft actuators: (a) PneuNet Bending Actuators, (b) Fiber Reinforced Actuators, (c) Pneumatic Artificial Muscles (PAM), (d) Tendon Operated Actuators, (e) Dielectric Elastomer Actuators, (f) Shape Memory Alloy (SMA) Actuators

There are many types of soft actuators but the most popular types (Fig. 2.8) are:

(a) Pneumatic Network (PneuNet) Bending Actuators ([31], [37], [43], [47]) - These are some of the easiest to fabricate and therefore most popular. As the name suggests, they are usually used to produce a bending motion and even though their morphology can vary wildly depending on the application, the principle is always the same - One or more inflatable chambers built from an elastomeric material attached to an inextensible (strain-limiting) layer on one side. When inflated the chambers expand. The side of the strain-limiting layer cannot stretch while the other side can, thus producing a bending motion. Depending on the morphology of the actuator, other types of motion can be produced, such as twisting and elongation. Actuators can also combine several different strategies to produce more complex compound motions.

(b) Fiber-Reinforced Actuators ([8], [38])- While very similar to PneuNets, Fiber-Reinforced Actuators deserve a category of their own. They work on the same principle as PneuNets, however, they usually feature a single large chamber, while PneuNets as the name suggests usually have a network of several interconnected chambers. The other difference is obviously the addition of fiber reinforcements, which are usually wound on the outside of the actuator in a helical pattern. The non-stretchable fibers used help to distribute the force generated by the pressure inside the chamber over the entire surface of the actuator. This results in durable actuators which while not indestructible are less likely to fail due to accidental over-inflation. Recent research ([14], [13]) has also shown that varying the fiber angle can "program" the actuator to do different things, such as twist, elongate, etc.

(c) Pneumatic Artificial Muscles (PAM) ([12], [28], [11]) - As mentioned earlier PAMs are the oldest type of soft-actuator. They are incredibly simple, which is also the reason for their durability and reliability. PAMs are essentially composed of an extensible bladder (e.g. balloon), which is encased in a mesh sleeve and capped at both ends. Inflating the bladder increases its volume until it becomes limited by the sleeve around it. Further inflation causes the bladder to stretch the sleeve to the side, reorienting the fibers in its mesh and reducing its overall length. Just like human muscles PAMs can only do one thing - contract. They have many benefits, in particular, light weight and excellent power-to-weight ratio, making them excellent for use in exoskeletons and other applications that require a lot of force. Recent research has discovered that as in the case of Fiber-Reinforced Actuators, the angle of the fibers matters and is a parameter that determines the efficiency and force produced by the PAM. Another novel idea called "SmartBraids" [19] uses sleeves made out of conductive fibers and employing inductance can accurately measure the change in length of the actuator.

(d) Tendon Operated Actuators ([32], [20], [17]) - As with the previous types of actuators the idea here is simple: a series of rigid or semi-rigid links are connected by passive compliant joints. A tendon (cable or other inextensible fiber) is connected to the tip of the actuator and routed through channels in the body to the base and then to a spool mounted on an electric motor. Shortening the tendon by winding it on the spool creates a pulling force on the tip which due to the compliant joints causes the actuator to bend. As in the case of other types of actuators, the materials used and the way the tendon is routed can be modified to produce different motions. This type of actuator is very reliable and often used in making fingers for under-actuated robotic hands, such as the ReFlex Hand.

(e) Dielectric Elastomer Actuators ([45], [52], [36], [48]) - This type of actuators requires a bit more background knowledge to understand but the concept is simple. They consist of 2 compliant electrodes with a dielectric (an electrical insulator that can be polarized by an applied electric field) elastomer sandwiched between them. Attaching an electrical power source to the electrodes creates an electric field which polarizes the dielectric elastomer close to the electrodes, creating a magnetic force that pulls them together. As a result, the distance between the electrodes is reduced, flattening the elastomer and making it stretch sideways. These actuators are usually small and used in groups stacked on top of each other, in order to produce a significant effect. Similar to PAMs, they are mostly used for making artificial muscles.

(f) Shape Memory Alloy (SMA) Actuators ([27], [22], [42]) - These are not very well known due to the relatively low popularity of SMA's. SMA's usually come in the shape of a metal wire, which can be "programmed" to return to a certain shape when heated. As an example, to design a bending actuator, the SMA wire is "programmed" to remember a bent shape, after which it is straightened. By passing current through the wire or through a separate heater placed around it, the SMA wire is heated and returns to its memorized position. Embedding such a system in a compliant material creates bending actuator. These usually have a pair of antagonistically positioned SMA wires - one for bending and one for straightening the actuator.

One of the main shortcomings of soft actuators is the fact that they are soft. Even when fully actuated (e.g. inflated with compressed air) they can be quite flexible, so finding ways to stiffen a soft actuator once it has taken up a certain desired shape is a topic that has received a lot of attention. The use of particle jamming ([9], [6], [29], [26], [21]) to produce variable stiffness actuators is a popular approach. Some alternatives are to use actuators in antagonistic configuration or combine pneumatic actuators and tendons. Unfortunately, these strategies usually increase stiffness by only 20-30% which is often insufficient, so this remains a popular area of research.

There are many new frontiers in the field of soft robotics such as the development of new types of sensors. Sensorizing of traditional rigid robots has been done for a long time and excellent sensors have been developed. Unfortunately, sensors used in traditional robotics usually cannot be used in soft robotics and the reasons are simple. In order to measure the degree of bending of a joint on a robotic arm, we need to know the exact location of the pivot point and the relative position of the 2 links connected to that pivot point. Measuring the bend of a PneuNet bending actuator is a completely different task since the soft actuator can be approximated by a combination of infinitely many joints connected to each other. It quickly becomes obvious that the sensors also need to be flexible themselves because they often need to be embedded within the actuators. In soft robotics, in addition to bending, it is useful to be able to measure twisting, stretch, strain and more.

While there is no best way of approaching this problem, sensors utilizing the principles of capacitance are becoming very popular due to their compact size and flexibility. Research on inductance-based sensors is also common for similar reasons. Optical bend sensors using graded PMMA fibers seems promising, however, they are difficult to manufacture and relatively fragile compared to inductive and capacitive sensors.

Since the majority of the actuators are SPAs that means they are usually tethered to an air source. There is an ongoing effort to produce miniaturized pumps with low power requirements as well as alternative methods of actuation such as combustion [44], [46] [7].

2.2.3 Fabrication of Soft Actuators

he majority of soft robots employ some type of elastomer. The elastomer material used for the majority of SPAs today is silicone rubber. For the inflatable portions of our actuators specifically, we are interested in hyper-elastic silicone rubber which can stretch many times its own size before breaking.

The production of a soft actuator using cast silicone rubber consists of 5 main steps:

- designing the actuator (shape, size, mophology)
- modelling it and simulating it's behavior
- designing the molds necessary to cast the actuator
- casting of the actuator
- assembly and testing

As you will see, the process of fabricating a soft actuator is long and labor intensive, which is often cited as a shortcoming, however having had some experience prototyping conventional robot components I disagree with that statement. Unless a "rigid" robot is entirely produced by an automated process such as 3D printing or CNC machining, it is no less labor intensive and can be much more expensive due to the higher cost of materials and tooling required.

Finger 3D Design

The design of a soft actuator is the iterative process of adjusting design parameters and testing, honing down on the best morphology for the task. There are two obvious ways of testing a design and its performance: using a computer simulation and using physical prototypes. Considering that the manufacturing process is rather time-consuming compared to running computer simulations one would expect that testing using physical prototypes is a last resort.

This, however, is not the case for a large part of the actuators manufactured. Due to the highly non-linear nature of the material and deformations that occur, modeling soft robots is a much more complex problem than its rigid equivalent - forward kinematics. The process and tools will be discussed in more details in the next section. Even though time-consuming, the process of building each actuator provided useful hands-on experience with the materials and equipment, which could not be obtained otherwise and sparked many ideas on how to optimize each step.

The design of the 3D model of the actuator, usually in its unactuated state, is done using 3D CAD software such as DS SolidWorks, Autodesk Inventor, FreeCAD, OpenSCAD, Autodesk Fusion360 or my favorite OnShape [33]. These CAD software are parameter-based, which means they can recalculate and update the morphology of the design by just changing a few numeric parameters, such as actuator length, chamber height, or number of chambers.

Modelling and Simulation

Even though the designs produced for this project were not modeled and tested in simulation, it is useful to outline the general process. Modelling and Simulation of soft actuators is an area of active research [14] [38] [23] and the number of tools available to us is still quite limited. In order to simulate soft robots, we use Finite Element Method (FEM) Analysis tools such as Abaqus FEA, Solidworks or the freeware SOFA Framework with the Soft-Robotics Plugin developed by Team DEFROST at Inria, France.

The workflow includes many steps and a lot of tweaking of parameters which is often the reason why designers get discouraged and actually prefer to use a physical prototype for their tests. Initially, a solid 3D model of the robot or actuator is loaded into the software. Then a mesh is generated by breaking up the solid into triangles or quads, the size of which is one of the important parameters involved in FEM analysis and unfortunately there is no perfect value - a finer mesh, in theory, should model the behavior of the actuator more accurately, however the extra nodes introduced by the finer mesh require considerably more computing resources or introduce rigidity. On the other hand, a mesh too sparse would compute faster, however, may not be as accurate.

After the model is meshed and assembled (if the actuator is comprised of multiple pieces - e.g. PneuNet actuators), material properties are specified for each piece (e.g. density, Yeoh strain energy, etc). Finally, gravity and other forces and loads are specified, and the simulation is run. In the case of SPA's the load is air pressure in the cavities of the actuator. The output from the FEM analysis software usually includes a short animation showing the deformations of the actuator as air pressure is ramped up, as well as coloring different parts of the actuator relative to the stress that area is currently experiencing (Fig 2.9).

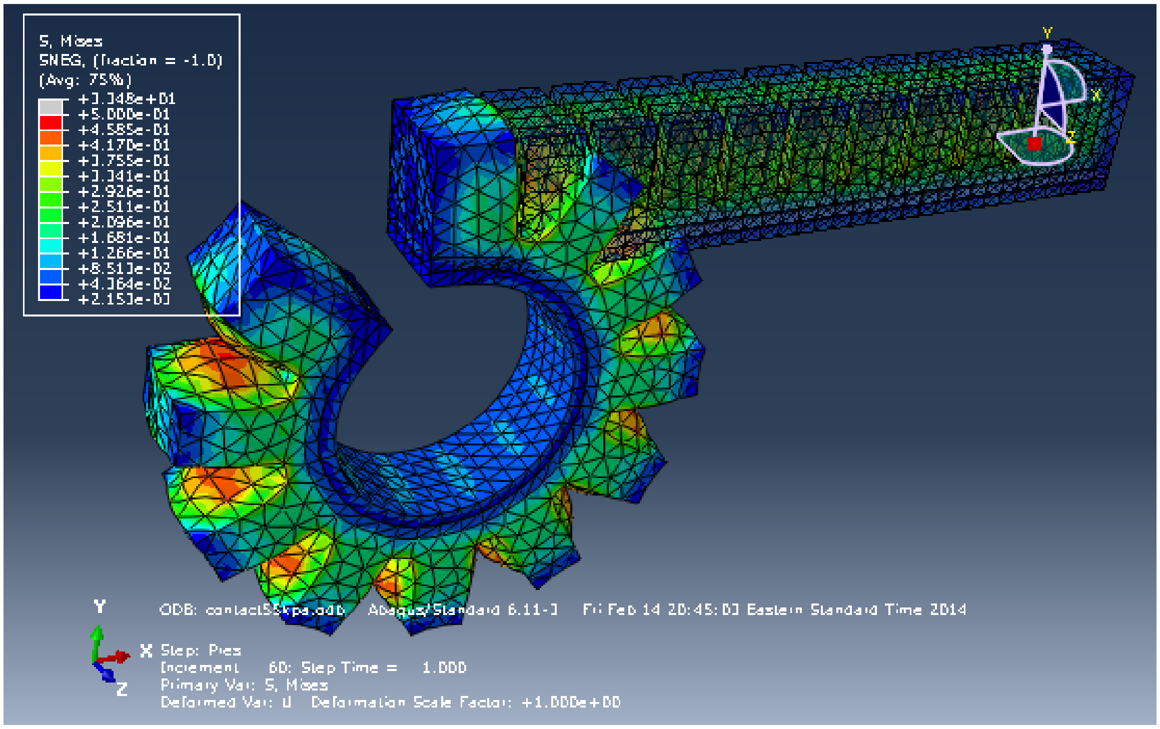

Figure 2.9: Usual output from Abaqus FEA when modelling Fast Actuating PneuNets (from Soft Robotics Toolkit website)

Unfortunately even though relatively straightforward to explain the process is rarely trouble-free. Often the mathematical model used for the simulation will refuse to converge or there will be a different error. Since a lot of the FEM analysis software is designed for modeling stress and deformation of all sorts of materials, there are hundreds of different options and a lot of background knowledge is required in order to properly set up a job and run it successfully. This is the main reason why modeling soft robots is not as popular as expected. Most of the FEM analysis software also happens to be very expensive.

The SOFA Framework, a freeware simulation framework initially developed for medical use, has recently gained a lot of popularity due to the Soft Robotics Plugin, which seems to be easier to understand and setup, and is also free.

The Casting Process

Chronologically casting comes after mold design, however, it is important to have a firm grasp of the casting process and the difficulties that go with it in order to fully understand the importance of proper mold design.

The majority of SPAs are fabricated from Room Temperature Vulcanizing (RTV) platinum-cure silicone rubber. It comes in 2 parts, which mixed together in specific proportions initiate a chemical reaction which causes the rubber to vulcanize (cure) and become solid. There are other elastomers which have the properties needed to build an SPA, such as many polyurethane rubbers, however, silicone has the advantage of only sticking to itself, which makes demolding it much easier and generally easy to work with.

Selecting the right elastomer for the job is a balancing act that involves several important variables:

- Elongation at break: how much the material will stretch before breaking. For soft robotics, especially SPAs we usually look for values of 400% or more.
- Hardness: This is measured on the Durometer Shore Scale (Fig. 2.10). The harder the silicone, the more air pressure will be required to actuate it and the more force it will generate.
- Tear strength: The amount of force (measured in kN/m or ppi - pounds per inch) required to cause an existing tear to propagate. This is very important and directly related to how resilient to damage the material is.
- Pot life: The amount of time from first mixing the 2 parts of silicone until it no longer behaves like a liquid. This is very important since it represents the time you have available to fully mix the rubber, degas it completely and transfer it to the mold. This is usually directly proportional to the time required to fully cure the rubber. One may be compelled to choose a rubber that cures faster and deal with the shorter pot life, however, while it is possible to speed up the curing process by using a lab oven, it is very hard to slow it down.
- Viscosity: The viscosity of the rubber when fully mixed and is usually measured in Centipoise (cps). It is one of the biggest sources of problems when casting silicone. The thicker the mixture, the longer it takes to degas and also to pour into a mold. It is usually proportional to the hardness of the material. For reference, here are the

viscosities of some common liquids: water is 1-3 cps, corn oil is 65 cps, honey is 2,000-3,000 cps, ketchup or mustard is 50,000-70,000 cps and silicone rubber is typically in the range 10,000-40,000 cps

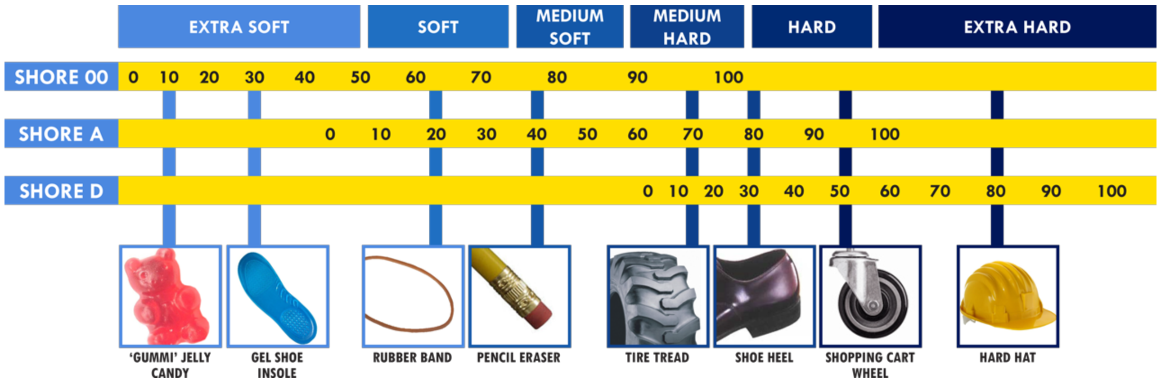

Figure 2.10: Durometer Chart by SmoothOn

The first step in casting is measuring the right quantities of rubber. Each silicone is different but they are usually mixed in proportions 1:1 or 1:10. These proportions are pbw - parts by weight, so the best way to measure the correct amounts is by using an accurate scale (0.1g resolution is more than sufficient and quite common). In case a scale is not available the 2 parts can be measured by volume, using disposable syringes or another method, however, accurate mini-scales can be purchased for as little as $20, so this is not recommended.

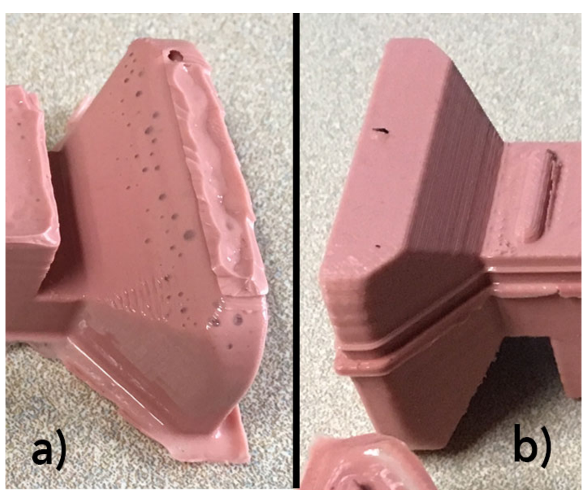

Figure 2.11: Effects of degassing: a) silicone cast without degassing; b) silicone cast after after degassing

When mixing silicone rubber it is important that a homogeneous mixture is achieved without any air bubbles trapped inside. The ideal way to achieve this is with the use of a planetary centrifugal mixer like the ones produced by THINKY USA. In addition to a very even mixture, the product of these types of mixers is almost entirely free of bubbles which dramatically reduces degassing time. Unfortunately, they are very expensive and rarely found in robotics labs. Badly mixed rubber can fail to fully cure but thankfully good results can be achieved mixing the rubber by hand.

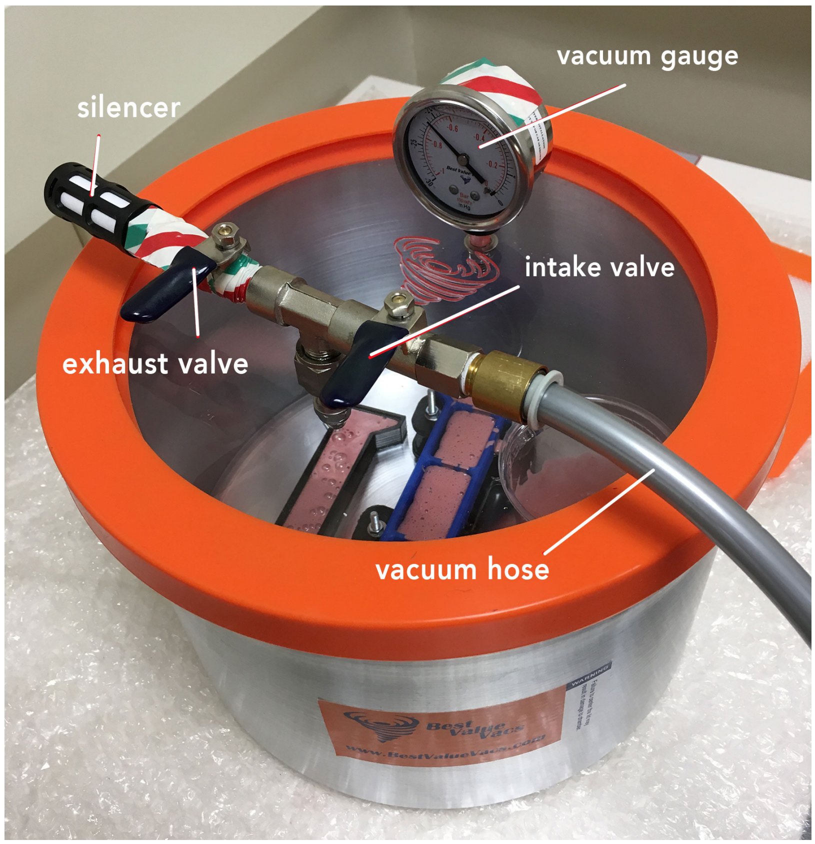

Figure 2.12: 3 gal. Vacuum Chamber from BestValueVac

The manual mixing process, no matter how gentle, causes the mixture to fold onto itself trapping air bubbles. Unless removed prior to transferring the mixture to the mold, these bubbles will create weak spots in the elastomer, which when inflated will be much more likely to rupture. The process of removing the bubbles from the rubber mixture is called degassing. See Fig. 2.11 for a demonstration of why degassing is important. It is achieved using a vacuum chamber. It is not necessary to have an industrial grade vacuum chamber.

An inexpensive vacuum chamber, big enough to hold your molds should be sufficient (Fig. 2.12). The vacuum source can be a vacuum pump or an air compressor coupled with an air ejector. This is the setup used in our lab and we are able to achieve and maintain vacuum levels of -800mbar which is excellent regardless of cost. Introducing the mixture into a low-pressure chamber causes air bubbles to travel to the surface where they pop (See Fig. 2.13). In general, the mixture should be degassed until no more bubbles can be seen.

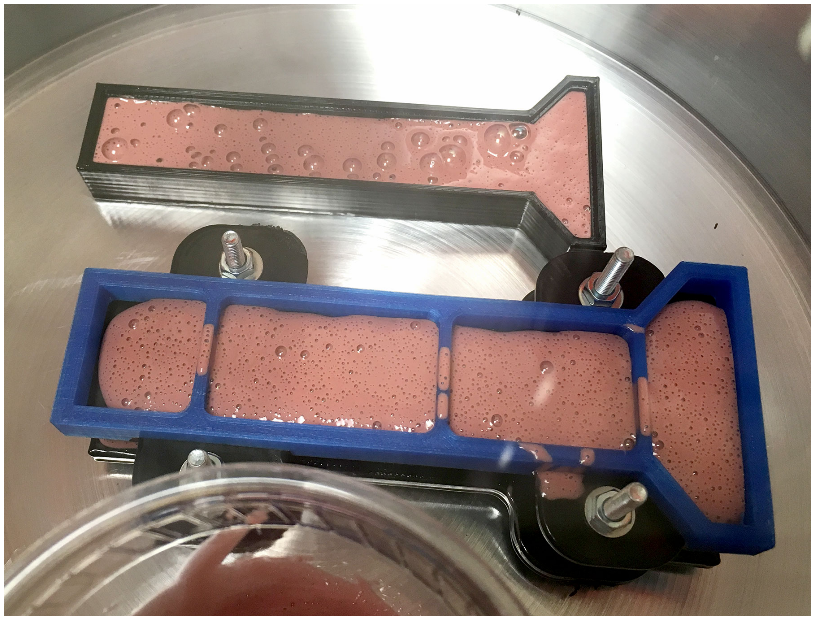

Figure 2.13: Degassing Silicone Rubber

Unfortunately, a limiting parameter is pot life, which is the time we have to work with the rubber before it begins to solidify. The problem with more viscous mixtures is that degassing can take longer than the pot life. The suggested method for speeding up the degassing process is to cycle the vacuum on and off every few minutes. Even though it makes a difference this method is not very efficient and can still take a long time. Another recommendation is to take the mold out of the vacuum chamber, pop the bubbles with a needle and return it to the vacuum chamber, repeating as necessary.

The process can also be sped up by agitating the mixture. Several methods were tested to identify the most efficient one. At first, the mixing cup was placed on top of a battery powered DC motor, which produced vibrations using an off-balance shaft. Unfortunately, the effectiveness of this method was negligible. Then it was noticed that the bubbles in the mixture responded well to a sharp tap on the side or bottom of the mixing cup, so the second device was constructed (Fig. 2.14) using a battery powered DC motor controlled by an Arduino Mini and a spring-loaded arm (rubber band works too). The frame was fabricated from laser-cut plywood. A notched wheel on the motor would repeatedly pull the arm back and release it. The potential energy stored in the spring/rubber band would cause the arm to slam into the bottom of the cup. Disappointingly, this prototype was also less effective than expected.

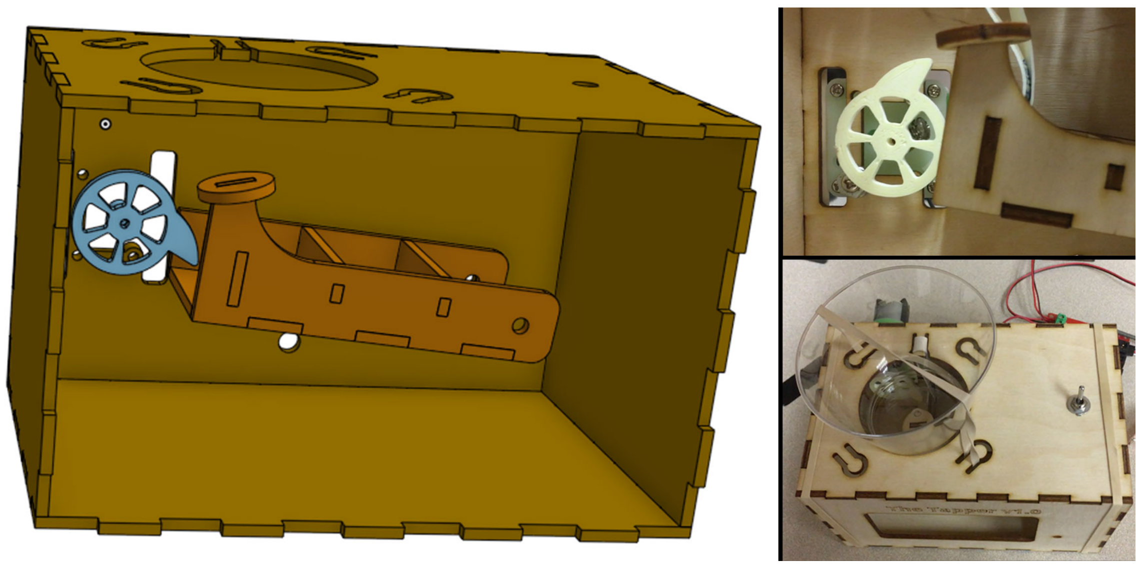

Figure 2.14: Silicon Rubber Degassing Tool: The Tapper v1

Finally, it was discovered that repeatedly tapping the mixing cup onto a hard surface worked best. The sudden change in velocity of the mixing cup caused the weight of the mixture to press down on any bubbles forcing them to the surface. A simple device using a battery powered DC servo motor and an arm attached to the servo was designed and built. The cup attaches to the arm, which in turn, repeatedly lifts the cup and suddenly drops it (Fig. 2.15). As with the previous design, the frame was constructed from laser-cut plywood and the motor was controlled by an Arduino. The device works very well and has reduced degassing time considerably.

For videos of the tappers in action, please visit the supplemental file respository [4].

After the rubber is degassed it needs to be transferred into the mold. The mold design is in part dependent on the elastomer of choice and in particular its viscosity. Low viscosity

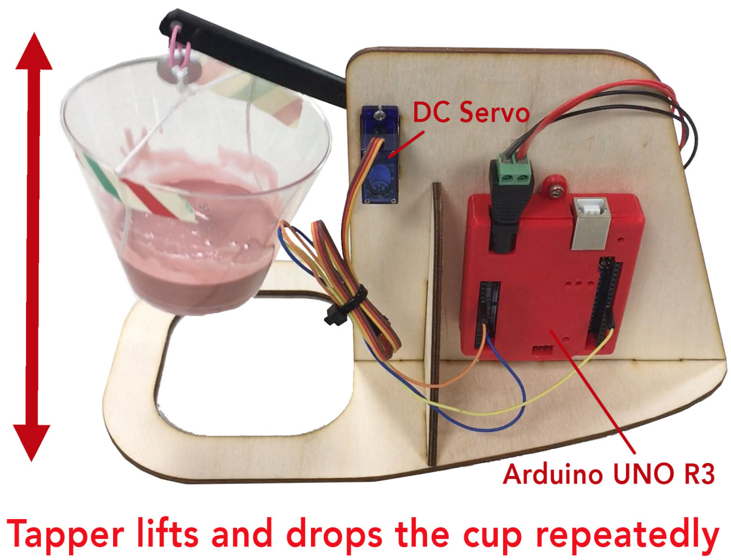

Figure 2.15: Silicon Rubber Degassing Tool: The Tapper v2

mixtures can work well with open-face molds where the silicone is poured from the top and then due to gravity flows into the mold and fills the voids. This does not work very well with molds where thin walls need to be cast and/or molds that are very tall. This is because surface tension of the liquid rubber and adhesion to the walls of the mold prevent the silicone from flowing down easily and result in air bubbles and sometimes even air pockets, which are a point of failure. This problem gets even more serious with more viscous silicone mixtures, which is the case for higher durometer rubbers. The recommended solution is a subsequent degassing of the rubber while in the mold, which adds more to the processing time.

In these cases, we can design the molds so that the rubber can be injected. These are known as “closed” molds and the process is called injection molding. Closed molds have one or more “sprues” (openings) through which the material gets injected. The injection sprue is usually as close to the bottom of the mold as possible. Sprues at the top of the mold are added to allow air to escape. See Fig. 2.16 for an example. If the process is carried out in vacuum the molds can be completely sealed. In order to save time, material and frustration due to failed actuators I experimented with injection molding with good results and the benefits are numerous. Since the rubber was injected from the bottom it filled all cavities, no matter how tight the tolerances and left no air pockets. The mixture was also not agitated in the process, so no air bubbles were reintroduced, which meant no need for additional degassing after the first one. The entire process was much quicker, cleaner and less frustrating. I now use injection molding almost exclusively.

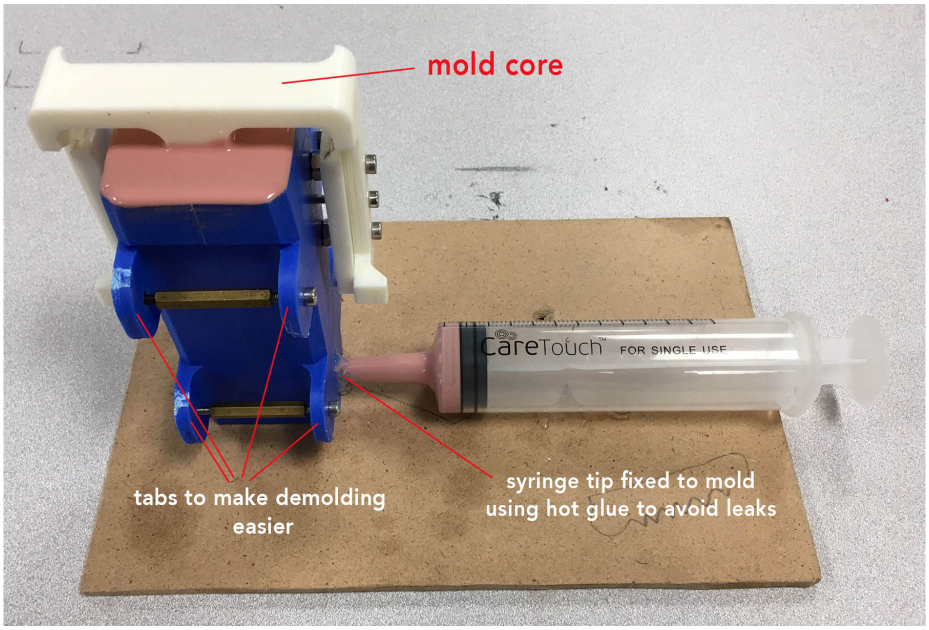

Figure 2.16: Injection molding being used to cast a soft finger.

Once the silicone is cast it needs time to cure. Even though it is designed to cure at room temperature the process can be sped up considerably by using a lab oven set to 60-65C. Just as with the vacuum chamber, an industrial grade lab oven is not necessary. A lab oven is easy to build as it is essentially an enclosure which maintains a constant preset temperature and optionally has a fan to move the air for more consistent temperatures. An electric fruit drier is a great alternative. There are many inexpensive models, which have a built-in thermostat and fan and they are designed to work in a similar temperature range.

Mold Design

As described in the previous section, the design of the mold is very important for a successful cast. Designing the mold for an actuator often takes longer than the design of the actuator itself, so it is worth spending some time to briefly go over the details.

Molds can be constructed from metal, plastic, wood or other materials, however, nowadays unless working on an industrial scale, it is common to use 3D printed molds. After the design of the robot is finalized, a negative of the 3D shape is used for the design of a 3D printable mold. The design software used for the mold design is usually the same as the one used for the actuator. There are multiple considerations that need to be taken into account when designing a mold. The first step is to decide whether to pour the rubber or use injection molding. In my experience injection molding is much more reliable and actually easier.

Next, it is a good idea to spend some time and evaluate different mold orientations and configurations which would allow the actuator to be cast in as few pieces as possible. While multi-piece actuators can be fabricated, the mating surfaces are usually a source of problems due to leaks and delamination. If at all possible, casting the actuator as a single piece is the best option.

The mold should be designed so that the actuator can be removed after it is cast. This usually means that the mold is made of multiple pieces, which are assembled together. It is important that the fit is tight and attachment points for clamping hardware are built-in. In some cases, especially when it is important to cast the actuator as a single piece, it can be impossible to remove the core or another part of the mold without cutting the actuator. In those cases, we can use the "lost wax" casting method where the core is made of wax which can be melted away after the rubber cures. Cutting and gluing the actuator can also be an option, depending on the silicone glue available.

There are several different 3D printing technologies such as Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS) and more. FDM 3D printers are by far the most common and least expensive and they work by melting a thermoplastic material and depositing it very precisely layer by layer. The majority of machines can produce models with layers ranging from 0.1mm to 0.4mm in height. Their precision in the X and Y directions (within layer) is usually much higher and resolutions as low as 0.01mm are common. As may be expected it is important to make the mold surface as smooth as possible in order to make demolding easier, so low layer heights are recommended. Even at 0.1mm however, which sounds very small, the layers are visible with the naked eye and can be easily felt with one's finger (Fig. 2.17). It is often recommended to use a mold release agent, which is applied to the mold before casting. This is good advice, however, it can leave residue on the rubber which can cause problems if working with an actuator that needs to be assembled or glued to other pieces.

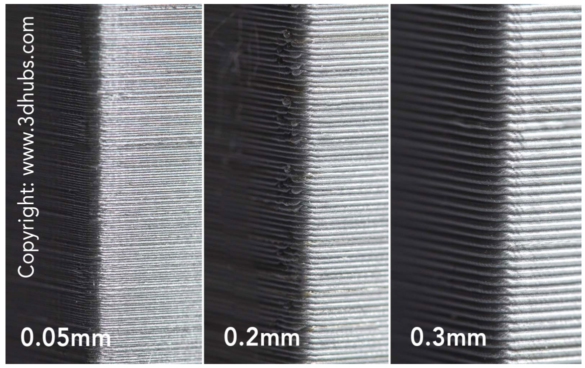

Figure 2.17: Print surface finish at different layer heights

Nowadays there is a wide variety of filaments available for FDM printers, however, the 2 main options are still Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) plastics. ABS is a higher temperature thermoplastic, so the molds produced are usually stronger due to better interlayer adhesion. Unfortunately, it suffers from warping as it cools, so molds with thin or tall features are hard to print. In addition to strength, ABS has another benefit - its surface can be smoothed with acetone. ABS dissolves in acetone, so placing the finished print in a chamber with acetone vapor for a couple of hours, gently melts the outside of the print. The result is a smooth and often glossy surface and inter-layer lines cannot be seen or felt (Fig. 2.18), which is ideal for casting silicone. It has been proved that vapor smoothing also improves inter-layer adhesion, making the print stronger, which is another plus.

Figure 2.18: Effects of acetone smoothing

PLA, on the other hand, cannot be smoothed but has other benefits. It does not suffer from warping, is easier to print with and can generally create prints with much finer details than ABS. It is also an entirely natural product made of plant-derived substances, is fully biodegradable and does not give off toxic gases during printing.

Even though silicone only sticks to itself, despite smooth mold surfaces, separating the mold pieces can be quite difficult. This is why it is important to incorporate finger holds or tabs into the design, which will allow you to apply considerable force without the need to pry the mold open and possibly damage it in the process.

Another important factor in the design of a mold that will be 3D printed is that FDM printers cannot print in mid-air. They can, however, use support material to print steep overhangs, which can later be broken away or dissolved. In general, it is a good idea to design the mold to print well without the need for supports unless absolutely necessary.

Due to the way FDM 3D printers work, laying down plastic layer by layer, prints are stronger along the layers than across. Delamination is when a print fails due to the layers separating from each other (between layers) and is much more likely to happen than having the plastic break along the layers. Since considerable forces may need to be applied when disassembling the mold and demolding the actuators, designing the mold to be printable in the right direction can make a big difference as far as its durability.

Post-Processing, Assembly and Testing

Depending on the actuator there may be more work left to do before it is ready for use. For example, many PneuNet actuator designs are made of multiple pieces which need to be assembled and glued together. Fiber-reinforced actuators need to have their fibers wound carefully by hand. Then air tubes need to be added, as well as mounting hardware for securing the actuator to other actuators, robotic hand, etc. The actuators are then tested, paying attention to any leaks, bubbles or other potential problems that could cause actuator failure. Air pressure at maximum inflation is noted as the actuator limit. If any problems are spotted they are addressed and the testing process repeated.

Chapter 3

The Solution

3.1 Components Overview

The solution described here has 5 distinct components, all of which were designed and built in-house:

- Pneumatically actuated soft-fingers
- Palm which accepts the fingers and secures them to the flexible arm extension
- Bellows-driven, vacuum-operated object lifting mechanism with suction cup in the middle of the palm
- Flexible arm extension, which is long and narrow to allow better reachability
- Base, used to attach the flexible arm extension to the robot's wrist

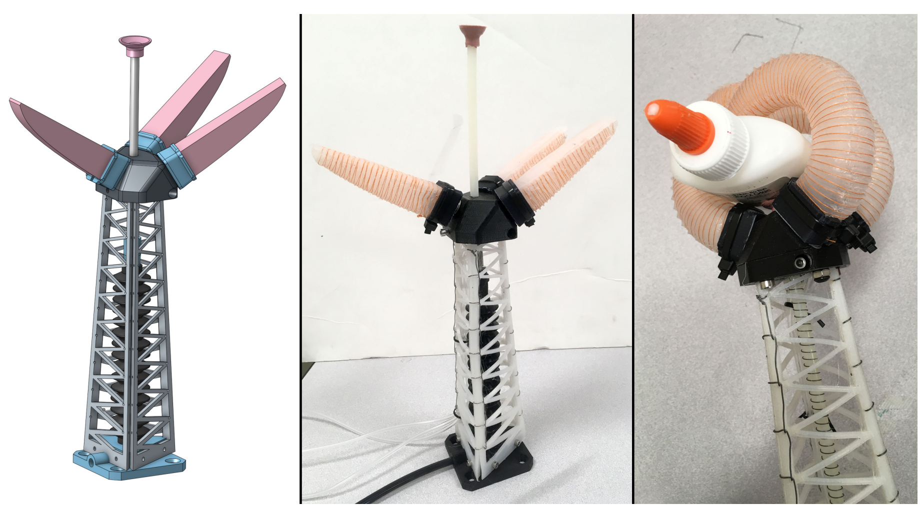

Figure 3.1: The solution: A robust hybrid soft and vacuum end-effector and compliant arm for picking in clutter

In order to be operated the hand also requires a pneumatics control board and air and vacuum source.

3.2 Fingers

The Soft Robotics Toolkit (SRT) and the wealth of information it offers was the inspiration for this project. With no prior experience in soft robotics and no first-hand knowledge of the capabilities of various types of actuators, elastomers properties, and manufacturing techniques, the project was a long journey and a wonderful learning experience. Several different types of fingers were built and tested before choosing the fiber reinforced actuators. A brief comparison of their pros and cons can be found below.

3.2.1 Fast Actuating PneuNet Actuator-Based Fingers

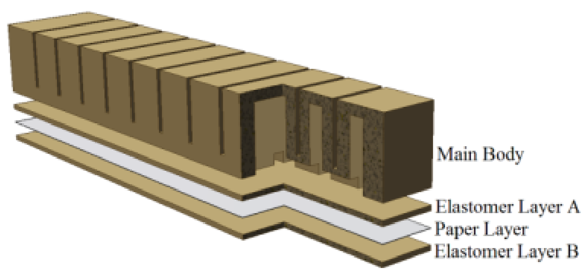

Figure 3.2: The basic structure of a PneuNet Actuator

The first actuator constructed was a Fast Actuating PneuNet bending actuator as described in the SRT [2]. It is one of the simplest actuators to build and a good starting point for any novice taking first steps in fabricating soft actuators. The basic structure of a PneuNet actuator consists of 2 main components (see Fig. 3.2): the main body and strain limiting layer, which is comprised of a paper layer (or another inextensible material) sandwiched between 2 thin elastomer layers. The main body and strain limiting layer are cast separately and assembled together using a layer of freshly mixed silicone rubber which acts as a glue.

It was indeed a great way to gain experience in working with the Wacker Elastosil M4601AB Silicone Rubber (Shore A28). Even though a vacuum chamber was used to degas the mixture it was quickly realized that by itself is not enough. As described in the

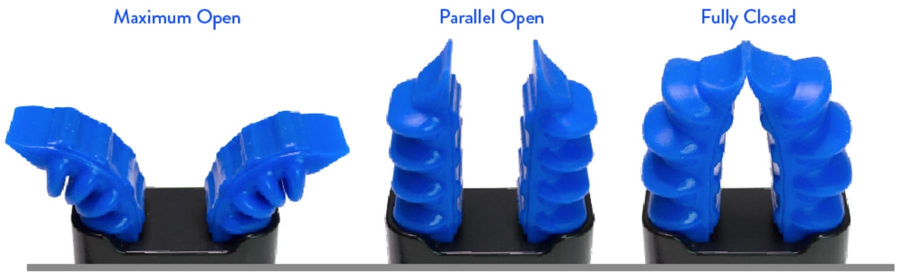

Figure 3.3: Demonstration of the capabilities of actuators used by SoftRobotics Inc. in their industrial soft grippers

2.2.3, due to the viscosity of the mixture and its limited pot life, it was necessary to explore various strategies to speed up the degassing process. See Section 2.2.3 for more details.

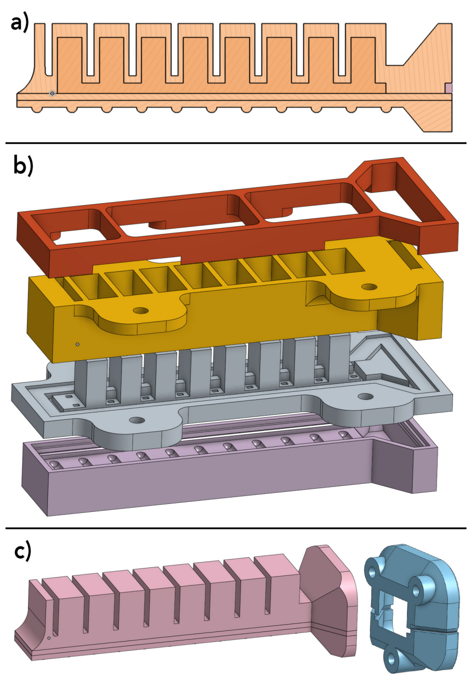

Figure 3.4: Fast-Actuating PneuNet Finger Designs. a) Finger cross-section; b) Mold design; c) Finger and mounting cap

The original design of the finger was identical to the one provided by the SRT, except for the addition of a sharp non-inflatable tip and a solid rubber base to help with mounting the finger. The idea for the tip or “fingernail” was inspired by the soft grippers designed by SoftRobotics Inc. (Fig. 3.3). Plastic end-caps for securing the rubber base to a laser-cut plywood palm were also designed (Fig. 3.4).

The different steps of casting and assembling a finger can be seen in Fig. 3.5.

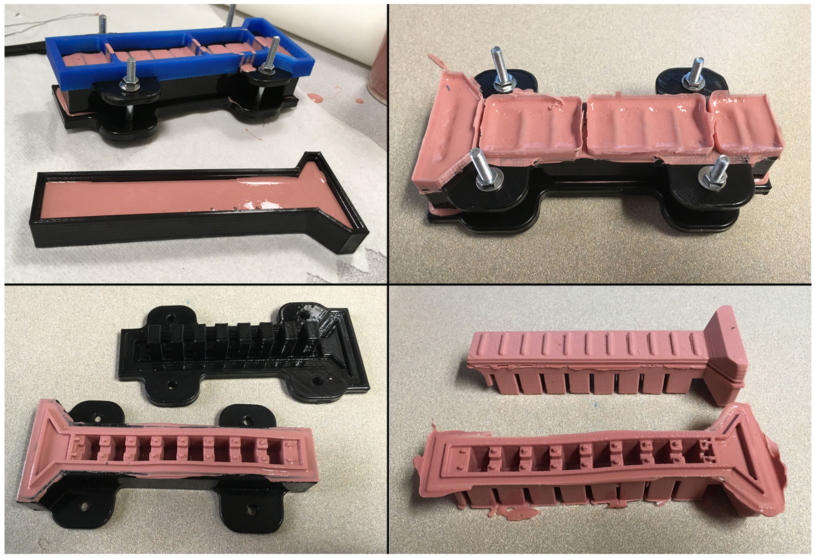

Figure 3.5: Fabrication of a Fast-Actuating PneuNet Finger: (top-left) casting the main body and strain limiting layer, (top-right) cured main body ready for demolding, (bottom-left) demolding, (bottom-right) a complete finger another halfway done

Several PneuNet fingers were built and assembled into a simple 3-fingered hand in order to better judge their capabilities. Fig. 3.6 demonstrates how the hand works. The fingers were all mounted on one plain, so it was hard to grasp larger objects. Fabricating a palm where the fingers could be mounted on 2 separate planes, at an angle to each other, would help with that issue. In their unactuated state, the fingers were quite flexible and depending on the orientation of the hand they would bend due to gravity and get in the way. The SoftRobotics Inc. gripper provided inspiration for the solution to this problem (Fig. 3.3) as it was noted that the application of vacuum should collapse the air chambers and possibly cause the fingers to curl backward. An extra valve to control the vacuum was added to the setup and the idea proved to work very well (Fig. 3.6c), however, the backward curvature produced was not very large. Upon applying vacuum, the rectangular tops of the air chambers of our fingers remained flat and prevented the fingers from bending very far back.

Mistakes were made and a lot was learned during the fabrication of these fingers, so their quality left a lot to be desired. The main problems experienced were air leaks due to delamination of the body and strain-limiting layer or leaks around the air tube, as well as ruptures due to bubbles in the rubber or accidental overinflation. While leaks and ruptures can be repaired and overall build quality would improve with experience the limitations of

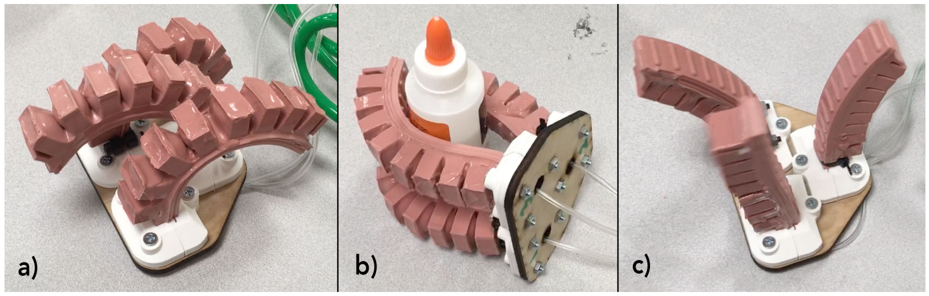

Figure 3.6: Prototype 3-Finger Hand with Fast Actuating PneuNet Fingers: (a) testing the fingers, (b) a sample grasp, (c) hand "open" by applying vacuum.

this design were easy to see. the PneuNet actuators didn't apply much force when inflated and didn't seem robust enough for our application. Before spending more time on this design it was decided it would beneficial to first gain a better understanding of the capabilities of other types of soft actuators.

3.2.2 The Kestrel Digit by SuperReleaser

The second type of finger constructed was the Kestrel Digit used in The Kestrel [49] (Fig. 3.7), an open source soft gripper designed by SuperReleaser [3], which will be featured a book by Maker Media [1] in early 2018. There were multiple difficulties with the Fast Actuating PneuNet fingers and clearly more hands-on experience was needed with different soft actuators before any particular type of could be chosen for use in this project. SuperReleaser generously provided the 3D design of the finger for testing purposes. The design is essentially a PneuNet actuator but seemed a lot more robust.

Figure 3.7: "The Kestrel" Open Source Soft Gripper by SuperReleaser

Even though a 3D model of the finger was provided, a mold had to be designed and built for it, which was a novel experience and highlighted a lot of the considerations involved in creating a mold. The most challenging part and biggest difference from the Fast Actuating PneuNet was that the Kestrel Digit was to be cast as one piece. This meant that the core of the mold could only be supported at one end, yet still needed to be precisely positioned every time and securely fixed in place. As seen in Fig. 3.8, the mold is quite different from the open-faced molds of PneuNets. Its vertical orientation posed additional challenges and necessitated the exploration of methods for injecting the silicone rubber rather than pouring it. Overcoming these challenges was a very useful technical exercise and a valuable learning experience.

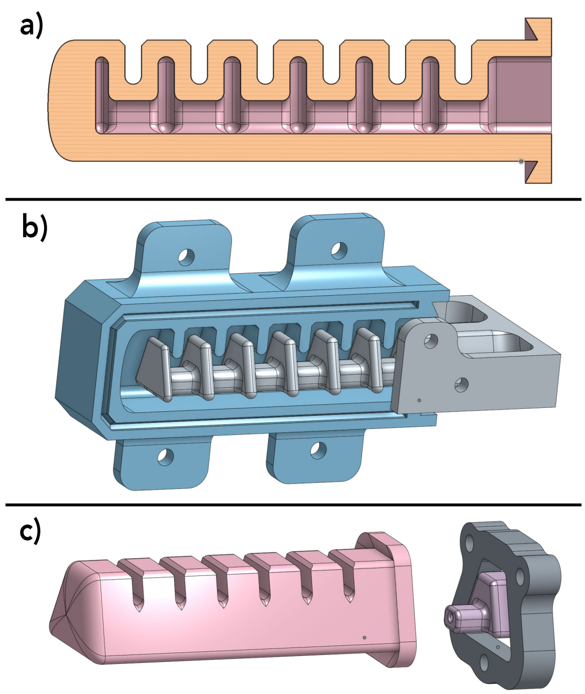

Figure 3.8: Kestrel Digit Finger Designs. a) Finger cross-section; b) Mold design; c) Finger, air tube insert and mounting cap

The design of the finger also provided some important insights into alternative and more reliable ways for attaching the fingers to a palm as well as securing the air tube. The finger features a small mounting lip and adding a plastic mounting cap that fit the lip ensures a clean and secure install with minimal waste of rubber compared to the solid rubber base design for the PneuNet fingers. The Kestrel digit, due to the presence of the core was not sealed but rather was designed to use a plastic insert to plug the hole at the base. The plug also serves as a mount for the air tube, which could either be glued or attached to a push-type quick connector screwed into the insert.

In order to be able to remove the mold core after casting, SuperReleaser recommended using rubber no harder than durometer 00-30. This is considerably softer than the Elastosil M4601AB (shore A28) which was the only elastomer readily available at that time. Despite the large difference in durometer, a decision was made to go ahead with the build. The experiment proved to be an excellent learning experience in mold design, injection molding and degassing. Unfortunately, as expected it was impossible to remove the core from the cast piece. This was an opportunity to experiment with silicone glues, so the finger was cut longitudinally and at an angle, to provide a larger surface area for the glue to work on. The glue used was inexpensive Loctite Clear Silicone Waterproof Sealant (908570). Surprisingly after gluing the cut and mounting the finger to a base it inflated successfully without any leaks (Fig. 3.9)

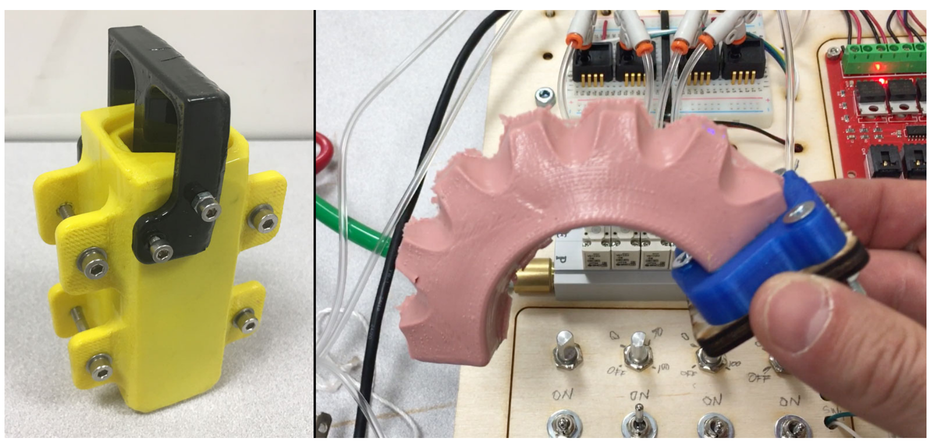

Figure 3.9: The Kestrel Digit: finger mold (left), finger (right)

Since the finger was designed for 00-30 durometer rubber, the walls of its chambers are quite thick and require considerable pressure to inflate which also allowes the finger to apply a much larger force. The design was promising, although a bit large for our application.

3.2.3 Single-Piece PneuNet Actuator-Based Fingers

The next step was an attempt to design an actuator which featured the benefits of Fast Actuating PneuNets without any of the drawbacks. The design produced featured triangular rather than rectangular chambers and just like the Kestrel Digit was to be cast as a single-piece. Other features it shared with the Kestrel were the mounting lip and air tube insert. The mold was almost identical to the Kestrel and featured an injection hole at the tip. See Fig. 3.10 for design details.

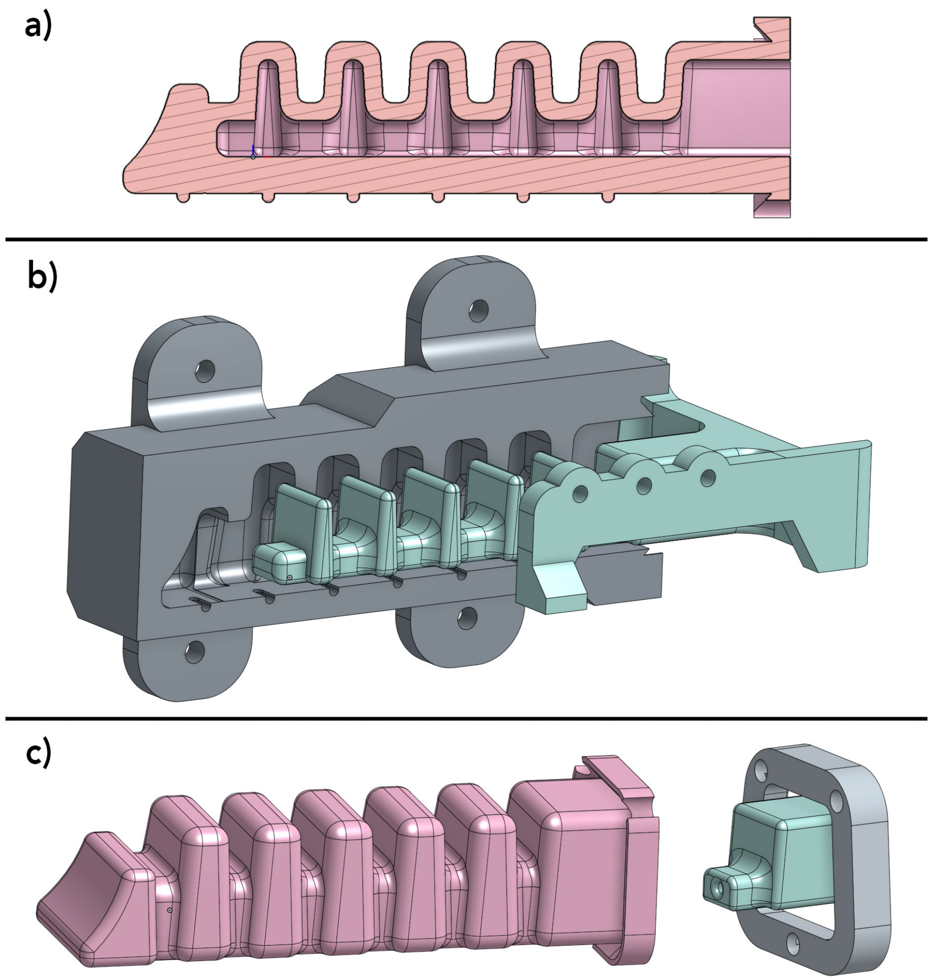

Figure 3.10: Single-Piece PneuNet Actuator-Based Finger Designs. a) Finger cross-section; b) Mold design; c) Finger, air tube insert and mounting cap

With considerable experience in working with silicone rubber at this point, using injection molding (Fig. 2.16), the fingers produced were of high quality and free of bubbles or other manufacturing process related imperfections. Just like the Kestrel they had to be cut and glued back together in order to be removed from the mold (Fig. 3.11). Just as in the case of the Kestrel digit gluing was successful and there were no leaks. Unfortunately, due to the different morphology and increase in length, these fingers were a lot less rigid than the Kestrel Digit and applied less force when inflated.

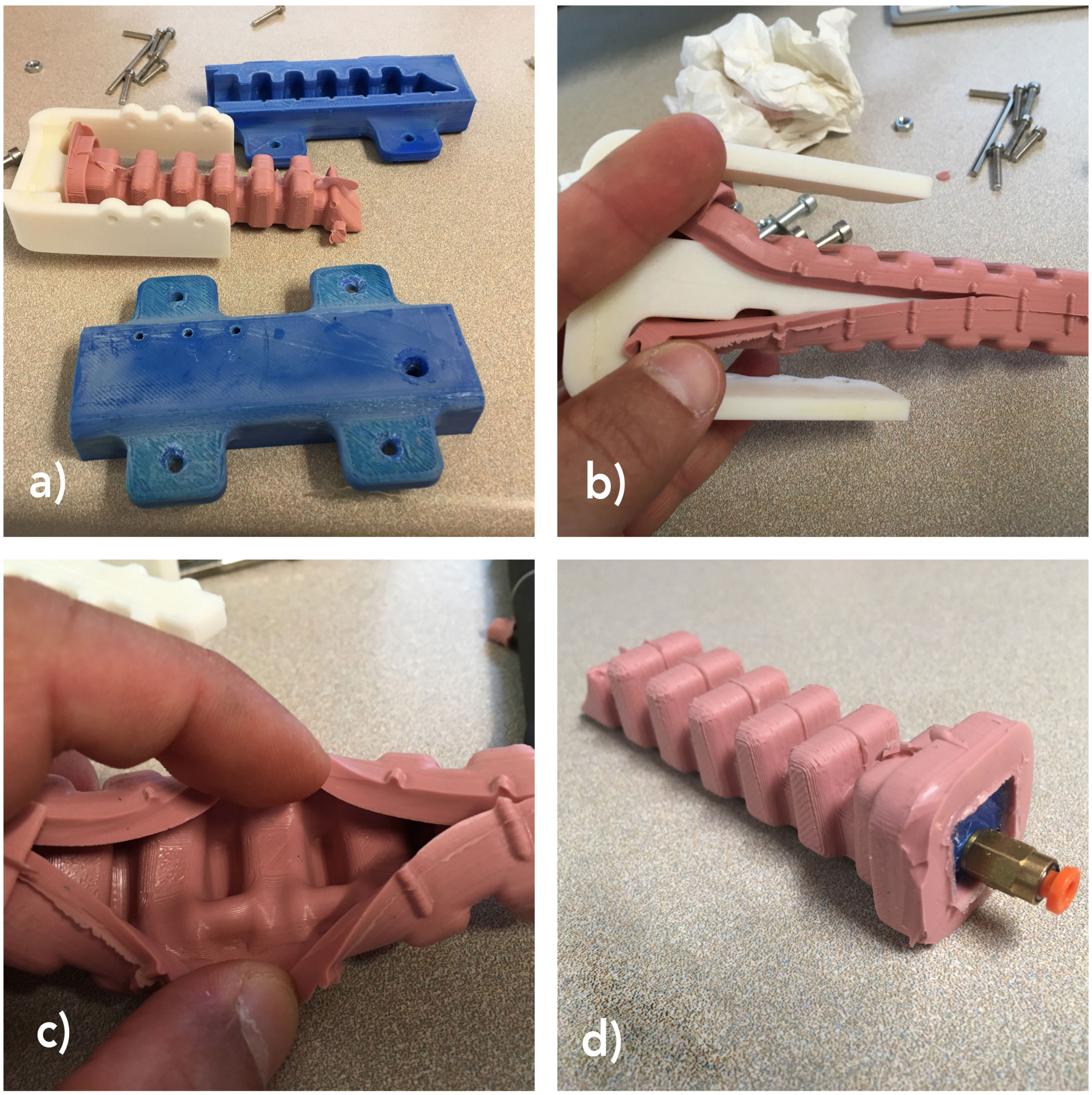

Figure 3.11: Single-Piece PneuNet Actuator-Based Finger. a) Demolding; b) Removing the core; c) Interior channel view showing excellent rubber quality; d) Assembled finger

3.2.4 Fiber-Reinforced Actuator-Based Fingers

While attending the Summer School on Soft Manipulation 2017 at Lake Chemisee, Germany, there was an opportunity to get first-hand experience of various actuators including the fiber-reinforced fingers used by the RBO Hand-2, as shown in Fig. 3.12. While very narrow and thin these fingers were able to apply impressive forces. The fiber reinforcement helps avoid punctures due to accidental over-inflation and adds to the robustness of the fingers.

Figure 3.12: RBO Hand 2

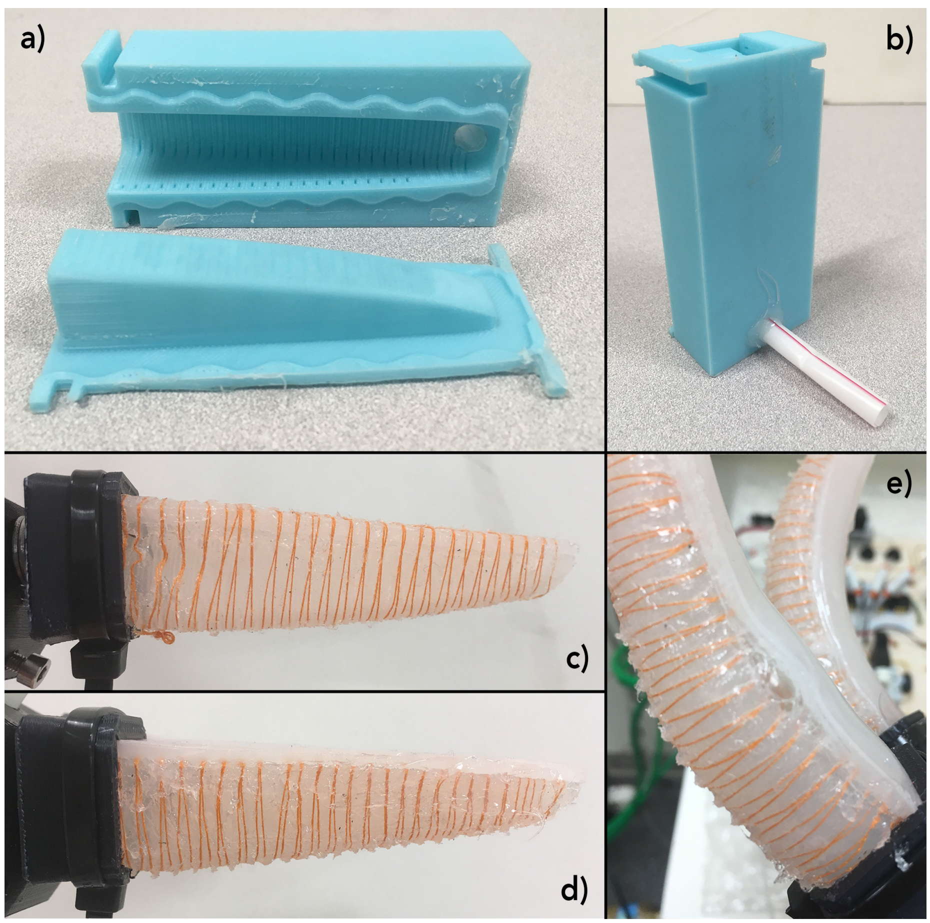

Figure 3.13: RBO-Style Fiber Reinforced Fingers: (a) and (b) Finger mold, modified for injection, (c) Finger with fiber reinforcement added after assembly with strain limiting layer, (d) Finger with strain limiting layer added after fiber reinforcement, (e) Delamination problems

Initially, the original finger mold designs provided by RBO were used with the only modification being the addition of a hole at the tip for injecting the rubber (Fig. 3.13a&b). The fingers were cast successfully without major difficulties using Quantum Silicones TrueSkin 20, an impressive material with Shore A20 hardness, elongation at break of 1000%, viscosity of just 10,000cps and a pot life of 20 minutes. High-quality polyethylene sewing thread was used for the fiber reinforcement and silkscreen for the inextensible base layer. According to RBO instructions, the fiber reinforcement is to be added to the body of the finger before assembling with the strain-limiting base layer as shown in Fig. 3.13d. 2 fingers were built in this manner, however, each thread passing between the 2 layers could be a potential air leak, so the next 2 fingers were first assembled and the fiber reinforcement added afterwards (Fig. 3.13c). While both designs worked well at the beginning, the fingers with fiber reinforcement added before assembly soon started to delaminate (Fig. 3.13e) and eventually failed.

Due to these issues, new molds were designed and fabricated (Fig. 3.14a), so that the entire air chamber of the finger can be cast as a single piece, eliminating the need for assembly and potential delamination problems down the road. While the designs for the RBO hand do not elaborate on the method of attaching the fingers to the palm, when examining them in person in Germany, it was noted that the base of each finger was sealed by a plastic plug glued in place. The plug featured an M4 metal fastener for mounting the finger and also served as an entry point for the air tube. A similar plug was designed and 3D printed. The result was a very robust mounting solution and trouble-free fingers.

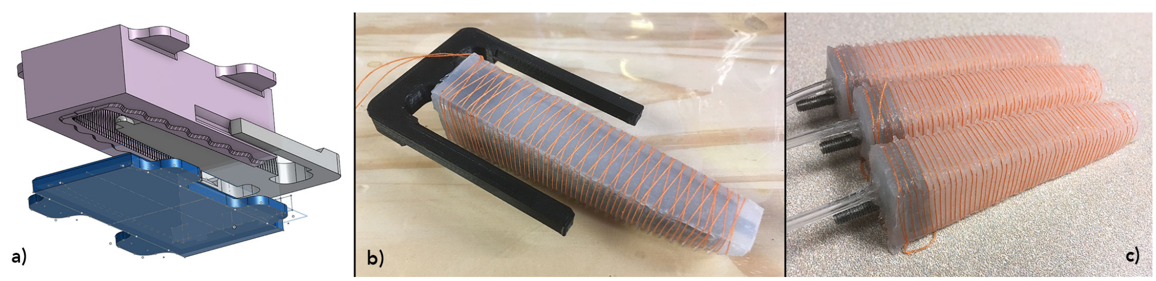

Figure 3.14: RBO-Style Fiber Reinforced Fingers: (a) and (b) Finger mold, modified for injection, (c) Finger with fiber reinforcement added after assembly with strain limiting layer, (d) Finger with strain limiting layer added after fiber reinforcement, (e) Delamination problems

The reason for not using Elastosil M4601AB as before is the fact that RBO's tutorial called for the use of rubber with Shore 00-50 (approximately Shore A7) durometer, in particular, Smooth-On Ecoflex 00-50 which is white. While our fiber-reinforced fingers perform very well and apply considerable force considering their size, first impressions are that they are not as strong as the fingers tested at the summer school. Those fingers were fabricated from blue silicone which may have been a different durometer. The design could easily be reused with Elastosil M4601AB or other higher durometer rubber if more force is required in the future.

3.2.5 3D Printed Fingers

It is worth noting that some work went into several (failed) attempts to produce a PneuNet-based finger that is 3D printable using PCTPE Filament. Since the fabrication of soft actuators is quite a manual and time-consuming process, over the past few years researchers have been working on developing new techniques and materials that can be used for 3D printing actuators rather than casting them.

After becoming familiar with the PCTPE Filament during the fabrication of the flexible arm extension (see Section 3.3) it was clear that even though not very elastic the material was very flexible and incredibly strong. It also offers excellent inter-layer adhesion, which meant air-tight models should be possible.

Due to the low elasticity of the material a bellows-like design was first tested (Fig. 3.15a). Unfortunately, when printed even with shell thickness of just 1mm (equivalent to 2 walls/perimeters) the object was too stiff. 3D printers offer another print mode, commonly known as "spiralized contour" or "vase mode". When printing in vase mode the entire 3D model is printed with a single wall. Regrettably, this also failed, since the printer had to print in mid-air when it reached the areas between the bellow folds. This resulted in holes, so even though the prototype was flexible it couldn't be inflated.

In order to solve the problem of producing an air-tight prototype in vase mode, a different morphology was adopted (Fig. 3.15b). The design featured more rounded features, eliminating any sudden changes in surface direction. The final design of this prototype is the result of multiple failed 3D prints and minute tweaks to the area between air chambers.

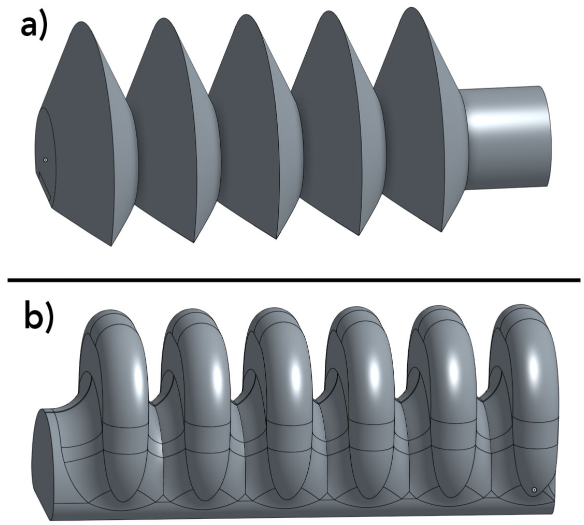

Figure 3.15: 3D Printable Actuator Prototypes

Eventually the results were much better than with the bellows-like design, however, it was never airtight.

As new 3D printing filaments are invented and become popular this topic should be revisited.

3.3 Flexible Arm Extension

The flexible arm extension is the main idea around, which the whole project came together. If done correctly its slender shape would allow for better reachability inside bins, absorb collisions and eliminate contact between the actual robot arm and the environment. In order to be usable it would need to be stiff enough to maintain its shape while lifting objects weighing up to 500g. In addition, it would need to be made out of a material that could sustain large deformations and then return to its original shape. This is very important since we need a constant geometry in order to plan our grasps correctly.

The design process began with a review of existing 3D printable flexible materials. The material had to be flexible but not soft, as well as very tough. The PCTPE filament from Taulman USA seemed like a good candidate. PCTPE is a type of nylon, which like other nylons is flexible but very resilient. After printing several tests I was very impressed with its properties and concluded that it would be a suitable material for this project.

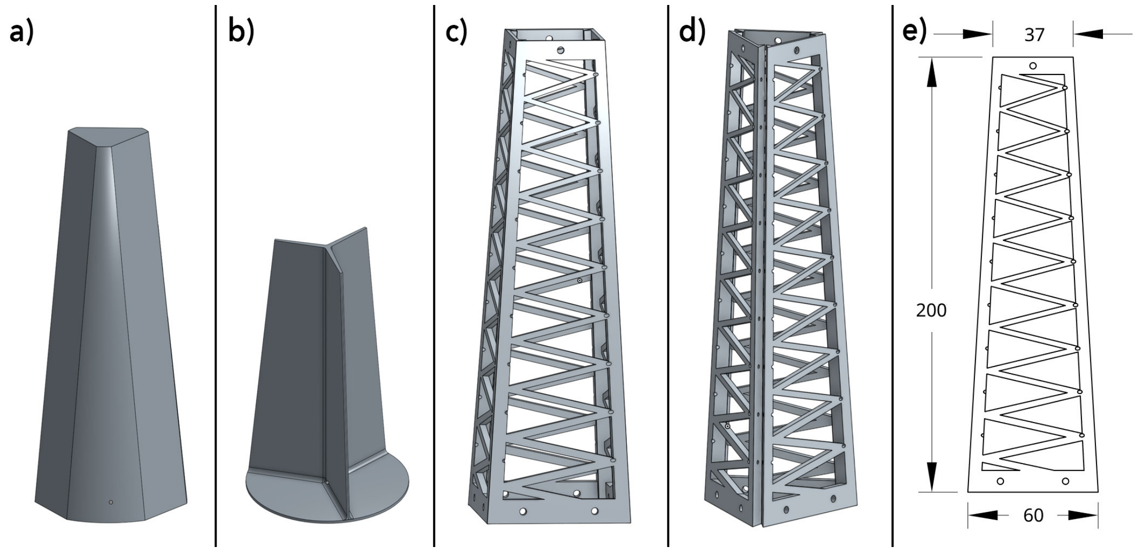

Figure 3.16: Flexible arm designs: (a) hollow truncated pyramid, (b)

The next step was to come up with a 3D printable design for the arm extension. Objects printed with flexible materials and minimal infill are often easy to deform. The first draft resembled a truncated 3-sided pyramid (Fig. 3.16a), however, this proved to be too stiff and unusable. This failed design provided the valuable insight that the arm extension probably needs to be completely hollow and the sides not completely solid.

The second design (Fig. 3.16b) featured a central spine with 3 thin blades at 120 degrees to each other. This was supposed to minimize the need for the material to stretch in order to deform since PCTPE is flexible but not very elastic. Unfortunately, this design was also rather inflexible and would leave any air tubes running to the fingers completely exposed and they could potentially get damaged.

Inspiration was then drawn from telecommunication towers which have a scaffold-like design and are made of parts which by themselves are not very massive or strong but due to the way they connect and reinforce each other the structure ends up being light but strong. The first prototype featured 4 sides (Fig. 3.16c) and showed promising results but it had some problems. It was too flexible and when deformed it would sometimes get stuck and fail to return to its original shape. These problems were easily solved by changing the design to have 3 sides (Fig. 3.16d) and increasing their thickness. The sides were designed to be printed flat and then assembled (Fig. 3.16d&e). Even though an arm closer to 300mm in length may be better, this prototype was limited to 200mm, the size of the 3D printer available.

Printing with PCTPE came with some challenges. Like most other nylon filaments, it is very hygroscopic and absorbs moisture from the air very quickly. Printing with it after leaving it in the open for only a day, loud pops could be heard during printing - moisture trapped in the filament boiling and exploding. This drastically reduced print quality and the material's properties. This is a well-known problem and was easily eliminated by constructing a dry box filled with silica (Fig. 3.17).

Figure 3.17: DIY 3D printing filament drybox

The second big problem was warping of the print due to cooling, with the edges of the print lifting off the print bed. Printing on a borosilicate glass plate, treated with extra-strong hold hairspray provided excellent bed adhesion and eliminated most of these problems.

3.4 Bellows-Driven Vacuum-Operated Lifting Mechanism and Suction Cup

As mentioned previously, during the APC it was often discussed that a suction cup in the center of the palm of most fingered hands would be very beneficial to grasp stability. Furthermore, our design was strongly influenced by RightHand Robotics' interpretation of this idea, as seen in Fig. 2.5. The fact that the suction cup is very small and is positioned far ahead of the fingers makes this setup very attractive for picking in clutter.

The retraction could be achieved in different ways using various electro-mechanical actuators, however, that would increase the complexity of the system and didn't align with the goal of the project to have a solution that is entirely made of deformable components. Drawing inspiration from industrial applications of suction it was easy to see that bellows could be used instead. Suction cups with bellows are standard in industry and used for the purpose of lifting objects.

Unfortunately finding commercially available bellows which could fit within the interior of the arm extension and also provide 80mm of lift (so that the suction cup could extend past the tips of the fingers) proved to be a real challenge. Having gained considerable experience in 3D printing and working with flexible materials the focus was turned towards designing and printing the bellows in-house.

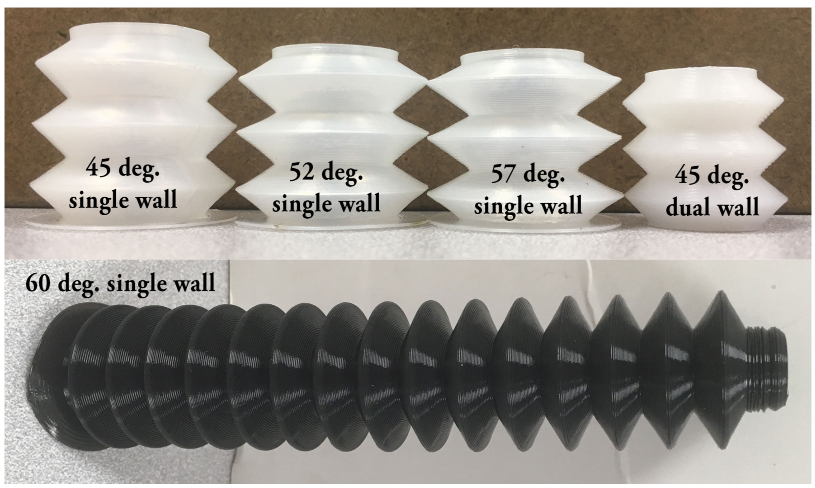

Figure 3.18: Samples of 3D printed bellows: printed using PCTPE (top), using Cheetah (bottom)

The bellows would need to be printed as one piece and in their relaxed state in order to avoid any leaks. Several tests bellows designs were printed using Taulman's PCTPE (Fig. 3.18). The first design featured bellows with 45-degree overhang. 45 degrees was the starting point because while some materials can print well with overhangs of up to 70 degrees or more (such as PLA), almost all should work fine up to about 45 degrees. The first test was printed normally (with dual perimeter walls) and was almost completely rigid. 3D printers also offer printing in single perimeter (vase mode) with no interior fill. The rest of the tests were printed in vase mode and exhibited excellent interlayer adhesion and airtightness. While the test prints were successful the material required some force to get the bellows to collapse and would then get stuck in this position until pulled apart. The bellows became more flexible as the overhang angle was increased. PCTPE printed well up to 57 degrees overhand however the bellows were still too stiff.

Two popular flexible filaments, Cheetah and NinjaFlex from NinjaTek, were chosen next. Ninjaflex proved to be very hard to print with and it was much too soft, while Cheetah gave excellent results. It printed successfully with an overhang of 60 degrees and was flexible enough to be easily collapsed and then extended without much difficulty (Fig. 3.18).

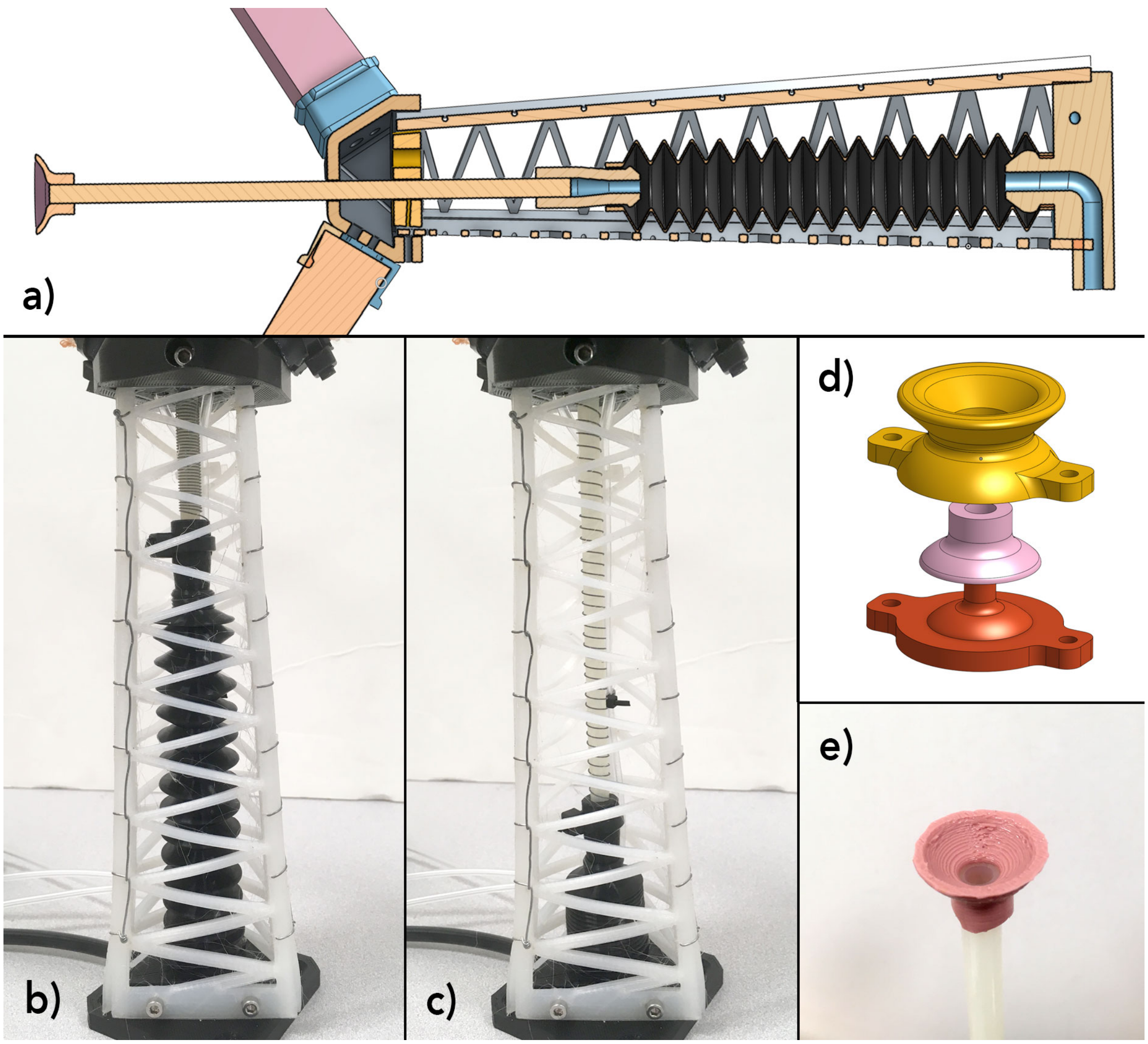

Figure 3.19: Bellows lifting mechanism: a) mechanism cross section, b) bellows with spring in relaxed state c) bellows collapsed under vacuum d) suction cup mold design, e) suction cup

The suction cup needed to be small to minimize leaks as well as bulk. Having become comfortable with casting elastomers the simplest solution was to design and cast the suction cup in-house. The mold was designed (Fig. 3.19d) and cup cast from Elastosil M4601AB without much difficulty. The suction cup featured in Fig. 3.19e is 18mm in diameter.

The final component of the mechanism is the tube that the suction cup is mounted on. It needed to be flexible enough to handle deformations due to collisions, while stiff enough to remain straight. 6mm OD polyethylene tubing (Durometer 45D) was selected for the task.

Preliminary tests of the mechanism were successful, however, it was discovered that the natural tendency of the bellows to return to the extended position was not enough to counter friction and the weight of the tube. Therefore a spring was added to assist with that. The final design of the mechanism, bellows and suction cup mold can be seen in Fig. 3.19. The bellows are 120mm long and 40mm long when collapsed under vacuum, which results in 80mm lift. The central air tube is 140mm long.

3.5 Palm

The palm design is very simple and serves several purposes:

- A mounting surface for the fingers
- A guide for the suction cup and tube
- An attachment point for the air tube spring
- A way to attach the fingers to the flexible arm extension

The palm was designed to be as small as possible while still fulfilling the requirements listed above. It has 2 parts (Fig. 3.20a&b). The bottom half, depicted in yellow, is the one that slides over the top of the flexible arm extension and features a triangular groove where the end of the arm fits. Bolt holes on the sides secure the flexible arm to the lower part of the palm. The holes within the triangular insert are for the central air tube, finger air tubes, and spring attachment. The 4 holes on the outside are for the screws that attach the top half.

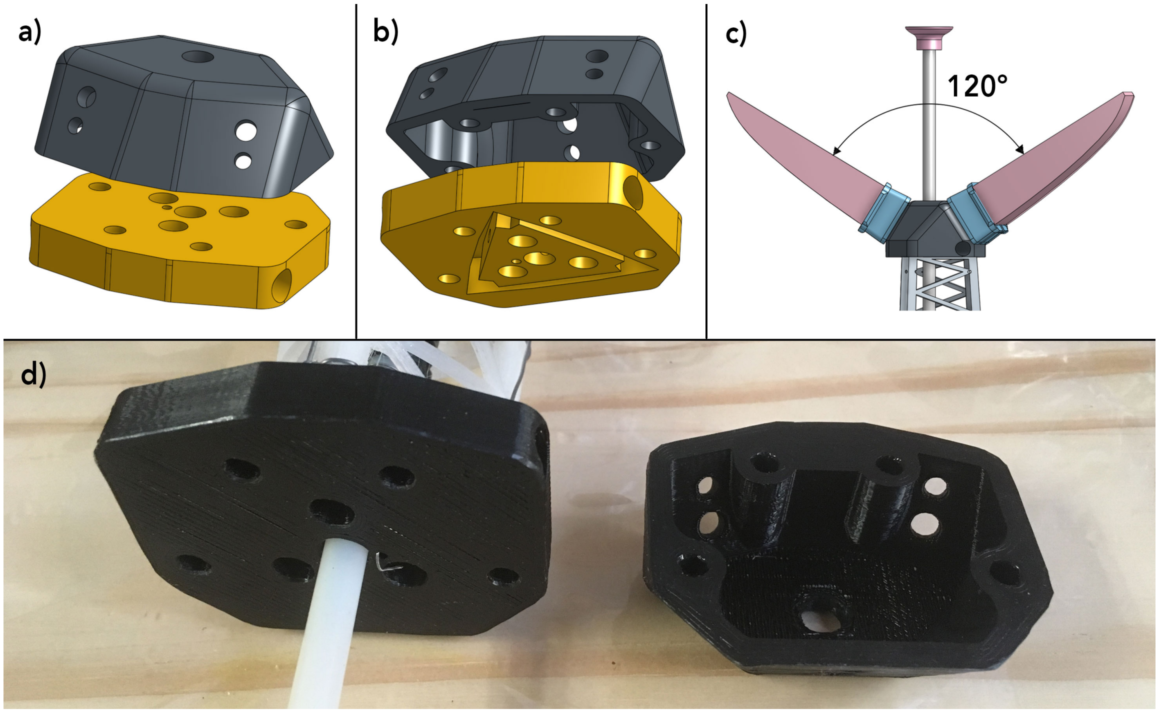

Figure 3.20: Palm: (a) from above, (b) from below, (c) illustration of finger angle, (d) 3D printed palm

The top half of the palm provides the mounting points for the fingers. Originally the top and lower parts of the palm were a single unit and the triangular insert was separate. This made it very difficult to install the fingers onto the palm and then to secure the palm to the flexible arm extension. The new modular design speeds up both of these steps considerably.

The 2 main parameters of the palm are the number of fingers it should accommodate and the angle at which the fingers are mounted relative to the palm surface. The first prototype featured an angle of 150 degrees however that was deemed to be inadequate. The current setup has an angle of 120 degrees (Fig. 3.20c).

Initially, for testing purposes, a 2 finger version was constructed but did not result in stable grasps. The 3 fingered version fabricated next works much better. Different palms with other angles and number of digits can easily be designed and printed. The modular design of the palm means only the top cap needs to be redesigned and printed unless the new design departs far from the current and needs a completely different base.

PLA plastic was the material of choice, due to its ease of use and fast printing speeds, however, the design could easily be printed using tougher and more flexible materials (e.g.

ABS, Nylon, etc.), if necessary.

3.6 Base

Just like the palm the base is simple and has multiple functions:

- Serves as a mounting adapter for the arm extension to the robot
- Serves as a mounting point for the bottom part of the bellows
- Accepts the vacuum tube for suction cup and channels the vacuum to the bellows without the need for additonal hardware

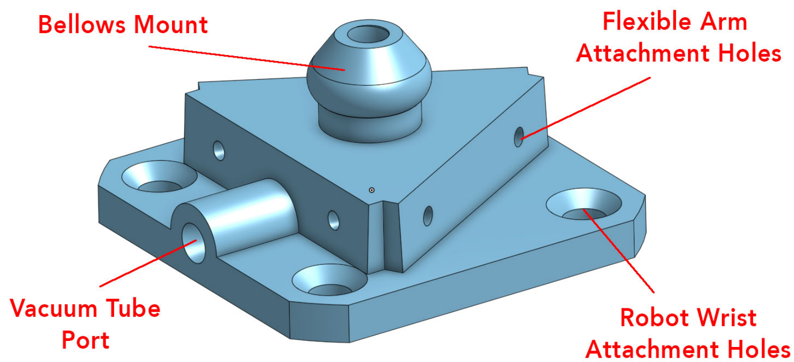

Figure 3.21: Flexible Arm Base Mount

As seen in Fig. 3.21 the design is functional and minimalistic. Similar to the palm it was printed using PLA plastic.

3.7 Pneumatics Control Board and Air Source

The control board used (Fig. 3.22) is very similar to the one described in the Soft Robotics Toolkit [53]. It features a DC power source, a couple of step-down voltage converters, fast-actuating air valves for controlling the fingers, a set of MOSFETs for turning the valves on and off, pressure sensors and potentiometers for adjusting the air pressure inside the fingers and a programmable logic controller to run the entire setup.

The control board's switches and potentiometers allow for manual control of the hand and of course, it can also be controlled programmatically using the Arduino's serial interface.

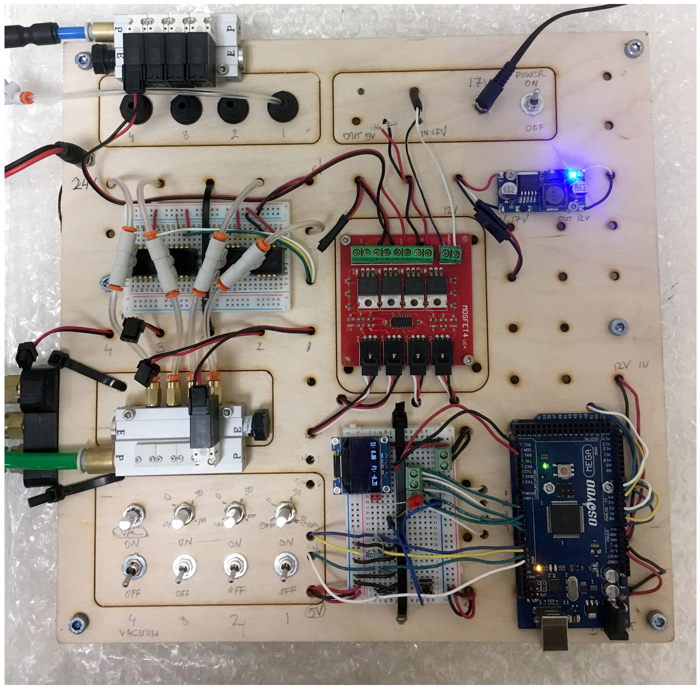

Figure 3.22: Fluidic Control Board

There are some differences between this control board and the one described in the SRT. An extra valve was added, for turning the vacuum on and off and the air source used is different. Instead of a DC air/vacuum pump, this solution uses an air compressor and a dual-stage air ejector, which were already available in our lab.

The biggest difference, however, is the way the fingers are controlled. Originally as outlined in the SRT, each finger was assigned a separate valve and a method called Pulse Width Modulation (PWM) was used to control the air pressure for each finger. All valves received compressed air and then by opening and closing very quickly (ms range) pressure in the fingers could be adjusted. The larger the ratio of time on/time off (the longer the pulse duration), the higher the pressure in the fingers. When the valve is turned off any air in the finger exits through the valve's exhaust port.

While this method works, it has some serious shortcomings, the biggest of which being that while the valves are on air is constantly being lost through the exhaust port. This means the valves need to keep pulsing constantly, which can be very loud and the air compressor needs to run a lot more often to replenish the lost air pressure, which again can be very loud depending on the compressor. Even though the valves used (SMC VQ100M) can pulse very quickly (in the order of ¡10ms) air pressure is constantly being adjusted and as a result the fingers usually exhibit twitches/tremors due to the changes in pressure.

As mentioned in Section 3.2.4, while at the SOMA 2017 Summer School, I had a chance to experience fiber-reinforced actuators first-hand. I was also exposed to another way of controlling them - using separate valves for inflation and deflation. Other than the additional initial investment to purchase extra valves the concept is simple. Unfortunately, after purchasing a second manifold and set of SMC VQ100M valves it was discovered that these valves were the wrong type for this purpose. In particular, the problem was that the input (high-pressure) port of all the valves on the same manifold was shared, which meant there was no way to connect different fingers to different valves unless each had a separate manifold.

It was decided that at this stage individual finger control is not necessary and the benefits of having separate inflation and deflation valves were sufficient reason to proceed with this design. The setup was simplified by connecting all fingers together and using one inflation and one deflation valve.

Even though the setup was correct in theory, the deflation valve failed to work as expected. While the LED light on the valve indicated it was turned on, it failed to open. Further research into pneumatics revealed that in order for valves to operate correctly, in addition to an electrical signal they also require a minimum air pressure. Apparently, the maximum inflation pressure of the fiber-reinforced fingers (0.6 bar) was below that threshold. Without a functioning deflation valve, the fingers had to deflate on their own, due to minute air leaks throughout the system, which could take up to 30 seconds. This is an issue that can easily be resolved and will be discussed further in Section 5.2.6.

Chapter 4

Experimental Setup

For additional images and videos of the fingers and degasssing tools in action, please access the supplemental file repository [4]

4.1 Hardware Setup

The robot used in the lab is a Yaskawa Motoman SDA10F dual-arm industrial robot.

Vacuum for the suction is provided by a VacuPlus VP04.012S air ejector (VacuPlus housing using Piab Si32-2-2 dual-stage air ejector cartridge), which is fed with compressed air at 8 bar pressure from a California Tools CAT-10020SPC 2.0HP air compressor.

4.2 Testing Soft Fingers

A simple test rig was fabricated (Fig. 4.1) in order to collect information about the amount of bending and force exerted by each finger at full inflation. It consists of a 3-sided plywood box with a checkered square pattern (square side is 25mm) on the back wall and a camera to photograph the tests. Force-torque sensors (e.g. the Nano17 Force Torque Sensor by ATI Industrial Automation [37]) are usually used to test the force exerted by each finger at the fingertip, however, these sensors are very expensive. It has been demonstrated [35] that an accurate digital scale can be used instead, to get approximate measures. The scale is set up so that the tip of each finger presses down on it and the maximum "weight" is recorded and converted to force applied (1,000g = 9.81N).

The test procedure was simple and identical for each finger:

- Mount finger on side wall

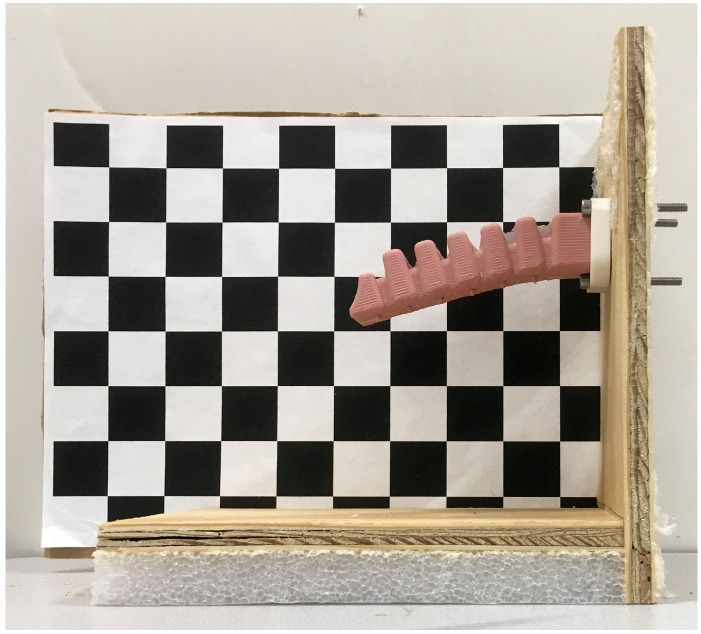

Figure 4.1: Finger Testing Rig

- Natural State: Photograph finger in its unactuated state to demonstrate the amount of bend due to gravity
- Bending at Maximum Pressure: Inflate finger fully. Note pressure required and photograph the finger
- Force Exerted: Deflate finger, position digital scale under finger tip and inflate the finger to the pressure recorded in the previous step. Photograph setup and record maximum reading on scale

The results from the tests can be seen in Fig. 4.2 and Table 4.1.

Table 4.1: Finger Test Results

Finger	**Natural Bend (deg)**	**Max. Pres. (bar)**	**Max Bend (deg)**	**Max Force (N)**
FA PneuNet	30	1	220	1.87
Kestrel Digit	10	2	140	2.95
Single Piece Pneu Net	18	1	170	3.95
Fiber Reinforced	12	0.6	180	2.52

Figure 4.2: Finger Test Results: (by column) FA PneuNet Actuator Finger, Kestrel Digit, Single-Piece PneuNet Actuator Finger, Fiber-Reinforced Actuator Finger

4.3 Testing Grasps

4.3.1 Objects and Poses

In previous research at the lab [30] we compared the effectiveness of a vacuum end-effector and a 3-finger underactuated hand. An effort was made to keep the experimental setup as similar to that as possible for comparability, so the same objects and number of trials were used.

A list of the objects used can be seen in Fig. 4.3. 12 grasps were tested per object, which can be divided into 2 groups based on the approach direction - regular and alternative. Since, the majority of the objects are rectangular, approaching any of the 6 sides directly is considered a regular grasp. Alternative grasps are the ones where the object was approached from the edge or another direction. The grasp strategies for non-rectangular objects are all different and are outlined below.

Figure 4.3: Grasp Test Objects: spark plug, cheez-its, crayola box, rolodex, elmerś glue, feline treats, sticky notes, kong duck toy, kyjen balls, book, outlet plugs, rubber ducky

During these tests, the hand was operated manually and was not mounted on the robot. When testing a grasp the object was approached with the suction cup and vacuum turned on unless specified otherwise. After successful attachment of the suction cup and bringing the object into the palm, the fingers were closed and the object lifted off the test bench. In the cases where the suction cup could not get good suction, either due to the approach direction (alternative grasps) or the surface of the object, a grasp with the fingers only was attempted. To test the stability of the grasp a shake test was performed to replicate disturbances the object may experience during transfer. A grasp was marked as failed when the object could not be lifted.

4.3.2 Results

Following is a detailed description of the test results. All the data collected is available in Table 4.1. A visual overview of the overall grasp performance of the hand can be seen in Fig. 4.4.

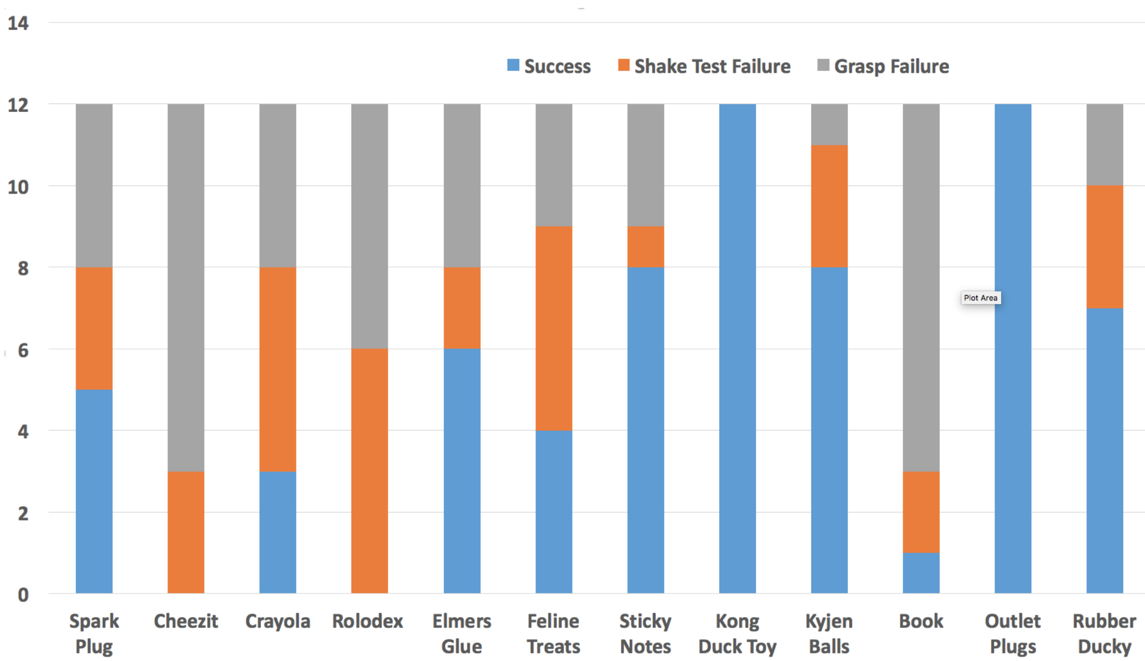

Figure 4.4: Visual overview of grasp data

- Spark Plug: The suction cup worked well every time it was possible to get a good seal, i.e. the flat sides of the object, however, the shake test failed for one of the cases where the suction cup was attached to the smallest side. Since the spark plug is a small object, the fingers could not cage it properly.

  Since the suction cup only works if flush against a surface, the alternative grasps were attempted with fingers only. In the cases when the spark plug was laying flat on the table the hand failed to grasp it successfully. When standing on its side it was grasped successfully, however, failed the shake test.

- Cheezit: Due to the weight of the box (380g) all shake tests failed. The 2 grasps approaching the large side of the box failed as well. The suction cup attached successfully as expected, however, the finger span was insufficient to wrap around the

Table 4.2: Grasp Test Data

	Spark Plug	**Cheezit**	**Crayola**	**Rolodex**
Success	5	0	3	0
Shake Test Failure	3	3	5	6
Grasp Failure	4	9	4	6
Dimensions (cm)	10x2.5x2	22x16x6	11.5x7.5x2.5	14x11x8
Volume (cm^3)	50	2112	215	1232
Weight (g)	63	380	92	94

	Elmers Glue	**Feline Treats**	**Sticky Notes**	**Kong Duck Toy**
Success	6	4	8	12
Shake Test Failure	2	5	1	0
Grasp Failure	4	3	3	0
Dimensions (cm)	15x6x3	21x15x5	10.5x5x4	13x7x3
Volume (cm^3)	270	1575	210	273
Weight (g)	128	174	165	32

	Kyjen Balls	**Book**	**Outlet Plugs**	**Rubber Ducky**
Success	8	1	12	7
Shake Test Failure	3	2	0	3
Grasp Failure	1	9	0	2
Dimensions (cm)	5 (dia.) x 3	21x13x1.5	19x9x6	13x10x7
Volume (cm^3)	525	410	1026	910
Weight (g)	47	175	76	68

object and when fingers were activated they pushed the box away. The alternative grasps used fingers only and all failed. The fingers are quite flexible, so even though they provide adequate force, they can be twisted and bent sideways. Also by the time the fingertips reached the flat sides of the box they were already curled too much, so instead of applying force towards the object, they bent lost their grip. This problem occurred multiple times and can be seen in Fig. 4.5.

- Crayola: This object is not very heavy and all of the regular grasps worked well, except when the box was laying flat on the surface and was approached from its long side with the fingers parallel to the surface. In that case, actuating the fingers broke the suction and friction with the fingers was insufficient to hold the object. The situation was similar with the alternative grasps where the fingers were not able to pick up the object while laying down and in 3 of the other cases the fingers had not wrapped around the object.

- Rolodex: This is a difficult object and can only be grasped in 1 of 4 ways - a) approaching from the top with fingers only, trying to grasp the the cup by the rim; b) approaching from the bottom, attaching the suction cup to the flat side of the base and then grasping with the fingers; c) approaching from the side using only the fingers, no suction and d) trying to grasp the edge, while having 1 or 2 fingers inside the cup. Each of these grasps was repeated 3 times. Grasps of type a) were all successful, b) suction worked well, however, inflating the fingers caused suction to break and friction with the fingers only wasn't enough to hold the cup in place, c) all were able to lift the cup but also all failed the shake tests, d) all failed due to insufficient friction.

- Elmers Glue: The smooth surface and almost cylindrical shape of the glue bottle resulted in excellent suction and caging grasps. All successful grasps passed the shake test. When approaching the bottle from the top it was sometimes possible to get good enough suction to be able to lift the object but the grasps didn't pass the shake test. Attempting to grasp the object from top or bottom without suction resulted in failed grasps.

- Feline Treats: The bag of treats could be approached from 4 general directions: front, side, top, and bottom. Suction was only used for front and side and produced good grasps, but 2 of the side grasps failed the shake test. The flexibility of the bag allowed suction to break and curling and twisting of the fingers resulted in insufficient friction to maintain the grasps. Approaching from the top or bottom without suction resulted in 3 failed grasp attempts and 3 grasps that failed the shake test.

- Sticky Notes: The low weight and smooth surface of this object meant suction could be used from all directions. Grasps were all successful and passed the shake test, with the exception of 3 grasps, trying to wrap the fingers around the longest side, which failed due to the fingers pushing the object away and breaking the suction. One of the successful grasps failed the shake test as well.

- Kong Duck Toy: For this object, grasps can be divided into 2 groups - grasps with and without suction. Suction was used whenever it was possible to attach the suction cup to the label. All grasps with suction were successful and passed the shake test. The small size and low weight allowed the fingers to wrap around the toy and produced successful grasps that also passed the shake test.

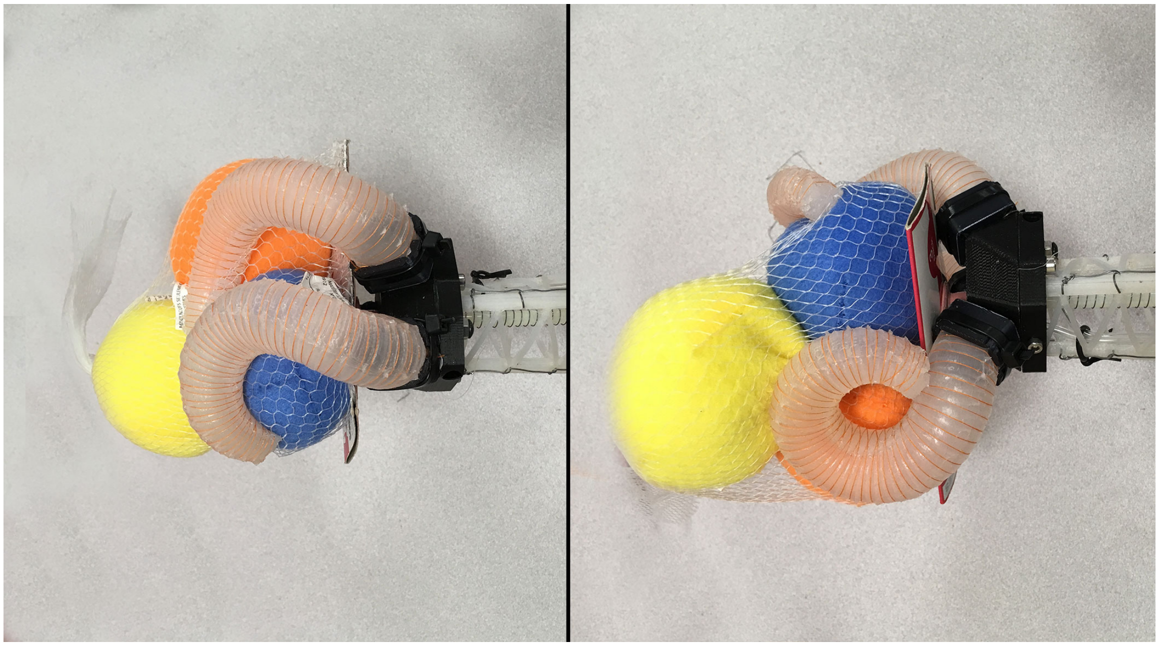

Figure 4.5: Illustration of the problem of the fingers curling up and twising sideways, resulting in inability to apply force in the direction needed and eventually a failed grasp

- Kyjen Balls: The grasping strategy here was the same as for the Kong Duck Toy. The results produced were also similar with the exception of grasps using fingers only. Successful non-suction grasps were only produced when the hand was positioned so that each finger ended up between 2 adjacent balls. Grasps of any other configuration eventually failed the shake test because the fingertips curled too much (Fig. 4.5) and the force exerted on the object was not enough to provide sufficient friction.

- Book: This was a very hard object as expected. When laying down it could only be approached from the top and when propped on its side suction could only be used if the spine was visible. 6 grasps were tested with the book laying down and 6 with the book standing up. When laying down suction was good and despite the book opening when lifted (since it was not sheathed), the fingers could sometimes wrap around the smaller side of the cover. This resulted in 4 failed grasps and 1 successful grasp that didn't pass the shake test. Standing the book up on its side made things worse as the suction cup could only be used on the spine and even in that case the fingers exhibited the curling problem mentioned before and the grasp failed the shake test.

- Outlet Plugs: The convenient size, low weight and smooth surfaces on this object made it an easy pick. As a result, all 12 grasps were stable and passed the shake test.

- Duck Toy: The large smooth label and smooth rubber surface of the duck offered a lot of options for using suction. Suction could be used for 8 of the grasps and only 1 was unsuccessful while 2 others failed the shake test. The grasps which used fingers only were less reliable as expected and out of 4, 1 was unsuccessful and 1 failed the shake test.

4.4 Probing The Hand's Limits

In order to find the limits of the hand's capabilities several properties needed to be measured: the maximum weight that could be lifted using suction only, maximum weight the fingers could hold and the maximum weight the arm could support without deforming too much from its original shape.

To test the maximum weight liftable by suction only, a light container was chosen because of its perfectly smooth top cap, which would offer the best suction. The container was gradually filled with weights and the suction force was tested until it could just barely lift the container. At this point any minor disturbances caused the container to fall. It was thus determined that the suction and bellows mechanism, under perfect conditions, was capable of lifting objects weighing up to about 650g (Fig. fig:suction-max-weight-limit-test).

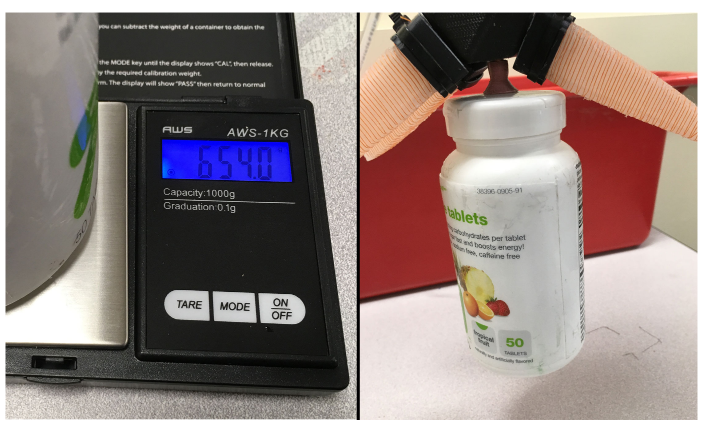

Figure 4.6: Testing suction's maximum weight lifting capability

The best way to test the maximum weight the fingers could support was to make sure they could fully wrap around the object they were holding. A 3lb exercise weight was perfect for the task. With the fingers wrapped around the handle and the palm of the hand facing down, the 3lb weight was lifted vertically up without difficulty. Reorienting the hand maintained the grasp for a while but it eventually failed and the weight was dropped.

Finally, in order to test how much weight the flexible arm extension could support, it was mounted on the robot wrist and positioned horizontally. The same 3lb exercise weight was used. Since maintaining the grasp using the hand was not possible, the weight was suspended from it with a string tied as close to the palm as possible. The wrist of the robot was then rotated 360 degrees in order to observe the deflections in all possible directions. As seen in Fig. 4.7 there was a slight deformation but overall the extension maintained its shape.

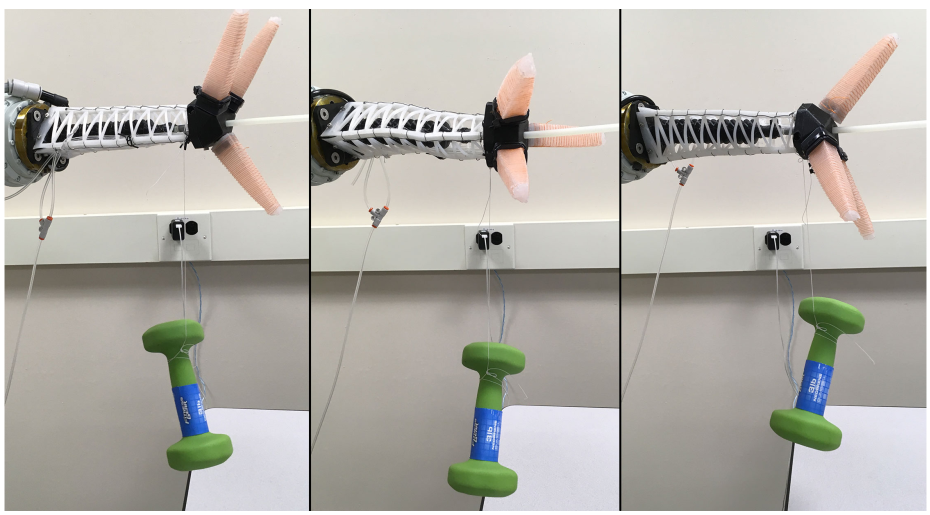

Figure 4.7: Testing the flexible arm extension's weight limit (3lb weight)

4.5 Durability Testing

One of the main claims made in this thesis is that the hand and flexible arm extension would be able to handle collisions with the environment with minimal or no damage. The only way to test this statement was to purposely initiate such collisions and record the result.

With the gripper securely mounted to our robot's wrist it was subjected to multiple violent collisions (see Fig. 4.8 for sample). A video recording of the tests is available

Figure 4.8: Durability testing: (left) the flexible arm deformed by a serious collision during testing, (right) after all the tests were completed the flexible arm extension had returned to its original shape and was straight. Notice the missing mounting cap on the top finger

at the supplemental file repository [4]. After a few collisions, the bellows-driven suction mechanism and the fingers were tested and proved to be still operational. In order to simulate real accidents, the fingers were left inflated for the second batch of collisions, since collisions can not only happen when reaching for an object (fingers not inflated), as well as after the object has been picked (fingers inflated). After all, it is easier to puncture an inflated baloon rather than an empty one.

In the end, the second set of collisions eventually destroyed the mounting cap of 1 of the fingers and introduced a small puncture. Another puncture was found on the second finger but the third was still intact. The suction mechanism continued to operate normally.

Chapter 5

Discussion

5.1 Conclusions

Working on this project was a long, interesting and rewarding learning experience. The experiments performed generated important insights, sparked many new ideas and revealed the parts of our solution that need could be refined. The data collected confirmed that even though not perfect, the solution described in this thesis is indeed quite capable and with some minor modifications could be improved even further.

Experimental results clearly showed that grasps which were able to utilize both suction and the fingers were the most stable and most of the failed grasps were ones where only the fingers or only suction could be used. Improving both of these components individually is not difficult and should reduce the number of failed grasps even further.

Suction worked well but the performance of the fingers left some to be desired. While they worked well for small light objects they clearly struggled with grasping and maintaining a good grasp on large and/or heavy objects.

Fortunately, both the fingers and suction can be easily improved. The following section describes possible solutions and some new ideas in more detail.

5.2 Future Work

5.2.1 Fingers

Designing, fabricating and testing the fingers was the most time-consuming and challenging part of this project. Even though multiple designs were built and tested, the Fiber-Reinforced fingers still seem the most promising. They did, however, have some shortcomings:

- They were too flexible and could easily be twisted to the side, which resulted in force not being applied in the right direction to hold the object and eventually in a failed grasp. This could be addressed by modifying the morphology of the finger to have thicker bottom/strain limiting layer and sidewalls. Another way that may work even better is to use a 3D-printed Nylon-based lattice structure instead of silk as the strain limiting layer. The goal in both of these approaches is to stiffen the strain limiting layer and sidewalls, so they are more resistant to twisting while remaining flexible enough to sustain collisions and unwanted deformations without damage.

- The tips of the fingers curled too much making it even easier for them to twist. This issue is related to the previous one and potentially both of them could be solved by carefully adjusting the fingers' morphology and strain limiting layer.

- The reason for many of the failed grasps was the lack of sufficient force exerted by the fingers. Solving the previous 2 problems should alleviate this automatically since force will be more likely to be applied towards the object rather than in another direction. In case this is still an issue the finger can be cast from a higher durometer rubber such as the familiar Elasosil M4601AB.

- 2 of the fingers punctured during the durability test. While the goal of this work is not to produce puncture-proof soft fingers, it was important to find out why they failed. Upon closer examination, it became clear that the punctures resulted in the rubber being pressed against sharp edges of the fingers' mounting caps. A minor redesign to eliminate these should greatly reduce the chance of punctures under similar conditions in the future.

- Several of the fingers produced did not bend in one plane but exhibited a small amount of twist. After taking a closer look it was noticed that the weave of the silkscreen in those fingers was not perfectly perpendicular to the plane of desired motion. Testing a small piece of silkscreen confirmed the suspicions - while the silk did not stretch either horizontally or vertically, applying force at an angle to the weave/diagonally caused it to stretch slightly. It is therefore important to pay attention in the future and make sure the fabric's weave is perpendicular to the plane of desired motion.

- Finally it should be noted that the fingers are not sensorized. The addition of bend sensors should allow for more precise control and in-hand manipulation if that is deemed necessary. Capacitive bend sensors are inexpensive, quite reliable and thin, which would make them easy to embed in the strain-limiting layer of the fingers.

5.2.2 Flexible Arm Extension

Overall the flexible arm extension was quite bulletproof and performed as required. It is easy, quick and cheap to fabricate and can sustain multiple serious impacts with little to no damage or permanent deformation. Its stiffness is also easily modified by adjusting the thickness of the side panels, however, at the moment it seems adequate. The only way to possibly improve it at the moment would be to make longer if needed.

5.2.3 Suction Mechanism

The lifting mechanism was intended to work this way: approach the object with the the air tube and suction cup fully extended, use suction to attach the suction cup to the object, bring the object into the palm using the lifting mechanism and finally close the fingers of the hand to improve the grasp and prevent the object from falling during transfer.

Suction performed well in the tests, however, there were some issues that should be addressed:

- It is impossible to use suction on some objects in which case the suction cup and tube are a hindrance. When testing with such objects it was realized that there is no way, built into the existing design, for retracting the suction cup. In the cases where fingers-only grasps needed to be attempted, a bottle cap was attached to the suction cup in order to get the air tube and suction cup to retract.

- As mentioned in Section 3.4, a spring was added to aid the bellows in returning to their natural extended state. Despite that when the vacuum was turned on, the suction force was so strong that the bellows would partially collapse even without an object attached to the suction cup. Approaching the object with vacuum turned off, doesn't solve this problem, as explained by the next point. The problem may be corrected by installing a stiffer spring, however, that would also take away some of the mechanism's lifting power. This is actually the reason why the spring chosen is the weakest one that could successfully overcome friction and return the bellows to their extended position.

- Another strange behavior observed was that the suction cup would repeatedly lose suction. Upon closer examination, it turned out that as an object partially blocked the suction cup opening, the vacuum in the bellows would build up, causing them to collapse and pull the suction cup away from the object. The suction cup would end up bouncing back and forth trying to get a good grip. It was clear that a mechanism was needed for keeping air tube fully extended so that it could be pushed against an object and not retract until full vacuum was achieved. This theory was tested by holding the air tube by hand, but it revealed another problem - upon releasing the tube the bellows would immediately try to collapse and this sudden motion caused the suction cup to disengage. To prevent this we would need a way to keep the air tube fixed at full extension and once released to dampen its acceleration and prevent any jerky motion.

  A possible solution would be to use a servo motor to control the position of the suction cup. This, however, adds another level of complexity to the design and negates all previous efforts to avoid electro-mechanical actuators, which was the reason for using bellows in the first place.

  While more thought needs to be put into this problem, it may be worth exploring the use stiffer springs. Even though not ideal this solution is the simplest and may work sufficiently well.

- Even though the mini suction cup cast in-house performed admirably its lip could not be made as thin as the Piab piGRIP suction cups, for example. A thinner and more flexible lip should conform better to uneven surfaces and attach even better to smooth ones. It may be worth exploring 3D printed solutions or commercially available ones.

- The 3D printed single wall (0.6mm) bellows performed admirably and turned out to be more durable than expected. Even after all the violent collisions and massive deformations (sometimes up to 90 degrees) of the enclosing flexible arm extension, the bellows were intact and fully functional. If reliability ever becomes an issue, bellows cast from stiff silicone rubber (e.g. Shore A70 or stiffer) should be sufficient.

5.2.4 Palm

Even though the new modular palm performed very well, a few small changes could make it even better and more durable:

- It could be reprinted using ABS or maybe Nylon which have better inter-layer adhesion and are less brittle than PLA plastic.
- At the moment the 2 parts attach to each other by threading the screws into the plastic. Embedding metal nuts into the design would help with the longevity of the piece and avoid stripped threads.
- The flat face of the palm was designed to be quite small, due to the workspace restrictions, however having a slightly larger palm might help with grasp stability.
- Since the palm is made of plastic its surface doesn't offer much friction. Adding a layer of silicone or other high friction material to the palm may further improve grasp stability as well.

5.2.5 Base

Just as the palm the base performed well. At this point it doesn't require any obvious refinements. If necessary, it could be made even more durable by reprinting it using ABS, Nylon or another high-strength material.

5.2.6 Pneumatics Control Board

Setting up the control board was a challenge. Much was learned about pneumatics, valves, hardware timers on the Arduino and more.

At present the board works well but could easily be improved further:

- The pressure sensors used have a working range of 0-100psi. Since we rarely exceed 10psi with the fiber-reinforced fingers, sensors with a range of 0-30psi would make more sense, operate exactly the same way and provide more accurate readings.
- The current setup doesn't include a vacuum sensor. Adding a vacuum sensor, will allow for grasp validation, which is important.
- As mentioned previously, all fingers are currently controlled by a single valve and there is no automatic deflation mechanism. Further research into the issue has revealed that separate inflation and deflation valves are not necessary. Instead, a type of valve known as 5/3 (compared to our 3/2 valves) would be able to control both inflation and deflation in one convenient package. A 5/3 (read 5 way/3 positions) valve, simply means it has 5 ports and the piston inside has 3 possible positions.

5.2.7 Control and Planning

In addition to improving the design and capabilities of the hand, it needs to be integrated with ROS. Grasp planning for compliant grippers is quite different, so a custom planner may have to be created. The SOFA Framework with Soft Robotics Plugin mentioned in 2.2.3 seems easy to use and quite good at simulating grasps with fiber-reinforced fingers like ours. It needs to be explored in more detail.

A considerable amount of additional research needs to be done on this topic before picking a direction.

For additional images and videos of the fingers and degasssing tools in action, please access the supplemental file repository [4]

References

[1] *MakerMedia*. https://makermedia.com/.

[2] *PneuNet Bending Actuators*. https://softroboticstoolkit.com/book/pneunets-bending-actuator.

[3] *SuperReleaser*. https://superreleaser.com/.

[4] *Supplemental File Repository*. http://www.kourtev.com/hristiyan/ms-thesis.

[5] *UniGripper*. http://www.unigripper.com/.

[6] John R Amend, Eric Brown, Nicholas Rodenberg, Heinrich M Jaeger, and Hod Lipson. A positive pressure universal gripper based on the jamming of granular material. *IEEE Transactions on Robotics*, 28(2):341–350, 2012.

[7] Nicholas W Bartlett, Michael T Tolley, Johannes TB Overvelde, James C Weaver, Bobak Mosadegh, Katia Bertoldi, George M Whitesides, and Robert J Wood. A 3d-printed, functionally graded soft robot powered by combustion. *Science*, 349(6244):161–165, 2015.

[8] Joshua Bishop-Moser, Girish Krishnan, Charles Kim, and Sridhar Kota. Design of soft robotic actuators using fluid-filled fiber-reinforced elastomeric enclosures in parallel combinations. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, pages 4264–4269. IEEE, 2012.

[9] Eric Brown, Nicholas Rodenberg, John Amend, Annan Mozeika, Erik Steltz, Mitchell R Zakin, Hod Lipson, and Heinrich M Jaeger. Universal robotic gripper based on the jamming of granular material. *Proceedings of the National Academy of Sciences*, 107(44):18809–18814, 2010.

[10] Tao Chen, Lining Sun, Liguo Chen, Weibin Rong, and Xinxin Li. A hybrid-type electrostatically driven microgripper with an integrated vacuum tool. *Sensors and Actuators A: Physical*, 158(2):320–327, 2010.

[11] Ching-Ping Chou and Blake Hannaford. Static and dynamic characteristics of mckibben pneumatic artificial muscles. In *Robotics and Automation, 1994. Proceedings., 1994 IEEE International Conference on*, pages 281–286. IEEE, 1994.

[12] Ching-Ping Chou and Blake Hannaford. Measurement and modeling of mckibben pneumatic artificial muscles. *IEEE Transactions on robotics and automation*, 12(1):90–102, 1996.

[13] Fionnuala Connolly, Panagiotis Polygerinos, Conor J Walsh, and Katia Bertoldi. Mechanical programming of soft actuators by varying fiber angle. *Soft Robotics*, 2(1):26–32, 2015.

[14] Fionnuala Connolly, Conor J Walsh, and Katia Bertoldi. Automatic design of fiber-reinforced soft actuators for trajectory matching. *Proceedings of the National Academy of Sciences*, 114(1):51–56, 2017.

[15] Nikolaus Correll, Kostas E Bekris, Dmitry Berenson, Oliver Brock, Albert Causo, Kris Hauser, Kei Okada, Alberto Rodriguez, Joseph M Romano, and Peter R Wurman. Analysis and observations from the first amazon picking challenge. *IEEE Transactions on Automation Science and Engineering*, 2016.

[16] Nikolaus Correll, Kostas E Bekris, Dmitry Berenson, Oliver Brock, Albert Causo, Kris Hauser, Kei Okada, Alberto Rodriguez, Joseph M Romano, and Peter R Wurman. Lessons from the amazon picking challenge. *arXiv preprint arXiv:1601.05484*, 2016.

[17] Aaron M Dollar and Robert D Howe. A robust compliant grasper via shape deposition manufacturing. *IEEE/ASME transactions on mechatronics*, 11(2):154–161, 2006.

[18] Clemens Eppner, Sebastian Höfer, Rico Jonschkowski, Roberto Martin Martin, Arne Sieverling, Vincent Wall, and Oliver Brock. Lessons from the amazon picking challenge: Four aspects of building robotic systems. In *Robotics: Science and Systems*, 2016.

[19] Wyatt Felt, Khai Yi Chin, and C David Remy. Contraction sensing with smart braid mckibben muscles. *IEEE/ASME Transactions on Mechatronics*, 21(3):1201–1209, 2016.

[20] Joshua Gafford, Ye Ding, Andrew Harris, Terrence McKenna, Panagiotis Polygerinos, Donal Holland, Arthur Moser, and Conor Walsh. Shape deposition manufacturing of a soft, atraumatic, deployable surgical grasper. *Journal of Medical Devices*, 8(3):030927, 2014.

[21] Maria Elena Giannaccini, Ian Georgilas, Ian Horsfield, BHPM Peiris, Alexander Lenz, Anthony G Pipe, and Sanja Dogramadzi. A variable compliance, soft gripper. *Autonomous Robots*, 36(1-2):93–107, 2014.

[22] RB Gorbet, DWL Wang, and KA Morris. Preisach model identification of a two-wire sma actuator. In *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, volume 3, pages 2161–2167. IEEE, 1998.

[23] David L Henann, Shawn A Chester, and Katia Bertoldi. Modeling of dielectric elastomers: Design of actuators and energy harvesting devices. *Journal of the Mechanics and Physics of Solids*, 61(10):2047–2066, 2013.

[24] Carlos Hernandez, Mukunda Bharatheesha, Wilson Ko, Hans Gaiser, Jethro Tan, Kanter van Deurzen, Maarten de Vries, Bas Van Mil, Jeff van Egmond, Ruben Burger, et al. Team delft's robot winner of the amazon picking challenge 2016. *arXiv preprint arXiv:1610.05514*, 2016.

[25] Donal Padraic Holland, Colette Abah, Marielena Velasco-Enriquez, Maxwell Herman, Gareth J Bennett, Emir Augusto Vela, and Conor James Walsh. The soft robotics toolkit: Strategies for overcoming obstacles to the wide dissemination of soft-robotic hardware. *IEEE Robotics & Automation Magazine*, 24(1):57–64, 2017.

[26] Allen Jiang, Georgios Xynogalas, Prokar Dasgupta, Kaspar Althoefer, and Thrishantha Nanayakkara. Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, pages 2922–2927. IEEE, 2012.

[27] Katsutoshi Kuribayashi. Improvement of the response of an sma actuator using a temperature sensor. *The International Journal of Robotics Research*, 10(1):13–20, 1991.

[28] Yong Kwun Lee and Isao Shimoyama. A skeletal framework artificial hand actuated by pneumatic artificial muscles. In *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, volume 2, pages 926–931. IEEE, 1999.

[29] Yingtian Li, Yonghua Chen, Yang Yang, and Ying Wei. Passive particle jamming and its stiffening of soft robotic grippers. *IEEE Transactions on Robotics*, 33(2):446–455, 2017.

[30] Zakary Littlefield, Shaojun Zhu, Hristiyan Kourtev, Zacharias Psarakis, Rahul Shome, Andrew Kimmel, Andrew Dobson, Alberto F De Souza, and Kostas E Bekris. Evaluating end-effector modalities for warehouse picking: A vacuum gripper vs a 3-finger underactuated hand. In *Automation Science and Engineering (CASE), 2016 IEEE International Conference on*, pages 1190–1195. IEEE, 2016.

[31] Bobak Mosadegh, Panagiotis Polygerinos, Christoph Keplinger, Sophia Wennstedt, Robert F Shepherd, Unmukt Gupta, Jongmin Shim, Katia Bertoldi, Conor J Walsh, and George M Whitesides. Pneumatic networks for soft robotics that actuate rapidly. *Advanced Functional Materials*, 24(15):2163–2170, 2014.

[32] Lael U Odhner, Leif P Jentoft, Mark R Claffee, Nicholas Corson, Yaroslav Tenzer, Raymond R Ma, Martin Buehler, Robert Kohout, Robert D Howe, and Aaron M Dollar. A compliant, underactuated hand for robust manipulation. *The International Journal of Robotics Research*, 33(5):736–752, 2014.

[33] OnShape. *OnShape.com*, 2015. http://www.onshape.com.

[34] Tae-Sang Park, Dong-Hwan Shin, Choong-Pyo Jeong, and Jinung An. Design of the hybrid gripper with the jaw-tip grip and suction. In *Ubiquitous Robots and Ambient Intelligence (URAI), 2012 9th International Conference on*, pages 595–596. IEEE, 2012.

[35] Bryan N Peele, Thomas J Wallin, Huichan Zhao, and Robert F Shepherd. 3d printing antagonistic systems of artificial muscle using projection stereolithography. *Bioinspiration & biomimetics*, 10(5):055003, 2015.

[36] Ron Pelrine, Roy Kornbluh, Joseph Eckerle, Philip Jeuck, Seajin Oh, Qibing Pei, and Scott Stanford. Dielectric elastomers: generator mode fundamentals and applications. In *Proc. SPIE*, volume 4329, pages 148–156, 2001.

[37] Panagiotis Polygerinos, Stacey Lyne, Zheng Wang, Luis Fernando Nicolini, Bobak Mosadegh, George M Whitesides, and Conor J Walsh. Towards a soft pneumatic glove for hand rehabilitation. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, pages 1512–1517. IEEE, 2013.

[38] Panagiotis Polygerinos, Zheng Wang, Johannes TB Overvelde, Kevin C Galloway, Robert J Wood, Katia Bertoldi, and Conor J Walsh. Modeling of soft fiber-reinforced bending actuators. *IEEE Transactions on Robotics*, 31(3):778–789, 2015.

[39] Rethink Robotics. *Baxter*.

[40] RightHand Robotics. *ReFlex Hand*.

[41] RightHand Robotics. *RightHand Robotics Hybrid Gripper*.

[42] Yu She, Chang Li, Jonathon Cleary, and Hai-Jun Su. Design and fabrication of a soft robotic hand with embedded actuators and sensors. *Journal of Mechanisms and Robotics*, 7(2):021007, 2015.

[43] Robert F Shepherd, Filip Ilievski, Wonjae Choi, Stephen A Morin, Adam A Stokes, Aaron D Mazzeo, Xin Chen, Michael Wang, and George M Whitesides. Multigait soft robot. *Proceedings of the National Academy of Sciences*, 108(51):20400–20403, 2011.

[44] Robert F Shepherd, Adam A Stokes, Jacob Freake, Jabulani Barber, Phillip W Snyder, Aaron D Mazzeo, Ludovico Cademartiri, Stephen A Morin, and George M Whitesides. Using explosions to power a soft robot. *Angewandte Chemie*, 125(10):2964–2968, 2013.

[45] Samuel Shian, Katia Bertoldi, and David R Clarke. Dielectric elastomer based grippers for soft robotics. *Advanced Materials*, 27(43):6814–6819, 2015.

[46] Constantinos Stergiopulos, Daniel Vogt, Michael T Tolley, Michael Wehner, Jabulani Barber, George M Whitesides, and Robert J Wood. A soft combustion-driven pump for soft robots. In *ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems. American Society of Mechanical Engineers*, pages V002T04A011–V002T04A011, 2014.

[47] Yi Sun, Yun Seong Song, and Jamie Paik. Characterization of silicone rubber based soft pneumatic actuators. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, pages 4446–4453. Ieee, 2013.

[48] Zhigang Suo. Theory of dielectric elastomers. *Acta Mechanica Solida Sinica*, 23(6):549–578, 2010.

[49] SuperReleaser.com. *The Kestrel compliant hand by SuperReleaser*, 2016. https://har.ms/blog/super-releaser-signed-book-deal-maker-media.

[50] Koichi Suzumori, Shoichi Iikura, and Hirohisa Tanaka. Development of flexible microactuator and its applications to robotic mechanisms. In *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on*, pages 1622–1627. IEEE, 1991.

[51] Harvard University and Trinity College Dublin. *Soft Robotics Toolkit*, 2014. https://softroboticstoolkit.com.

[52] Michael Wissler and Edoardo Mazza. Mechanical behavior of an acrylic elastomer used in dielectric elastomer actuators. *Sensors and Actuators A: Physical*, 134(2):494–504, 2007.

[53] Ali Alazmani Alexandre Campo Zheng Wang, Panagiotis Polygerinos. *Fluidic Control Board Instructions*, 2014. https://softroboticstoolkit.com/book/control-board.

Acknowledgment of Previous Publications

Zakary Littlefield, Shaojun Zhu, Hristiyan Kourtev, Zacharias Psarakis, Rahul Shome, Andrew Kimmel, Andrew Dobson, Alberto F De Souza, and Kostas E Bekris. Evaluating end-effector modalities for warehouse picking: A vacuum gripper vs a 3-finger underactuated hand. *In Automation Science and Engineering (CASE), 2016 IEEE International Conference* on, pages 11901195. IEEE, 2016.