# Mini-Hand Extension - Team R.E.A.C.H.

**Sponsored by**

**In collaboration with**

**California Polytechnic State University, San Luis Obispo**

**Cal Poly Mechanical Engineering Department**

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# Disclaimer

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# Abstract

Lam Research supplies equipment for manufacturing silicon wafers used in semiconductor manufacturing. Their equipment is highly sophisticated and therefore costly, both in time and money, to repair. Much of the time and money spent to service those machines when they require maintenance or repair is spent on disassembly, so Lam seeks a faster way to service their equipment. Al Schoepp, a Senior Technical Director at Lam Research, came to Cal Poly seeking a team of students to design and build a device that could emulate the human hand well enough to handle hardware and thread nuts and bolts but also be usable inside one of the manufacturing machines at Lam. Team R.E.A.C.H., consisting of Aulivia Bounchaleun, Haden Cory, Scott Onsum, and Zack Phillips, have designed a device called the R.E.A.C.H. device, which stands for Reach Extender And Component Handler, to help Lam Research save both time and money when servicing their equipment. The device is operable with one hand, has an integrated vision and lighting system with a wireless monitor, can extend the user's reach up to almost 24 inches, and can fit through a two inch diameter hole while carrying a ½-13 nut. This report details the design process that Team R.E.A.C.H. used to develop the R.E.A.C.H. device starting from the initial background research and problem definition all the way up through the detailed analysis and technical drawings of the prototype.

# Chapter 1: Introduction

## Sponsor Background and Needs

Lam Research is a major supplier of Wafer Fabrication Equipment (WFE) that services the semiconductor industry. Lam Research's products are used in chip-making methods like "thin film deposition, plasma etch, photoresist strip, and wafer cleaning" (Lam Research, 2014). With large consumer demands for the smaller and faster chips that can be found in smartphones and tablets, Lam Research's customers include some of the top producers of semiconductor chips in North America and Asia, such as Intel and Samsung. Lam's headquarters is in Fremont, California, but they have facilities in Asia, North America, and Europe (Schoepp, 2014). Lam Research has requested a Mini Hand Extension to aid in the servicing of their WFE. Lam Research will benefit from the completion of this project by having a tool that can aid in the repair of their equipment in a shorter time than their current method and that can offer various functions under strict constraints. The ability to service their equipment faster will save the company time and money and those savings will benefit semiconductor manufacturers down the line as well. While designing this prototype to fit the needs and requirements of Lam Research, the use of this device will span a range of users including both trained technicians and inexperienced users.

## Problem Definition

Servicing the wafer manufacturing equipment at Lam Research is terrifically costly and time consuming. This is because the machines cannot be easily serviced without significant disassembly because there is no opening large enough for a hand to fit through and the components are too far inside the machines. There is a need for a device that would allow a technician to service the machines without having to disassemble them to such a degree, and ideally not at all. We need to design a device that allows a technician to reach inside these machines, while maintaining their dexterity, and service them without disassembling them. Although this product will be designed specifically for Lam Research, our sponsor wants the final device to require no special training - meaning the device can be used by automotive mechanics, service technicians, plumbers, and anyone in need of a device that can aid in reaching inside of and working in confined spaces.

## Development of Objectives and Specifications

The goal of this project is to design, build, and test a functional mini-hand that can maneuver through a hole of specified diameter and extend to a required length, grip various nuts and bolts, and apply specified torque and rotation. The prototype will be used to provide a faster method to service machines such as ELD Modules at Lam Research. The goal of this project is to develop, produce, and test a functional prototype with the specified and desired requirements for Lam Research and Al Schoepp.

### Objectives

There are situations where the human hand is not small enough or cannot reach far enough to make precise movements in confined spaces, such as threading a nut or picking up small objects while servicing the silicon wafer manufacturing equipment at Lam Research. The current method is to disassemble the machine until the problematic area or part can be accessed. This method can be too costly and/or time consuming. The primary problems with the current repair strategy are that the machines cannot be easily serviced without significant disassembly due to the lack of an adequate opening for a hand to fit through, the components are too far inside the machines for a service technician to reach, and the equipment's complex nature requires careful and time-consuming disassembly. Although there are existing products that are able to perform some of the functions desired in the R.E.A.C.H. device, they lack versatility. Our initial research of existing products focused on different functions the R.E.A.C.H. device will perform, consisting of gripping devices/mechanisms, extension methods, bending methods/joints, and video and lighting systems.

We collected the following customer specifications from our discussions with our sponsor and the initial presentation they made to the ME 428 class:

***The specified <u>requirements</u> from Lam Research:***

- The extended length of the device must be 12'' to 24''.
- Able to be operated with one hand while servicing
- Light enough to use with the arm extended
- Able to transmit a maximum torque of 10 in-lbf
- Able to rotate at minimum of 20 rpm
- Able to grip different size and shape objects
  - #4 to ¼-20 socket head cap screws
  - #6-32 to ½-13 hex nuts
  - Oddly shaped parts
- End effector must be able to pass through a 2" diameter hole
- Extension must be able to bend at least 180 degrees with a max 3" radius
- For portability and remote use, the device should be battery powered if necessary
- Must have vision system with light to operate in dark corners
- Interchangeable tool-heads

***The specified <u>desires</u> from Lam Research:***

- Articulating wrist motion
- Magnetic retention of small parts
- Touch feedback/force sensing
- Ability to ensure orthogonality of the extension to the work surface
- Verification method for proper thread engagement before disconnecting

The goal of this project is to deliver a device to Lam Research that assists in the repair of their equipment. This device should meet all provided design constraints as well as be simple enough to be operated and used by a new user in any application where a reach extension could be helpful. The one caveat to the specifications provided by Lam Research is that we were given permission to omit any specifications we found to be outside the scope of the project after clearing it with Al.

## Specifications

Our engineering specifications for this project are shown in Table 5 below. These were derived from the sponsor's requirements for the device. A few requirements, such as device weight and instruction time required, were defined by us to make the device a better fit for our sponsor's vision of the project. To determine and organize these specifications we used a process called Quality Function Deployment, typically abbreviated as QFD, which includes an exercise called the House of Quality. We started with determining who our end users would be, then developed a list of requirements for the device based on what the users wanted. We then ranked the users desires by importance based on our understanding of what they wanted. We then looked at what already existed in the marketplace and determined where those products succeeded and failed when it came to the needs of the customer. Next, we tackled the question of what our device needed to do in order to meet the entire list of user desires. This iterative process yielded a quantifiable list of specifications that were testable and accurately described what our device has to be capable of accomplishing. These specifications are collected and presented in the House of Quality, a tool used to help us turn the criteria the sponsor provided into a list of engineering specifications. The House of Quality is included in the Appendices under Appendix B.

See Table 1 below includes our parameters, the target values, the tolerances on those values, the risks associated with meeting those parameters, and how we will determine whether our device complies or not. The risk associated with meeting each specification can be listed as: Low, Medium, or High; and the compliance testing methods are Analysis, Testing, and Inspection. The risk assigned to each parameter indicates how challenging we foresee accomplishing that particular goal to be. For example, the length parameter has a rather wide tolerance and there are not very many factors that will limit our ability to meet our target, so it has a low associated risk. The compliance values indicate how we will measure our success in delivering a device that meets all of the prescribed parameters. The analysis is what we will use for the calculations and/or the device specifications to determine our success. Testing will require us to develop a way to experimentally prove that our device accomplishes what we set out to accomplish. For example, our maximum torque specification could be verified using a torque wrench set to 10 in-lbf. Compliance by inspection indicates that we will be able to observe the device and determine whether or not it meets a particular parameter. Measuring the length of the device to see that it is within our acceptable range would be an example of the inspection compliance testing.

*Table 1: Formal Engineering Specifications*

| Spec # | Parameter Description | Requirement or Target | Tolerance | Risk | Compliance |
|---|---|---|---|---|---|
| 1 | Length | 18” | ±6” | L | A, T, I |
| 2 | Hands Required for Operation | 1 | max | M | T |
| 3 | Weight | 5 lbf | max | H | A, T |
| 4 | Torque | 10 in-lbf | max | L | T |
| 5 | Rotation Speed | 20 rpm | min | L | T |
| 6 | Grip Capabilities | Able to grip #4 to ¼-20 socket head cap screws, #6-32 to ½-13 nuts | min | M | T |
| 7 | End Effector Diameter | 2 in | max | H | I, T |
| 8 | Bending Angle | 180° | min | L | I, T |
| 9 | Bend Radius | 6 in | max | M | A, I, T |
| 10 | Battery Life (operating time) | 1 hour | min | L | A, T |
| 11 | Vision and Lighting System | Operator can observe part manipulation | N/A | M | T |
| 12 | Instruction Level Required for Use | 10 minutes | Max | M | T, I |
| 13 | Tool Interface | Equipped | N/A | L | I, T |
| 14 | Magnetized Part Retention | Equipped | N/A | L | I, T |
| 15 | Force Feedback | Equipped | N/A | M | A, I, T |

Discussion of Specifications:

1. The length of the product is a major design specification. The purpose of this device is to extend the reach of the user and the length of the device is a significant aspect of that.
2. As requested by our sponsor, this device has to only require one hand during operation. This is because it will not be uncommon for a technician to be “arm-deep” in a machine during the repair process. This would make two handed operation impossible.
3. Due to the devices one-handed operation, we realized that the operator may have to hold the device at a straight-arm position. Therefore, we chose to have the device weigh less than 5 pounds to make it easier to use the R.E.A.C.H. device in this position.
4. The torque requirement of 10 in-lbf is specified to be able to tighten hardware but prevent tightened hardware from being over-torqued.
5. The rotation speed is a requirement in accordance with the goal of decreasing the repair time. A slow rotational speed will make operations like tightening fasteners take longer.

6. The grip capabilities of the device are important because the device needs to be able to pick up and manipulate a variety of nuts, bolts, and oddly-shaped objects.
7. This device will mostly be used in confined spaces, so the end should be no more than 2 inches in diameter to access these spaces.
8. The bending angle is an important specification for our device since it dictates the ability of the technician to manipulate objects around blind corners or on the other sides of walls.
9. The device needs to be able to bend 180° within 6 inches to be usable in confined spaces.
10. Battery life is a requirement because this device has to operate long enough to complete a repair which could take over an hour of constant use.
11. The vision and lighting system is important for this device as it is an essential tool in helping the operator navigate the device and manipulate objects in dark, confined spaces.
12. To quantify making this device truly easy to use, we chose to have the final project require no more than 10 minutes of instruction time.
13. To make this device more capable of handling currently unforeseen jobs, the device is required to have an interchangeable tool interface.
14. To assist the operator in not dropping objects such as nuts and bolts, the device should have a magnetized part retention system.
15. Force feedback is desired for this project so that the operator can tell when they have grabbed or let go of the object they are manipulating.

The most difficult specifications to meet will be our weight and end effector diameter. Improving most other aspects of the device will tend to impact the weight. Similarly, improving the gripping capability of the device will tend to increase the diameter of the end effector.

## Desired Specifications (possible inclusion in prototype)

The first desired specification we chose to address was magnetic part retention. This is important given the intended use of the device where it will be handling a lot of small hardware that can easily get lost if dropped. We can accomplish this by simply inserting magnets or electromagnets at the end of the tool attachment; electromagnets might be a good choice so that the device will not stick the body panels of the machine while it is being inserted.

The second desired specification of interest was wrist articulation. This would be a 1:1 replication of the movements of the user's wrist motion at the end effector. Our research into this application led to the idea of using several gimbals that held the end effector and were directly connected to the user's wrist that would transfer the motions of the wrist to the end effector. We would only need two gimbals, one for the pitch axis and one for the yaw axis, since the roll axis would be handled by the rotation function.

The final desired specification that we are considering is the option of including touch feedback. Some research led us to a company called Tekscan who makes force sensing equipment. Their website features a story about robotic surgery and how their force sensors were used by Cambridge Research & Development to make a system that provides haptic feedback to surgeons using laparoscopic grabbers (Cambridge R&D, 2013). This technology could also likely be applied to our device but more research would have to be done once we have designed our grabber.

# Chapter 2: Background

To better understand the scope of the project, we started by dividing the customer's required specifications into a collection of functions that the device needs to perform. The R.E.A.C.H. device will need to grab/grasp objects, rotate them, apply torque to them, extend the user's reach, maneuver inside the machine, and allow the user to see what they're doing. Currently, there are no products available that meet all of these criteria. Due to the lack of competition we started looking at existing products that could accomplish at least one of the outlined functions. Our method of approach is to find a collection of products that can handle one particular function very well, and then combine the relevant aspects of those projects to synthesize a product that would accomplish all of the specified functions. Our initial research is presented below and all of the sources used are included in the bibliography in Appendix A.

## Existing Products

### Grabbing Devices

The research into grabbing devices brought up many options for robotic hands but other devices looked more promising given our important size constraints. Mechanical multi-pronged grabbers and a threefingered robotic gripper by Robotiq (based in Quebec) offered good inspiration for deployment of the device and grabber articulation, respectively. The grabber in patent US 20110170281 A1, which can be seen in Figure 1, contains a device with a magnetic multi-pronged end, a light, and a flexible extension (Shih, 2011). However, this grabber device has no means by which a user can apply torque, nor does it have a video feed system. The Robotiq 3-Finger Adaptive Robot which can be seen in Figure 2 has what have been termed "mechanically intelligent fingers" that grip what the robot is holding and that joint design would be a good starting point for our device (Robotiq, 2014).

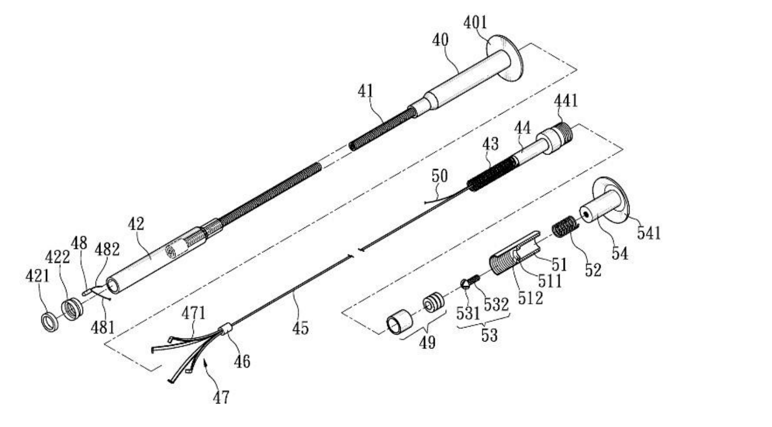



*Figure 1: Grabber Patent US 20110170281 A1 (Shih, 2011)*

However, Robotiq's device does not meet our requirements in two primary areas: our device will require a gripping mechanism that comes together at a central point instead of having the grippers move in parallel planes and our device needs to be portable and lightweight, which the robotic gripper is not. Table 2 summarizes the alternatives we have covered for the Grabbing function.

*Figure 2: Robotiq 3-Finger Adaptive Gripper holding round stock (Robotiq, 2014)*

*Table 2: Pros and Cons of Existing Devices for Grabbing Function*

| Existing Product(s) | Specification(s) Met | Specification(s) Not Met |
|---|---|---|
| Lighted & magnetic pick up tool | Retracting claw | No rotation/torque capabilities |
| 3-Finger Adaptive Gripper | Independent fingers controlled remotely | Size, portability |

## Extension Method

Our research into reach extension did not prove as fruitful. Most reach extension products are simple grabbing devices and often do not provide the dexterity and precision necessary to pick up and manipulate small and oddly-shaped parts. These devices would help in the retrieval of objects from confined spaces, but they lack the ability to manipulate the object precisely enough to perform actions such as threading a screw. The vast majority of approaches to this problem simply gave the user a glorified stick with a simple and mildly effective clamp at the end. One such product is The Grappler as seen in Figure 3, designed for picking up trash up to the size of a full 24 oz. bottle of liquid (Grapplers Inc., 2014). This product works for extending reach to grab objects, but does not appear to be very versatile. It can be used single-handedly, but can need stabilization to use effectively. From this device we have learned that we will need to find a way to stabilize our device without the need of the user's other hand.

Most of the grabbers we found online were fixed length and all were very similar. Some had a hinge, but this hinge was intended (according to the marketing materials) as a way to make the device easier to store, not to make it more versatile. Our device cannot just be a clamp stuck to a stick; it needs to be configurable to a particular circumstance and we therefore need at least one highly mobile joint, with a high probability of multiple joints as discussed below.

*Figure 3: The Grappler, a typical grabbing device (Grapplers Inc., 2014)*

## Bending Mechanism

For bending methods, our research led us to systems such as a universal joint (U-joint) and flexible shafts. Universal joints are a pair of rods oriented at 90 degrees to each other and connected by a cross shaft as seen in Figure 4. The advantages of universal joints include varying velocity, variable angle, and power transmission through a bent shaft. Comparable to the universal joint is the constant velocity joint (CV joint) which is intended to transmit power at a constant rotational speed. There is also an option to use a U-joint if we need to rotate the whole device (Alberta Department of Agriculture and Rural Development, 2014). However, because this device will be used in a clean-room environment, there cannot be greases or other lubricants. CV joints use grease and will not work for our final device. We must ensure that our final bending mechanism or any other mechanism in our device does not require lubrication.

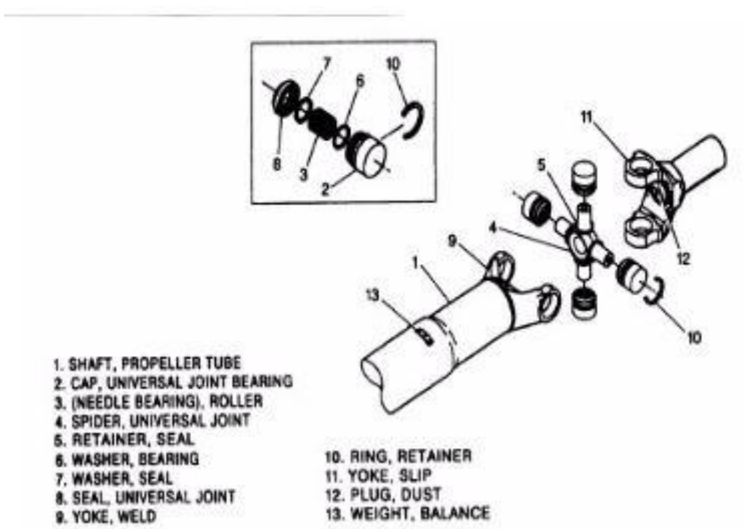



*Figure 4: Universal joint (Alberta Department of Agriculture and Rural Development, 2014)*

Flexible shafts offer simplicity and the versatility to maneuver around corners. Flexible shafts are comprised of an inner shaft or mandrel that is encased with multiple layers of wires as can be seen in Figure 5 (S. S. White Technologies, 2014). Other advantages of flexible shafts include elimination of problems, low parts cost, low installation cost, high efficiency, and lighter weight. They also require looser tolerances and no special tools or skills to install unlike solid shafts. Flexible shafts are 90-95% efficient since there are fewer frictional losses (S. S. White Technologies, 2014).

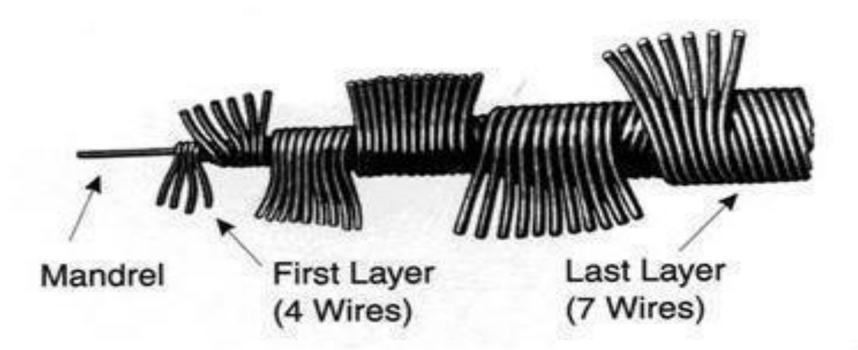



*Figure 5: Diagram of the anatomy of a flexible shaft (S. S. White Technologies, 2014)*

Another option is a simple sequence of hinges and rigid connections between them. Research into hinges with large angular ranges yielded a product by Rock West Composites called push button ratchet joints that are shown below in Figure 6. This would prevent us from transferring power along the length of the extension, but if we can isolate the rotation to the end effector then we could probably make this method work for the Bending function.

*Figure 6: Push button ratchet joints by Rock West Composites (Rock West Composites, 2014)*

Table 3 below shows a summary of the options we have considered for the Bending function.

*Table 3: Pros and Cons of Existing Devices for Bending Mechanism*

| Existing Product(s) | Specification(s) Met | Specification(s) Not Met |
|---|---|---|
| Flexible shaft | Highly configurable | Weight |
| Constant velocity joint | Smooth rotation transfer | Rigidity, Grease-Packed |
| Push button ratchet joints | Indexable bending | No power transfer along length |

## Rotation

There is also the option of keeping the rotation limited to the end effector. This would eliminate the need for an extension method to be capable of power transmission and would greatly increase our options for Extension options. These options could now be considered to include a series of pin joints, a tension-controlled cable alignment system, or even a shaft with overlapping scaled sections similar to the scales found on fish. A summary table of the existing rotation projects is included at the end of the "Torque" section.

## Torque

We have a very low torque requirement which means that we can open up our options to both manually driven and powered alternatives. A ratcheting system would likely reduce the overall weight of the system since we could use plastic gears due to the small torque load. McMaster-Carr has a wonderfully broad selection of small plastic gears, which is certainly something to consider when it comes to manufacturing and/or building this device. Maybe even an annular ring gear could be used to tie the torque application method in with the rotation function.

If we go with a motor, we will want a small, light motor that is capable of delivering no more than 10 in-lbf of torque while rotating at 20 rpm. One option is the ServoCity Planetary Gear Motor as seen in Figure 7 (ServoCity, 2014). Its maximum rotational speed is 116 rpm which is higher than we are looking for but its stall torque is very close to 10 lbf-in. This would prevent the user from accidentally damaging a screw with our device. However, stalling a motor is not a very long-term solution for limiting torque so we may need to expand our options if we choose to use a motor. Table 4 below lists the options we have considered so far and their various features.

*Figure 7: The ServoCity Planetary Gear Motor that matches the torque spec (ServoCity, 2014)*

*Table 4: Pros and Cons of Existing Devices for Rotation Function*

| Existing Product(s) | Specification(s) Met | Specification(s) Not Met |
|---|---|---|
| Motor | Automatic, great variety in size/power | Size |
| Ratchet system | Size, weight, needs no external power | Slow speed, hard to operate at a distance |

## Vision and Lighting System

A wide variety of articulable video systems were available, some including wireless image transmission and almost all including a lit camera. Cameras came in several sizes, and using the smallest available size camera will allow us to save valuable area to meet our size requirement. Snake cameras, an example of which can be seen in Figure 8**,** are commonly used in the plumbing industry seem to be the most promising option due to their small size and appropriate cable length.

*Figure 8: Example of snake camera used for inspection (DogcamSport, 2014)*

The General Tools model DCS 400-05, as seen in Figure 9, has a 5 mm probe that would be a great boon when it comes to minimizing the size of our end effector (General Tools, 2014). The video system itself will likely need to be as small as possible, so this system would be preferable. There are other systems, even other models of this same system, that have larger cameras that would also work but this is certainly a case where smaller is better.

*Figure 9: General Tools DCS400-05 is one option for a video feed (General Tools, 2014)*

There is, however, a point of compromise. Bronchoscopes have camera systems less than 4mm in diameter, like the Pentax EB1170K which has a 3.8mm end (Pentax, 2010). However, bronchoscopes and other endoscopes are used with external image processors that would be too heavy to be portable and not serve our purpose very well. The complete system necessary to use a bronchoscope can be seen in

Figure 10.  We could also use a videography device like the Tunewear snake cam shown in Figure 11 that uses a smartphone application to deliver video to the user (Tunewear, 2014).  It has a larger camera but the added convenience of no more weight than a technician would already be carrying in their pocket.


*Figure 10: Pentax EB1170K Bronchoscope and LH-150PC Video System pair (Pentax, 2010)*

*Figure 11: Tunewear Snake Cam with Smartphone Mount vision system (Tunewear, 2014)*

A description of each existing vision and/or lighting product's strengths and weaknesses can be seen below in Table 4.

*Table 5: Pros and Cons of Existing Devices for Vision/Lighting System*

| Existing Product(s) | Specification(s) Met | Specification(s) Not Met |
|---|---|---|
| General Tools DCS 400-05 | End Effector Diameter, Vision/Lighting System | -- |
| Pentax EB1170K | End Effector Diameter, Vision/Lighting System | Weight, Portability |
| Tunewear Snake Cam | Vision/Lighting System | -- |

## Mounting/Interface System

When it comes to mounting the device, we want to limit our mounting method to below the elbow so as to hinder the movement of the user as little as possible. The best options we were able to find for a mounting system that would accomplish this would be something that resembled the style of arm guard worn during archery, sometimes called a bracer. This would allow the wearer to have complete freedom of movement at the wrist and feel the least restrictive. A second component would likely be mounted to the bracer to allow for better positioning of the control interface, but the bracer itself would be rather rigid and be the main component of the mounting system.

The other realistic option is a long glove or gauntlet, essentially a glove with a cuff that runs the length of the forearm. This would provide a convenient place and path for mounting the control interface but would limit the movement of the user more. We also are considering using several wide straps to allow for a wide range of sizes, though that might limit our component mounting capabilities. We do not have hard specifications for the mounting/interface system because how we address that part of the device will be determined by which options are chosen for the functions listed above. Figure 12 below shows a bracer and a gauntlet side by side.


*Figure 12: Bracer and gauntlet, possible mount options (Bohning, 2014; Southcombe, 2014)*

The control interface for the device is highly dependent upon how each function is performed. If most of the functions will be controlled electronically then we will want an electronic keypad of sorts attached to the mounting system. If the device uses mostly mechanical connections, we will need an interface system through which we can route cables, springs, and other mechanical components. Whatever we use will need to be rather ergonomic and have all of the inputs within easy reach. Our research into this problem led us to gaming keypads or command pads, like the Razer Orbweaver pictured below in Figure 13. Attaching this to the mounting system would provide both a good control interface and some extra space for routing connections and packaging hardware.

*Figure 13: Razer Orbweaver gaming keypad, one concept for our control interface (Razer, 2014)*

In general, our research showed us many devices that could handle certain aspects of our problem, but none that could handle all of them.  It did, however, give us a lot of good idea springboards and sources of inspiration.  Finding these kinds of results narrowed our realm of possibilities down to concepts that improved upon what already existed and ways we could modify those products to suit our needs.

Aside from the specifications our product needs to meet, there are a few ideas that Lam Research would like to see in the product; we have termed these ideas "desired specifications".  There are three in particular that we see as realistically possible to integrate into the R.E.A.C.H. device, but we are not going to fully commit to delivering those as they are supplemental to the necessary functionality of the device and we would rather spend our time improving the device's primary functions.  The project specifications will be discussed in the following chapter, but the three desired specifications in particular we chose to consider merited some background research and will be discussed briefly below.

# Chapter 3: Design Development

The completion of this project consists of multiple stages: the design, the build, the test, and the delivery stages. The design stage was completed in the first quarter and consisted of developing a problem statement in the third week that accurately reflected the needs of the sponsor. This stage involved extensive research to understand and explore the problem to enable us to define the customer's needs and requirements, review any existing solutions, products, patents, or previous works, and perform early analysis.

The process for selection and implementation of the specified requirements used a Quality Function Deployment chart (see Appendix B). This aided us in establishing engineering specifications for the specified requirements. This stage also involved brainstorming to gather a multitude of ideas and narrowing them down to a few concept designs. These steps were completed by week five of the quarter.

Once a few concept designs were selected, mock-prototypes were constructed to test and expand on the designs. These mock-prototypes were made with very simple construction methods and materials. These concepts were evaluated using Decision and Pugh Matrices to select the most feasible concepts within the constraints of strength, size, material, performance, cost, etc. This was accomplished by the seventh week.

Next came the detailed design phase of the project. This phase was where we took the concepts we had determined to be the strongest and pulled from them the options that were combined to form our prototype. These chosen ideas were then put through the analytical wringer so that we could work out the details of the prototype. Stress/strain calculations, weight distributions, and many other things were considered, calculated, and then optimized in the design phase all with the goal of having the best prototype we could at the end of the project. The R.E.A.C.H. device also required some ergonomic testing, meaning that part of what influenced our design was how the device feels to use. This means that our design phase was more focused on building mock-ups in the early phases, then blitzing into analysis once we had enough information about how the various combinations of ideas work together and feel when worn. By the end of this phase we were ready to present our final design to our sponsor for their approval, and once they were on board we began the build phase.

The build phase spanned the end of the second quarter and beginning of the final quarter of the Senior Project sequence and was where we focused on putting our fabrication skills to the test. Any off-the-shelf parts were ordered as soon as possible, then we shopped for and ordered stock to begin manufacturing. The next priority was the outsourced parts that required a longer lead time so that they were ready when the rest of the device was finished. CNC parts were programmed and cut, manually manufacturable parts were fabricated, and assembly proceeded as parts were delivered and completed.

Once everything was assembled, testing began. We ran through the list of metrics we established and made sure that our device passed each test. When the device did not perform satisfactorily, we re-worked the faulty component and built an improved version. Descriptions and results of these tests can be seen in Chapter 6.

By the end of the third quarter, we had completed a functional prototype of the R.E.A.C.H. device. This was where we presented the process, the design, the analyses and the prototype at the Project Expo. A description of deliverables, due dates, and project leads can be seen below in Table 6**.**

*Table 6: Project deliverable due dates and leaders*

| Deliverables | Due Date | Project Lead |
|---|---|---|
| Intro Letter to Sponsor | October 2, 2014 | Haden |
| Team Contract | October 7, 2014 | Aulivia |
| Problem Statement | October 9, 2014 | Aulivia |
| QFD House of Quality | October 16, 2014 | Scott |
| Concept Models/Mock Prototyping | November 4, 2014 | Haden |
| Pugh/Decision Matrices | November 13, 2014 | Aulivia |
| Preliminary Design Report | November 18, 2014 | Haden |
| Preliminary Design Review with Sponsor | December 3, 2014 | Haden |
| Design Analysis | January 15, 2015 | Scott |
| Cad Modeling/BOM | January 29, 2015 | Scott |
| Critical Design Review Presentation | January 30, 2015 | Haden |
| Critical Design Review with Sponsor | February 6, 2015 | Scott |
| Prototyping (Manufacturing) | April 27, 2015 | Haden |
| Testing Grabber | May 5, 2015 | Zack |
| Testing Gooseneck | May 5, 2015 | Zack |
| Testing Bracer Stability/Comfort | May 5, 2015 | Zack |
| Project Update Memo | March 12, 2014 | Haden |
| Senior Project Expo/LAM Research | May 29, 2015 | Scott |
| Final Report | June 8, 2015 | Haden |

A graphical representation of the project deliverables can be seen in Team R.E.A.C.H.'s Gantt chart below. The Gantt chart displays the progression of the project deliverables and highlights the duration of time that should be spent working on each.  Our Gantt chart indicates that we are on time and progressing through the project at a reasonable pace.

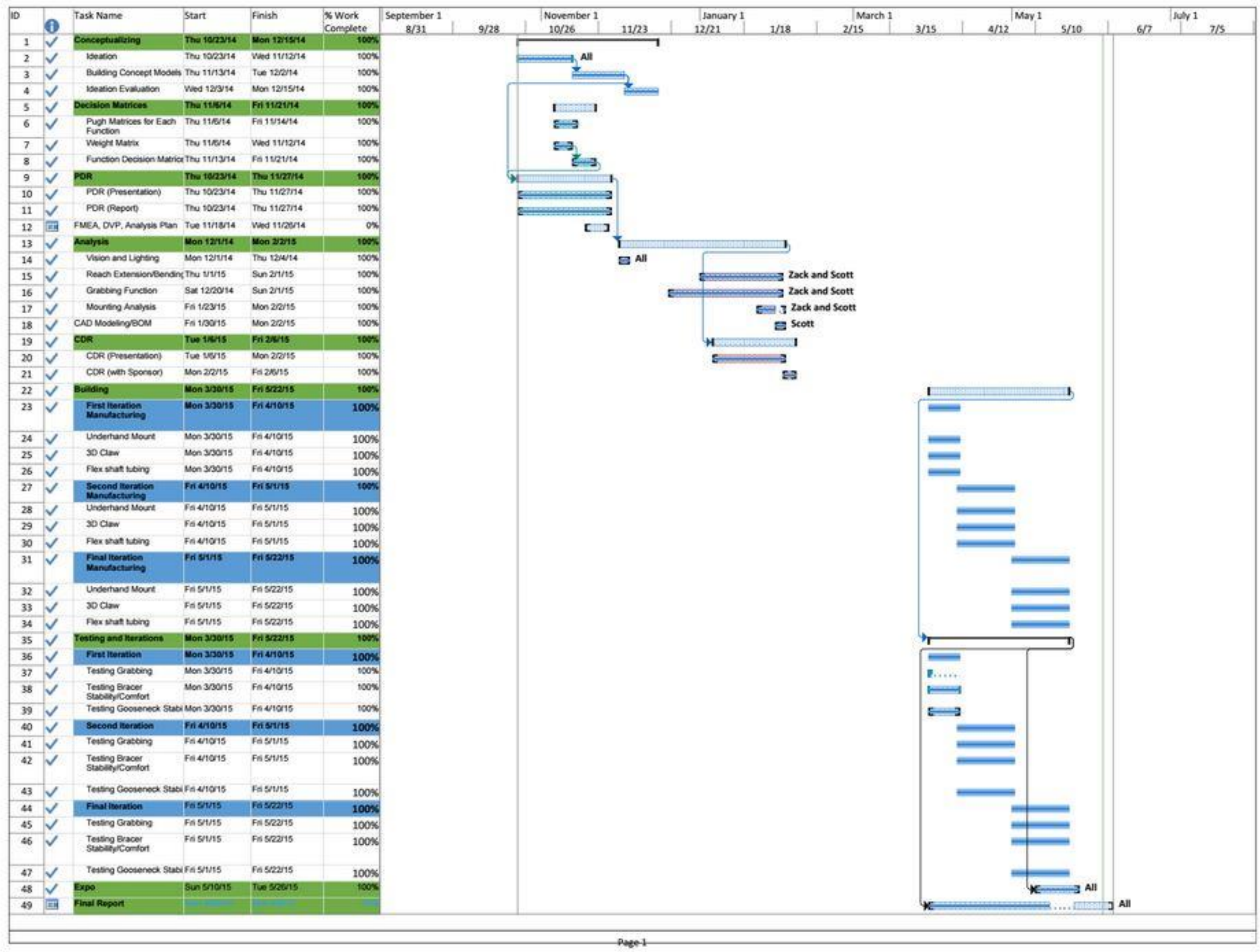



*Figure 14: Team R.E.A.C.H.'s Gantt chart*

## Design Phase

Having developed an understanding of our customer's needs and requirements, the next steps in the design phase consist of Ideation, Concept Model Building, and Idea Evaluation. The Ideation phase is where the functions of the product are developed.  The term "function" used in this instance signifies an action that one particular component of the product is meant to perform. It can be considered as transforming input to output. There are two types of functions, primary functions and secondary functions. Primary functions are the specific tasks that need to be completed, whereas secondary functions are what support the accomplishment of the primary functions. We used Brainwriting, Brainstorming, and the SCAMPER method during our ideation phase to develop and refine ideas for how the R.E.A.C.H. device might be able to perform the various required functions.

In Brainwriting, each person in the team creates a list of ideas that accomplish a given function's action and then passes their paper to the next person after five minutes. Each team member then builds on the ideas already listed on the paper they were passed for the next five minutes. This continues until everyone has contributed to the list. This exercise eliminates criticism while supporting the generation of ideas, focusing on quantity rather than quality. In Brainstorming, everyone participates in creating a list that accomplishes the function's action. This exercise focuses on many ideas and builds on each idea; once again, this exercise focuses on quantity rather than quality. Finally, the SCAMPER method was used. This method is much like the Brainstorming method but with “trigger” words or phrases. The trigger words/phrases stem from the letters in the word SCAMPER and are Substitute, Combine, Adaptability, Modify, Put to other use, Eliminate, and Rearrange/Reverse. Employing various ideation methods led us to develop a multitude of ideas for how tackle each of our functions. To narrow down the top ideas for each function, we developed Pugh matrices to evaluate the realistic/possible ideas we accumulated during our ideation exercises. We ended up with four defined functions for our product: Reach Extension, Grabbing, Rotation/Torque, and Maneuvering. These are different than the initial functions we conceived of because the ideas we generated led us to combine several of our previous functions. This does not, however, invalidate the previous functions which is why we decided to include them in this report.

## Pugh Matrices

To make our Pugh matrices, we listed the different options for each function on the top row and compared each of them to a datum to qualify how well they fit/performed for each criterion. The options are rated with three symbols: “+”, “-”, or “S”. If the option is rated as better than the datum, it is rated with the “+”. If the option is rated as worse than the datum, it is rated with the “-“. Finally, if the option is comparable the datum, it is rated with the “S”. The “+”, “-”, and “S” ratings are then tallied for each option. The Actual Total is calculated by subtracting the “-” rankings from the “+” rankings. If the resulting number is negative, a Total is calculated by offsetting the lowest Actual Total to be zero. The options with the highest Total value are then selected and further evaluated in a Function Decision Matrix. Please note that Pugh matrices include a drawing of the option being evaluated in the top row along with the name of the option; our original Pugh matrices include these drawings and are included in Appendix H.

The Reach Extension function was developed to assist with finding the top options that met the required criteria established by Lam Research. For the Reach Extension function, the criteria were: a device length between 12” and 24”, one-handed operation, lightweight, ability to fit through 2’’ diameter hole, and the ability to bend 180 degrees with a 3” radius as seen in Table 7. Each option was compared to a datum, which in this case was a solid pole. The options with the highest Total scores were the Gooseneck tubing and Hinged Extension. These options were then selected and evaluated using weights to establish the best option for the Reach Extension function.

*Table 7: Reach Extension Pugh Matrix*

| Concepts/ Criteria | Solid Pole | Hydraulic Extension | Collapsible Pole | Toggle Linkage | Gooseneck tubing | Hinged Extension |
|---|---|---|---|---|---|---|
| 12"<Device Length<24" | DATUM | s | s | s | s | s |
| One-Handed Operation | DATUM | s | s | s | s | s |
| Lightweight /Portable | DATUM | - | + | s | s | s |
| Fits through 2" hole | DATUM | s | s | - | s | s |
| Bends | DATUM | s | s | + | + | + |
| Bend 180 degrees with 3" radius | DATUM | s | s | s | + | + |
| Sum of + | DATUM | 0 | 1 | 1 | 2 | 2 |
| Sum of - | DATUM | 1 | 0 | 1 | 0 | 0 |
| Sum of S | DATUM | 5 | 5 | 4 | 4 | 4 |
| Actual Total | | -1 | 1 | 0 | 2 | 2 |
| Total | | 0 | 2 | 1 | 3 | 3 |

Our frontrunners for the Reach Extension function came out to be the Collapsible Pole, Gooseneck tubing, and Hinged Extension. The Collapsible Pole option was nixed after a conversation with our sponsor indicated that the R.E.A.C.H. device would have to thread its way through switchback-like paths, but we realized that we could incorporate the collapsibility feature into the hinged extension option by having the sections between the hinges be collapsible, so all was not lost. With this inclusion, the Hinged Extension would be comprised of three sections of tubing connected with two ratcheting/locking hinges, one facing each direction and each hinge capable of more than 180 degrees of rotation. Gooseneck tubing is a highly positionable and mechanically strong material essentially consisting of a coil spring wrapped in a metal ribbon. It is hollow in the middle and would allow us to run electrical connections down the middle of it, which would be convenient if we use anything requiring electricity at our end effector.

The Grabbing function was developed to assist with finding the top options that met the required criteria established by the sponsor. For the Grabbing function, the criteria were size, weight and/or portability, versatility, rotational capability of 20 rpm, applicable torque of 10 in-lbf, ability to fit through a 2” diameter hole, magnetic retention, and touch feedback as seen in Table 8. Each option was compared to a datum, which in this case was a human hand. The options with the highest Total scores were the Independent Fingers and Expanding Claw. These options were then selected and evaluated using weights to establish the best option for the Grabbing function.

*Table 8: Grabbing Function Pugh Matrix*

| Concepts/ Criteria | Human Hand | Claw | Independent Fingers | Magnet | Vacuum | Suction Cup | Deformable Foam | Expanding Claw | Aperture Grip |
|---|---|---|---|---|---|---|---|---|---|
| Size | DATUM | + | + | + | - | + | + | + | s |
| Weight and/or Portability | DATUM | + | + | + | - | + | + | + | s |
| Versatility | DATUM | - | - | - | - | - | s | - | s |
| Rotation: 20RPM | DATUM | s | s | - | - | + | - | + | + |
| Torque: 10 in-lbf | DATUM | - | s | - | - | - | - | - | - |
| Fits through 2" hole | DATUM | + | + | + | + | + | + | + | + |
| Magnetic | DATUM | + | + | + | s | s | s | + | + |
| Touch Feedback | DATUM | - | - | - | - | - | - | - | - |
| Sum of + | DATUM | 4 | 4 | 4 | 1 | 4 | 3 | 5 | 3 |
| Sum of - | DATUM | 3 | 2 | 4 | 6 | 3 | 3 | 3 | 2 |
| Sum of S | DATUM | 1 | 2 | 0 | 1 | 1 | 2 | 2 | 3 |
| Actual Total | | 1 | 2 | 0 | -5 | 1 | 0 | 2 | 1 |
| Total | | 6 | 7 | 5 | 0 | 6 | 5 | 7 | 6 |

Independent Fingers and an Expanding Claw design won out for the Grabbing function. The Fingers would consist of three equally spaced appendages that would have three joints with roughly the same relative spacing as human fingers do. They would all be controlled by their own input so that they could each be bent differently to accommodate strange parts. The Expanding Claw would be composed of four or five pre-bent, mildly elastic arms with no joints along their length, similar to what can be found in

some arcade machines.  These arms would all converge to the center of the grabber and move in unison with the intent that the uniform pressure distribution would keep the part held evenly.
The Rotation/Torque function was developed to assist with finding the top options that met the required criteria established by the sponsor. For the Rotation/Torque function, the criteria were weight and/or portability, rotational speed of 20 rpm, torque output of a maximum of 10 in-lbf, and the ability to fit through a 2’’ diameter hole as seen in Table 9. Each option was compared to a datum, still a human hand for this function. The options with the highest Total scores were Motor and Ratchet & Pawl. These options were later evaluated using weights based on the importance of their various performance aspects to establish the best option for the Rotation/Torque function.

*Table 9: Rotation/Torque Function Pugh Matrix*

| Concepts/ Criteria | Human Hand | Claw | Motor | Hand Drill Thingy | Ball Bearings | Torsional Springs | Belt Drive | Sprocket | Ratchet & Pawl |
|---|---|---|---|---|---|---|---|---|---|
| Weight and/or Portability | DATUM | s | s | - | s | s | - | - | s |
| Rotation: 20RPM | DATUM | + | + | + | + | - | + | + | + |
| Torque: 10 in-lbf | DATUM | - | + | + | - | - | - | + | + |
| Fits through 2" hole | DATUM | + | + | - | + | + | - | - | + |
| Sum of + | DATUM | 2 | 3 | 2 | 2 | 1 | 1 | 2 | 3 |
| Sum of - | DATUM | 1 | 0 | 2 | 1 | 2 | 3 | 2 | 0 |
| Sum of S | DATUM | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 |
| Actual Total | | 1 | 3 | 0 | 1 | -1 | -2 | 0 | 3 |
| Total | | 3 | 5 | 2 | 3 | 1 | 0 | 2 | 5 |

When it came to deciding our top options for Rotation, radial space was very important.  It would make sense that our top two choices for rotation were the most space efficient options from our field.  The motor option would likely be a small gear motor, sometimes referred to as a micromotor, that would be hooked up to the grabber either directly or via an annular gear attached to the grabber, depending on how we needed to adjust the output of the motor.  The ratcheting system would be used to translate a linear pull by the user in in the horizontal plane to a rotation in the vertical plane using spur gears and miter gears.  The drivers would be spring loaded so that they could return to the driving position without catching on the drive gear.

The Maneuvering function was developed to assist with finding the top options that met the sponsor’s required criteria. These criteria were: ability to fit through a 2” diameter hole, and the ability to bend 180 degrees with a 3” radius as seen in Table 10. Each option was compared to a datum, which in this case was also a solid pole. The options with the highest Total scores were the Gooseneck tubing and the U-Joints. These options were then evaluated using weights to establish the best option for the Maneuvering function.

*Table 10: Maneuvering Pugh Matrix*

| Concepts/ Criteria | Solid Pole | Twist-to-lock joints | Gooseneck tubing | Cable-Pulley System | U-Joints |
|---|---|---|---|---|---|
| Fits through 2" hole | DATUM | s | s | - | s |
| Can bend 180 degrees | DATUM | + | + | + | + |
| Can bend 180 degrees with a 3” radius | DATUM | + | + | s | + |
| Ease of use | DATUM | - | + | + | s |
| Sum of + | DATUM | 2 | 3 | 2 | 2 |
| Sum of - | DATUM | 1 | 0 | 1 | 0 |
| Sum of S | DATUM | 1 | 2 | 1 | 2 |
| Total | | 1 | 3 | 1 | 2 |

Our choices for the maneuverability portrayed the widest discrepancy.  The Gooseneck tubing was also an option for the Reach Extension function, making it highly desirable.  It would ideally be flexible enough that the device could work off the walls of the machine and position itself, after a fashion, if we used the Gooseneck tubing.  The U-joints would be a good option if we choose to keep the motor back by the mount and transfer the power along the length of the device, though it would probably require a secondary support structure.

## Weights

From the Pugh Matrices, the top options for each of the functions were further evaluated to determine their weights or significance. The weights were determined by comparing the importance of the listed criteria to the function as seen in Table 11. The criteria were ranked on a scale of 1-5, with 1 being “least favorable” and 5 being “most favorable”. The scores were then summed and the weights for each criterion were determined as a percentage of the total score.  Categories were included for interface and mounting even though we did not complete Pugh matrices for them because we needed to evaluate them but had no datum against which to compare the options we chose for consideration.

*Table 11: Determination of Weights for the Criteria for Each Function*

| Function | Criteria | Rating | Weight (%) |
|---|---|---|---|
| Rotation/Torque | Weight | 4 | 22 |
| | Size | 5 | 28 |
| | Rotational Speed | 4 | 22 |
| | Torque | 5 | 28 |
| Reach Extension | 12" < length < 24" | 5 | 20 |
| | Adjustable Length | 1 | 4 |
| | One-Handed Operation | 5 | 20 |
| | Weight | 4 | 16 |
| | Size | 2 | 8 |
| | Bends 180 degrees within a 3" radius | 5 | 20 |
| | Maneuverability | 3 | 12 |
| Grabbing | Size | 5 | 24 |
| | Weight | 4 | 19 |
| | Versatility | 4 | 19 |
| | Magnetic Part Retention | 2 | 10 |
| | Touch Feedback | 3 | 14 |
| | Grip Strength | 3 | 14 |
| Interface | Ease of Use | 4 | 25 |
| | Adaptability | 4 | 25 |
| | Precision | 5 | 31 |
| | Comfort | 3 | 19 |
| Mounting System | Comfort | 2 | 13 |
| | Stability | 5 | 33 |
| | Weight | 3 | 20 |
| | Ease of Use | 2 | 13 |
| | Versatility | 3 | 20 |

For the Rotation function, the criteria were the weight of the device, the size of the device, the rotational speed supplied, and the torque applied. There were fewer variations in the ranking of the criteria for this function because each criterion was “more favorable” for the rotation function. The weight of the device and the size of the device were important features because a device with a heavy weight or large surface area will negatively affect the rotation function by reducing the rotational speed.

For the Reach Extension, the criteria were the length of the device (12” < length < 24”), adjustability in the length of the device, the ability of the user to operate the device with one hand, the weight of the device, the size of the device, the ability of the device to bend 180 degrees within a 3” radius, and maneuverability of the device. The criterion with the lowest ranking was the adjustable length because it was not a requirement for the device, but it was a feature that would enhance the versatility of the device. As a result, adjustable length had a weight of 4 percent of the total percentage when compared to other criteria. The criteria with the highest rankings were length and one-handed operation because it was important for the user to be able to extend into the module and operate the device with one hand while servicing the module.

For the Grabbing function, the criteria were the size of the device, the weight of the device, the versatility of the grabbing mechanism, magnetic part retention, touch feedback, and grip strength. The criterion with the lowest ranking was the magnetic part retention because it was not a requirement for the device, but it was a feature that would enhance the effectiveness of the device. As a result, magnetic part retention had a weight of 10 percent of the total percentage when compared to other criteria. The criterion with the highest ranking was the size of the grabbing mechanism because of the important size constraints. The grabbing device had to be able to fit into a 2” diameter hole and when engaged could not be more than 3.5” at its widest point.

For the Interface function, the criteria were ease of use, adaptability of the interface, precision, and the comfort of the device. The criterion with the lowest ranking was the comfort. As a result, the comfort criterion had a weight of 19 percent of the total when compared to other criteria. The operator interface of our device was a critical aspect of our final device and had to allow the user the ability to operate our device at a very high level of precision. While we wanted our device to be comfortable, ease of use, precision controls, and the adaptability to be used with multiple tool heads were the primary focus of our interface design.

For the Mounting function, the criteria were the comfort, the stability, the weight, the ease of use, and the versatility of the mounting system. The criteria with the lowest rankings were the comfort and the ease of use because the stability, adaptability, and weight of the mounting system are paramount to the rest of the design. Without meeting these criteria, our device would not be feasible. As a result, comfort and the ease of use criteria each had a weight of 20 percent of the total percentage when compared to other criteria.

## Function Decision Matrices

To find the best option for each of the functions, Function Decision Matrices were developed. For each Function Decision Matrix, we compared at least two options through sets of criteria that reflected the customer’s requirements. The options were evaluated against each criterion on a 1-5 scale, with 1 being “not meeting standard” and 5 being “meeting standard exceptionally”. The scores were then weighed to determine the Final Score. The Final score for each option was then summed, and the option with the highest total was determined to be the best option for that function.

The Rotation Function Decision Matrix, seen below in Table 12, was used to further evaluate the best option for this function. The top options were derived from the Rotation Pugh Matrix (Table 9) and the weights for each criterion were developed by comparing the significance of each criterion to the performance of the Rotation function.

*Table 12: Rotation Function Decision Matrix*

| Concepts/ Criteria | Motor | Ratchet & Pawl | Weights | Motor Score | Ratchet & Pawl Score |
|---|---|---|---|---|---|
| Weight | 2 | 4 | 22 | 44 | 88 |
| Rotational Speed | 5 | 3 | 22 | 110 | 66 |
| Torque | 5 | 2 | 28 | 140 | 56 |
| Size | 2 | 4 | 28 | 56 | 112 |
| Total | | | | 350 | 322 |

The best option for the Rotation function was the Motor. The Motor had a Total score of 350, while the Ratchet & Pawl had a Total score of 322. The motor had a higher score than the Ratchet & Pawl in both the Rotational Speed and Torque criteria, each with weights of 22 and 28 respectively.

The Reach Extension Decision Matrix (Table 13) was used to further evaluate the best option for this function. The top options were derived from the Reach Extension Pugh Matrix (Table 7) and the weights for each criterion were developed by comparing the significance of each criterion to the performance of the Reach Extension function.

*Table 13: Reach Extension Function Decision Matrix*

| Concepts/ Criteria | Collapsible Pole | Flexible Rod | Hinged Extension | Weights | Collapsible Pole Score | Gooseneck Tubing Score | Hinged Extension Score |
|---|---|---|---|---|---|---|---|
| 12"<length<24" | 5 | 5 | 5 | 20 | 100 | 100 | 100 |
| Adjustable Length | 4 | 1 | 1 | 4 | 16 | 4 | 4 |
| One-Handed Operation | 5 | 5 | 5 | 20 | 100 | 100 | 100 |
| Weight | 4 | 3 | 2 | 16 | 64 | 48 | 32 |
| Size | 5 | 5 | 4 | 8 | 40 | 40 | 32 |
| Bends 180 degrees within a 3" radius | 1 | 5 | 4 | 20 | 20 | 100 | 80 |
| Maneuverability | 1 | 4 | 3 | 12 | 12 | 48 | 36 |
| Total | | | | | 352 | 440 | 384 |

The best option for the Reach Extension function was the Gooseneck Tubing. The Gooseneck Tubing had the highest Total score of 440, the Hinged Extension had the second highest score of 384, and the Collapsible Pole came in last with a score of 352. The Gooseneck tubing received consistently higher scores than the other two options in the ability to bend 180 degrees within a 3’’ radius criteria and in satisfying the length and one-handed operation requirements.

The Grabbing Function Decision Matrix, which can be seen in Table 14, was used to further evaluate the best option for this function. The top options were derived from the Reach Extension Pugh Matrix (Table 8) and the weights for each criterion were developed by comparing the significance of each criterion to the performance of the Grabbing function

*Table 14: Grabbing Function Decision Matrix*

| Concepts/ Criteria | Independent Fingers | Expanding Claw | Tongs | Radially Adjusting Wrench | Weights | Independent Fingers Score | Expanding Claw Score | Tongs Score | Radially Adjusting Wrench |
|---|---|---|---|---|---|---|---|---|---|
| Size | 4 | 4 | 4 | 2 | 24 | 96 | 96 | 96 | 48 |
| Weights | 5 | 5 | 5 | 2 | 19 | 95 | 95 | 95 | 38 |
| Versatility | 5 | 3 | 2 | 4 | 19 | 95 | 57 | 38 | 76 |
| Magnetic Part Retention | 5 | 5 | 5 | 5 | 10 | 50 | 50 | 50 | 50 |
| Touch Feedback | 4 | 3 | 1 | 1 | 14 | 56 | 42 | 14 | 14 |
| Grip Strength | 4 | 3 | 2 | 5 | 14 | 56 | 42 | 28 | 70 |
| Total | | | | | | 448 | 382 | 321 | 296 |

The best option for the Grabbing function was the Independent Fingers with a score of 448 due to its ability to meet size and weights restrictions and its versatility in the range of motion for each finger.

The Mounting Function Decision Matrix, which can be seen in Table 15, was used to evaluate the best option for this option. The weights for each criterion were developed by comparing the significance of each criterion to the performance of the Mounting function.

*Table 15: Mounting Function Decision Matrix*

| Concepts/ Criteria | Bracer w/ Hand Strap | Gauntlet | Straps | Weights | Bracer Score | Gauntlet Score | Straps Score |
|---|---|---|---|---|---|---|---|
| Comfort | 4 | 3 | 2 | 13 | 52 | 39 | 26 |
| Stability | 4 | 5 | 2 | 33 | 132 | 165 | 66 |
| Weight | 3 | 2 | 5 | 20 | 60 | 40 | 100 |
| Ease of Use | 3 | 4 | 2 | 13 | 39 | 52 | 26 |
| Versatility | 4 | 2 | 5 | 20 | 80 | 40 | 100 |
| Total | | | | | 363 | 336 | 318 |

The best option for the Mounting function was the Bracer, which received a score of 363. The second most feasible option is the Gauntlet, which received a score of 336. These options ranked consistently high in stability criteria; this is very important for the user when servicing the module in order to maintain precision of the end effector.

## Concept Models

Having developed the list of functions required for our device, we found the best options for each function to centralize the main components for our device. The best options for each function are summarized in Table 16 below.

*Table 16: Leading concepts for each function of the R.E.A.C.H. device*

| Function | Selection |
|---|---|
| Grabbing | Independent Fingers |
| Reach Extension And Bending | Flexible Rod |
| Rotation and Torque | Motor |
| Vision And Lighting | Borescope |
| Mount | Bracer |
| Interface | TBD |

To maximize a significant number of concept models, we produced several preliminary sketches (A-C). In Figure 15, Sketch A is a Finger-Camera Combination which identifies how to incorporate the camera onto the end effector without jeopardizing the grabber's functionality and versatility. A way to incorporate the vision system onto the end effect is to have the camera positioned at the center of the end effector.


*Figure 15: Sketch A: Finger- Camera Combination*

Sketches B (Figure 16) and C (Figure 17) are Finger-Rotation Combinations which identify how to incorporate rotation into the motion. Sketch B illustrates the use of internal gears that rotate the end effector, whereas Sketch C illustrates the use of an internal motor housed inside a case. The fingers would be attached to the case rather than the internal motor. This combination would allow for distinct motions to control the motor and the engagement of the fingers separately. The reason for this is to allow attachable tool heads on the motor.

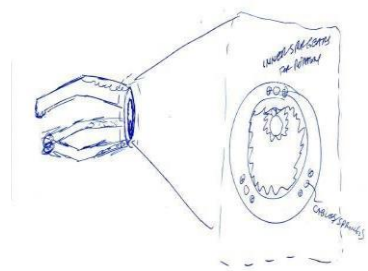


*Figure 16: Sketch B: Finger-Rotation Combination 1*

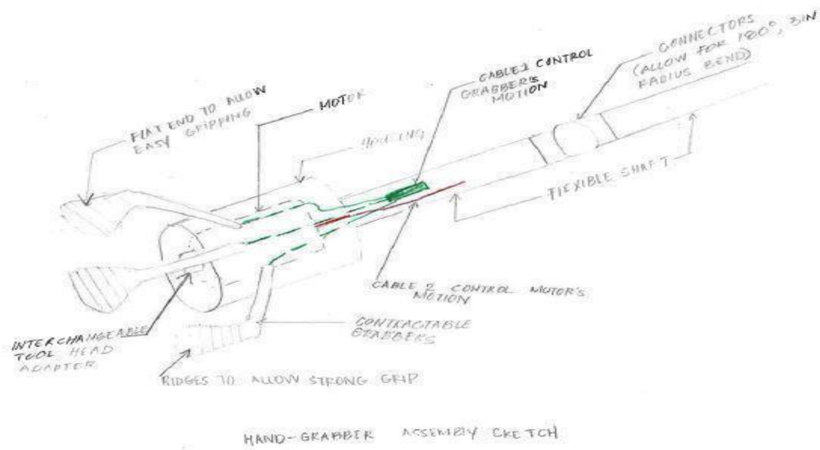



*Figure 17: Sketch C: Finger-Rotating Combination 2*

To further evaluate possible ranges of motion of the grabbers, we also constructed small-scale concept models. The 3-joint, independent curling fingers as seen in Figure 18 allows for the grabber to be able to hold on to oddly shaped objects more securely than the 2-joint motion independent (Figure 19) curling fingers.

*Figure 18: 3-joint motion curling independent fingers*

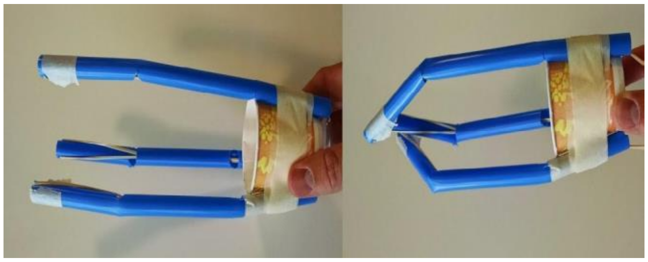


*Figure 19: Two-joint motion curling independent fingers*

The flexible gauntlet in Figure 20 allows the user to control distinct functions by moving one of their fingers up or down. The wristband stabilizes the contraption while allowing a one-to-one wrist articulation motion.

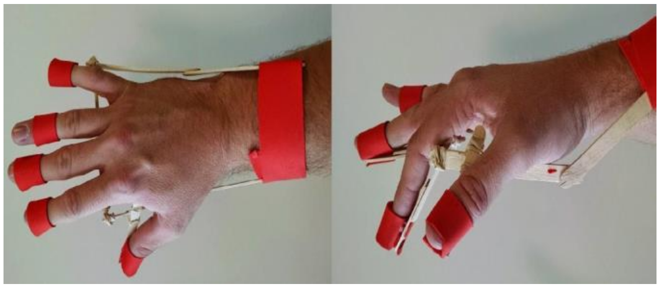


*Figure 20: Flexible gauntlet*

## SolidWorks Modeling

We produced and collected SolidWorks models for each of our functions. These are not final models; they were constructed to help us and our sponsor better understand our concepts and ideas for each function. Figures 21-27 on the following pages depict some of our highest-ranking components.

*Figure 21: Model of push button ratchet joint (Rock West Composites, 2014)*

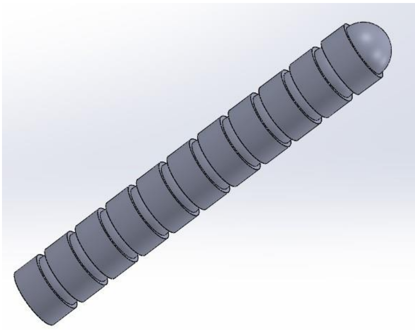


*Figure 22: Model of flexible rod concept*

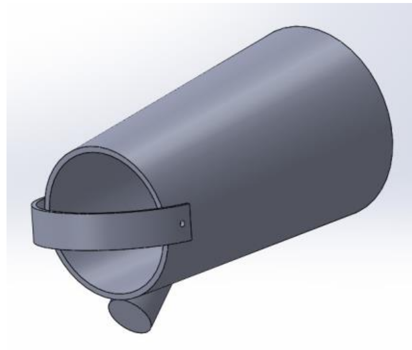


*Figure 23: Model of bracer mounting concept*

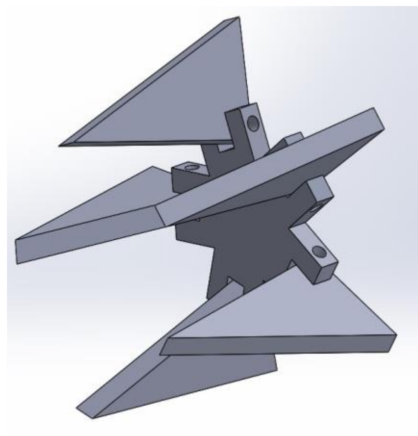


*Figure 24: Model of claw grabbing concept*

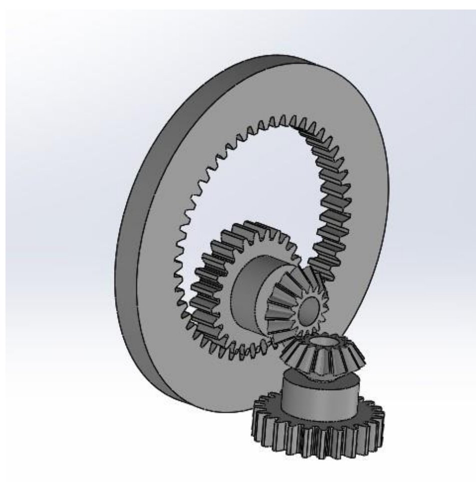


*Figure 25: Model of rotating gear system (Rushgears, 2014)*

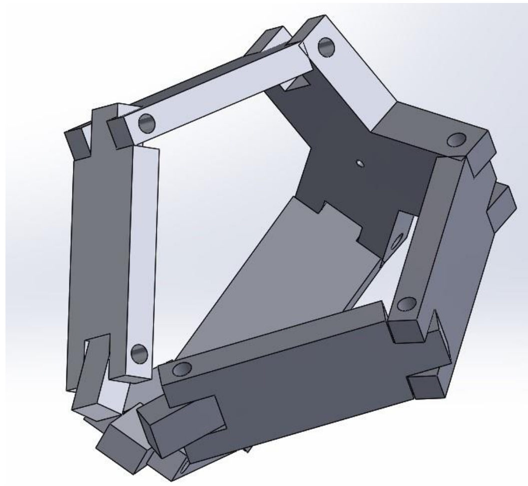


*Figure 26: Model of finger grabbing mechanism*

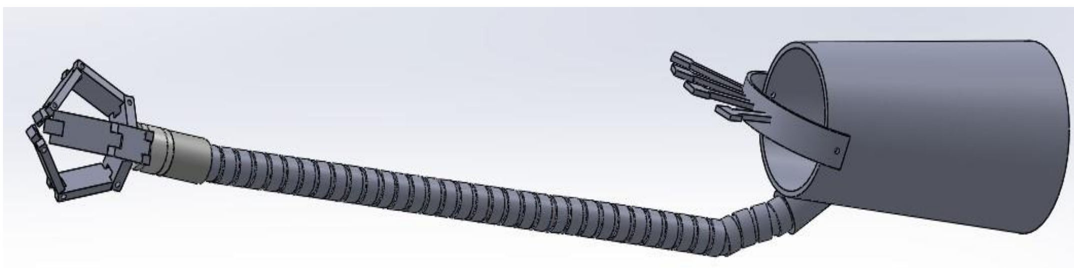
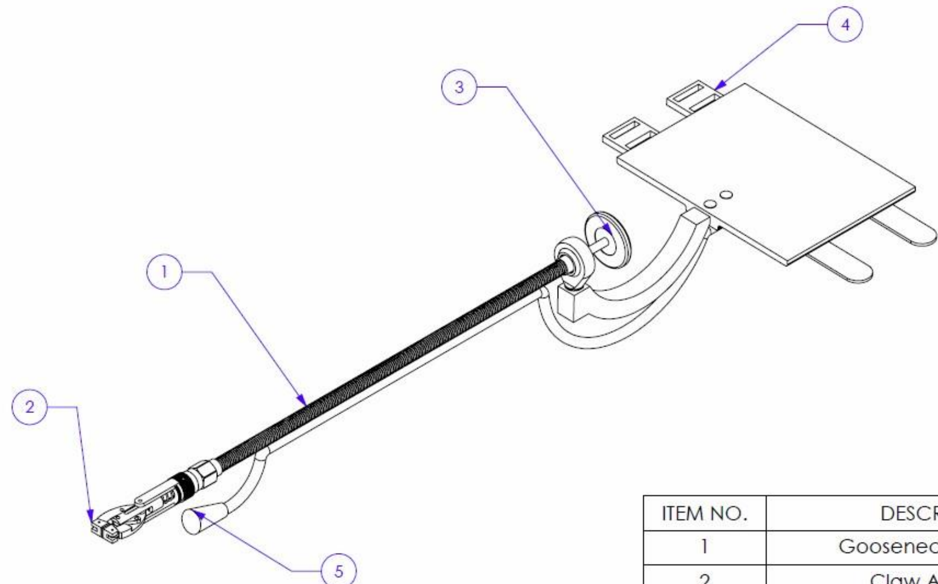


*Figure 27: Model of highest ranked concepts combined into a single device*

# Chapter 4: Description of the Final Design




| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Gooseneck Assembly | 1 |
| 2 | Claw Assembly | 1 |
| 3 | Flex Shaft Assembly | 1 |
| 4 | Mount Assembly | 1 |
| 5 | Wireless Camera | 1 |

*Figure 27: Detail drawing of final design*

## Design Description

The main goal of this section is to provide a thorough documentation of our chosen final concept for our design with appropriate models, drawings, engineering analysis, cost analysis for the prototype and production, manufacturing plan, and proposed testing. This section will conflict with the previous content to a great degree due to the development of the design throughout the past few months. The previous iterations and designs are still included so that the entire history of the project can be documented.

The goal of this project is to design, build, and test a functioning mini-hand extension that would aid in servicing equipment at Lam Research by improving the repair time by requiring minimal to no disassembly of the equipment. The device should allow technicians to gain access into restricted or constrained spaces to service the equipment at Lam Research using only one hand.

Although there are minimal changes to the requirements and desires, there are some clarifications to be added for this design. During one of the first meetings with our sponsor we discussed the original list of required and desired specifications found in Chapter 1. Al told us that if we found any of the specifications to be outside the scope of the project or not attainable with reasonable effort that we could omit them from the list with his approval. The only major alteration made to the original list was to narrow the focus of the device to manipulating hardware exclusively and not focusing on what were termed the “oddly shaped parts”. First, the rotation speed and torque application does not need to be continuously applied as previously assumed, meaning these specs do not need to be controlled via a motor, clutch, etc. Second, the end effector can have a max opening inside the machine of no more than 3.50” from the widest end of the claw; this would allow the end effector to engage objects that are 2” in diameter. Nuts or bolts whose diameters exceed 0.75" are not able to be removed through the 2" diameter opening due to the size of the claw. Lastly, we primarily focused on the end effector being able to grip nuts and bolts of specified dimensions due to time constraints although device still has the capability to grab oddly shaped parts.

Previously we defined five functions for our initial concept: rotation/torque, reach extension and bending, grabbing function, vision and lighting, and mounting. The final design will now only have four functions to consider: reach extension and bending, grabbing, vision and lighting, and mounting. The rotation/torque function has been removed in favor of a completely mechanical system controlled by the user. After the Preliminary Design Review with our sponsor, we determined that the rotation requirement of 20 rpm and the torque requirement of 10 in-lbf could be controlled mechanically by the user. Per the requirements, there were no specifications that the rotation had to be continuous and by removing the motor it simplified many of our concerns and problems. Some of the concerns that we had with the inclusion of a motor were size, rotational speed, possible speed reduction, torque applied, torque limitation, and weight of the end effector. The outer diameter of the ServoCity Planetary Gear Motor (refer to Figure 7) we would have likely used is 21.6 mm, which is about 0.85 inches as seen in Figure 28 below.

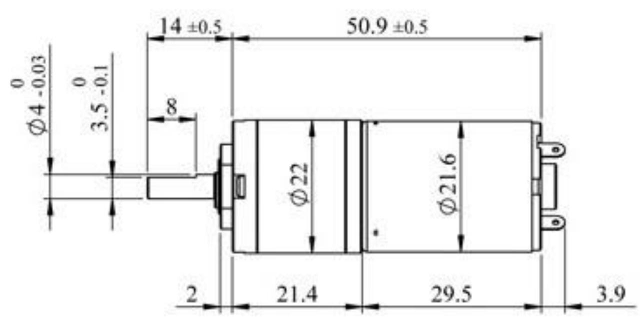



*Figure 28: Dimensions of Servocity Planetary Gear (Servocity, 2014)*

Per the specified requirements the device needs to be able to fit through a 2 inch opening, thus it is preferable that the outer diameter of the motor be as small as possible to provide enough clearance and movement in the gooseneck because the motor wires and flexible shaft would be running through the gooseneck. When researching motors with outer diameters of less than an inch there were multiple complications with the motor selection because the rotation speeds were more than six times the specified requirements, or the torque applied was very low as seen in Table 17 below. To get a speed near 20 rpm we would need to reduce the speed with gears and to get a torque of no more than 10 in-lbf we would need a torque limiter or clutch. If the motor applied more than 10 in-lbf of torque then the inclusions of these considerations would add on to the weight of the end effector.

*Table 17: Motor Options and Specs*

| Name | Rpm | Torque (in-lbf) | OD Size (inches) |
|---|---|---|---|
| SparkFun Micro Metal Gearmotor, ROB-12497 | 430 | 0.16 | 0.5” |
| SparkFun Micro Gearmotor, ROB-12125 | 140 | 0.75 | 1.02” |
| BatterySpace DC Motor Gear I | 200 | 3.30 | 0.98” |
| BatterySpace DC Motor Gear II | 600 | 0.70 | 0.98” |

By removing the motor, we simplified our design for a more mechanical system without revising most of the requirements and desires while shedding some extra weight and reducing the diameter of the end effector.

The final functions and concepts for our design are summarized by Table 18 below.

*Table 18: Final Function and Concepts*

| Function | Final Concept |
|---|---|
| Reach Extension and Bending | Gooseneck (External) and Flexible Shaft (Internal) |
| Grabbing | Two-Finger Claw |
| Vision and Light | Camera Wand with Wireless Monitor |
| Mounting | Bracer |

## Reach Extension and Bending Function

Gooseneck tubing is perfect for this application due to its adjustability. It provides a rigid structure that can also be easily shaped to allow the end effector to follow complicated paths. The tubing can be manufactured to any length, making it easy to achieve our targeted extension length. It is available in a variety of diameters and stiffnesses. It is wrapped in vinyl, ensuring cleanroom compatibility.

This is a purchased part manufactured by an outside party, Uniprise International, Inc. Our final gooseneck is 18” long, with an OD of 0.460” and an ID of 0.265” (Figure 29). We are using the “Light” strength model, which can hold approximately 0.35 lbf at 18” without yielding, well above the weight of our claw assembly and held part.  Our rendering of the gooseneck is below with an air fitting on the end that was originally used to connect to the claw assembly.

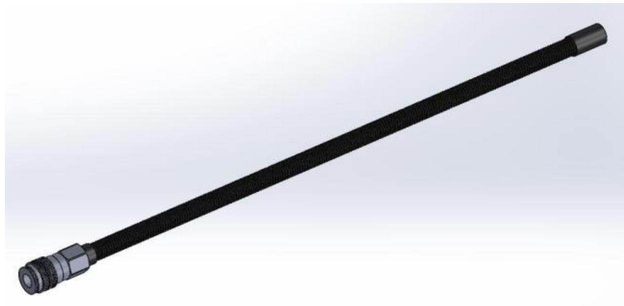
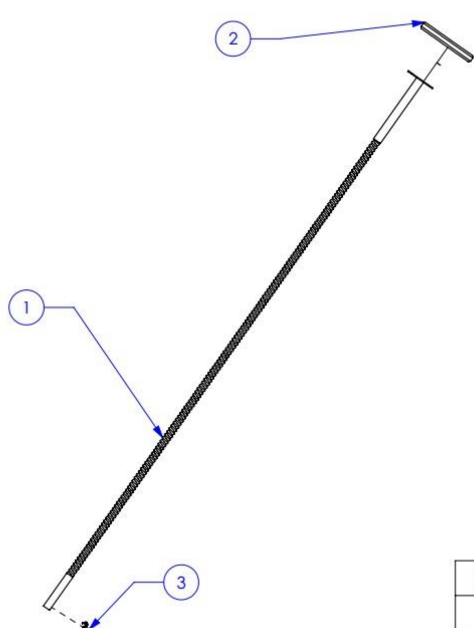


*Figure 29: Gooseneck assembly*

The flexible shaft behaves as a rigid body in our system since the steel ferrules at both ends are the only pieces that interact with other system components. The gooseneck prevents deflection of the flexible shaft, ensuring that all linear and rotational motion applied by the operator is passed along to the end effector. The flexible shaft is made by modifying a purchased flexible spring grabber and removing its grabbing function, leaving just the external housing of the original flexible grabber. The flexible shaft is manufactured by Ullman Devices and is called a No. 16 Flexible Spring Claw. We modified the standard model with a hole drilled in the end sleeve to allow us to bolt it to the claw assembly. We also machined a control wheel to allow a user to control the end of the flex shaft more easily. This was done on a lathe then the control wheel was glued to the end of the flex shaft. The complete flex shaft assembly can be seen below in Figure 30.




| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Flex Shaft | 1 |
| 2 | Control Wheel | 1 |
| 3 | Spring Pin Assembly | 1 |

*Figure 30: Flex shaft assembly with control wheel and sprung pin*

## Grabbing Function

The final design for the grabbing function is a claw with two fingers. To find the appropriate number of fingers we researched the effectiveness of a two-finger, three-finger, and four-finger grabbers. The grabber only has to handle the specified hardware from the original requirements, the small end of which was the most influential requirement when it came to choosing a grabber style. We also assumed that the claw would engage with the object axially rather than normal to the object.

The four-finger claw option had limited grabbing functionality because the tip of the finger would need to be designed to be very sharp and small to be able to grab small nuts and bolts such as the #4-40 screw. We realized that the two-finger claw would be most appropriate because it will be able to grab #4-40 screw most successfully and would require less material and weight than the three-finger or four-finger claws.

The tip of each finger on the first claw had a pivoting foot attached so that the claw could grab each part squarely. The feet could also only rotate a small distance without coming in contact with the fingers, preventing them from falling out of plane with the grabber. Each foot had a layer of silicone rubber attached to the gripping surface to better pick up parts. Per the desired specifications, a small magnet was added behind the silicon rubber for improved part retention. The claw dimensions were set so that it was able to grip a ½-13 nut axially and still able to pass through a two inch hole. An illustration of the claw can be seen below in Figure 31.

The claw opened using two linkages pinned to the claw a small distance up each finger and to each other in the middle. When the pin attaching the two linkages together was pulled back, it forced the angle between the linkages to increase which in turn forced the fingers apart. A pull bar was attached to the pin connecting the two linkages and attached rigidly to the flex shaft. There was a compression spring between the pull bar and the quick connect and around the flex shaft to return the claw to the closed position when the flex shaft was not being pulled by the user. The spring needs to apply no more than 4 lbf at maximum draw and needed to be able to compress at least ½ inch. At maximum draw, the claw opened up to 1.5”. The pull to open operation was chosen to make the device easier to use.

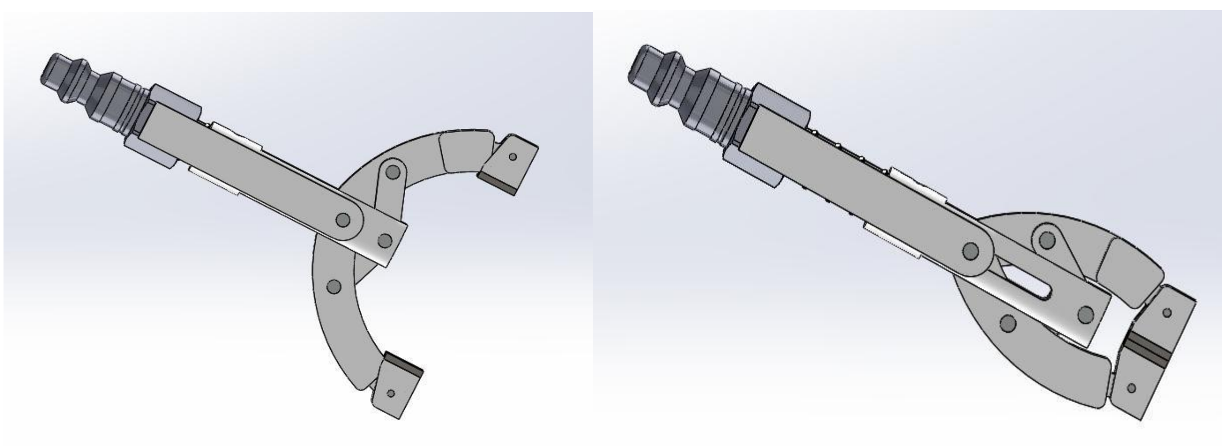


*Figure 31: Claw in both fully open and fully closed positions*

There is some concern with the fingertips not seating against the part properly, especially on smaller parts. if the part being picked up is not intersected by a plane going through the center of the fingertip pins, then there will be a moment generated that could rotate the fingertips outward or inward and possibly drop the part. Our solution to this is to include small magnets behind the silicone rubber pads as per the desired specifications to better hold on to the parts.

The structural components of the claw will be made of ABS plastic. These will be rapid prototyped for our prototype, but the full production model will be injection molded. The pins will all be stainless steel and purchased from McMaster-Carr and cut to the necessary lengths (see Appendices C & D for cost summary and detailed product information).

### Vision and Lighting Function

The final design for the vision and lighting function was a snake camera wand with a wireless monitor. Previously we considered the borescope for our vision and lighting function, however there were complications with the hand holder attachment and monitor being permanently attached to the hand holder. Our initial concept was to disassemble the borescope and run the camera along the gooseneck and have the monitor be part of the mounting system. This proved to be more trouble than it was worth since the wireless model we chose cost less than the wired model we originally selected and solved the problem of video transmission at the same time. When researching different types of camera there were three options: borescope with phone holder, separate camera and monitor, and camera wand and monitor. The borescope with phone holder is like the borescope that we had initially considered, but with no permanent monitor. The technician can use their mobile phone as the monitor via wireless internet. The camera wand option also allowed for a flexible and non-permanent placement on the gooseneck. The separate camera and monitor allowed for a more flexible placement on the gooseneck because there is no tubing to consider. To evaluate the best option for the camera we constructed a decision matrix as seen in Table 19 on the following page.

*Table 19: Final Camera Decision Matrix*

| **Camera/Criteria** | Borescope with Phone Support | Separate Camera and Monitor | Camera Wand and Monitor | **Weight** | Borescope with Phone Support | Separate Camera and Monitor | Camera Wand and Monitor |
|---|---|---|---|---|---|---|---|
| Light Weight < 1 lb | 5 | 5 | 5 | 14 | 69 | 69 | 69 |
| Small Size ( D < 10mm and L < 1") | 5 | 2 | 5 | 14 | 69 | 28 | 69 |
| Flexible Tubing | 5 | 0 | 5 | 11 | 56 | 0 | 56 |
| Small Tube Size ( T < 10mm) | 5 | 0 | 5 | 14 | 69 | 0 | 69 |
| Camera Not permanently attached to existing holder | 1 | 5 | 5 | 8 | 8 | 42 | 42 |
| High Resolution | 5 | 5 | 5 | 11 | 56 | 56 | 56 |
| Wireless Monitor/Detachabl e Monitor | 5 | 5 | 5 | 6 | 28 | 28 | 28 |
| Length of Tube ( T > 3') | 5 | 0 | 3 | 8 | 42 | 0 | 25 |
| LED Lights | 5 | 5 | 5 | 14 | 69 | 69 | 69 |
| | | | | **Total** | 467 | 292 | 483 |

Although the separate camera and monitor allowed for a more flexible placement on the gooseneck, the dimension of the camera was the potential concern (as seen in Figure 32). There are multiple ways to attach the separate camera to the gooseneck such as clipping the camera onto the gooseneck or attaching the camera to a tube to wrap around the gooseneck, however the large diameter of the camera, some 20 mm (0.78"), would not allow enough clearance to go through the 2 inch opening if it was to be attached to the gooseneck.

*Figure 32: Wireless camera and monitor system*

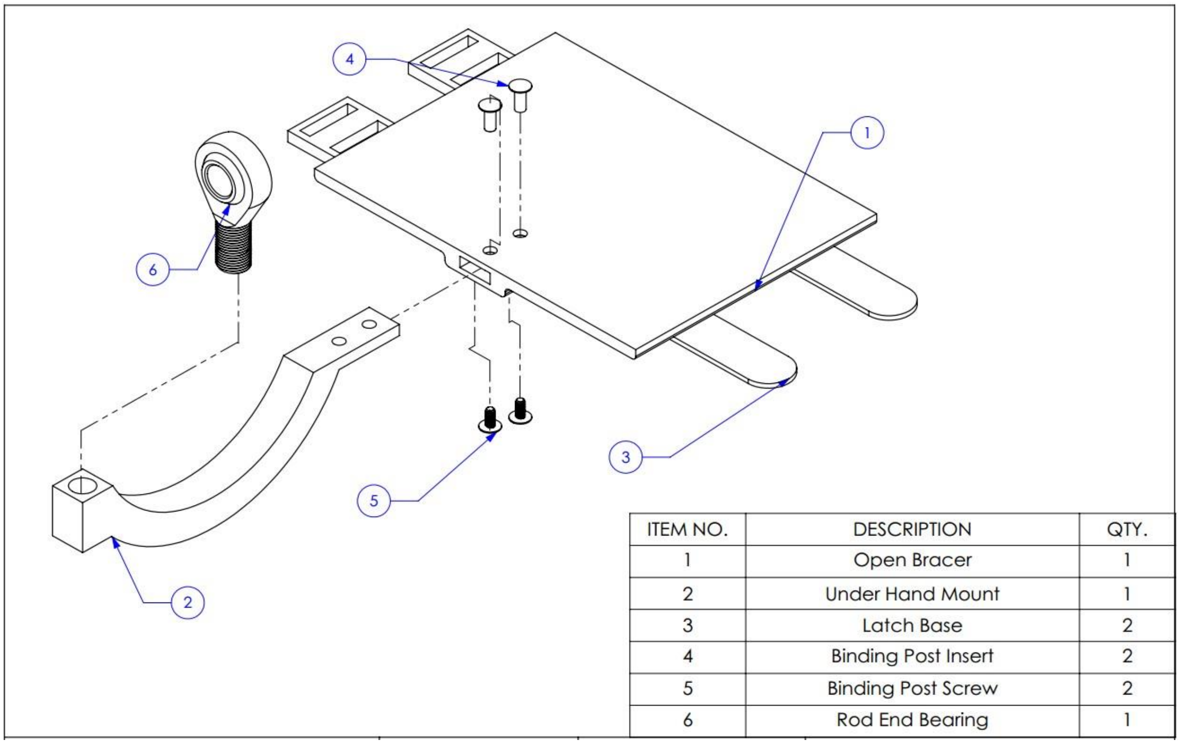
The best option for the vision and lighting function was the camera wand with separate monitor as seen in Figure 33. The camera tubing was run along the gooseneck and the wand itself was part of the mounting system. This allowed the camera orientation to be relative to the movement of the end effector (i.e if the user moves their arm to the left then the camera would be displaying the correct feedback). This camera option allowed the user to see and maneuver around dark and confined spaces.

*Figure 33: Snake camera with wireless viewing monitor*

## Mounting Function

The gooseneck/claw assembly is attached to the user's arm using a wrist guard. A wrist guard was chosen because it allows the most stability while still only requiring one hand to operate. A rod end bearing, also known as a heim joint, is used to hold the gooseneck so that small adjustments in position and angle can be performed with the user's wrist.

The guard itself is an adjustable sleeve that fits over the forearm and is held in place using hook and loop straps. A curved beam extends from the bottom of the sleeve and under the hand and is held in place with binding posts.  A low-profile variety of binding post was used to maximize the user's comfort. The heim joint is screwed into the end of the curved beam and positioned so that the extension is concentric with the wrist guard. See the exploded view below in Figure 34 for a visual of how the pieces fit together.




| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Open Bracer | 1 |
| 2 | Under Hand Mount | 1 |
| 3 | Latch Base | 2 |
| 4 | Binding Post Insert | 2 |
| 5 | Binding Post Screw | 2 |
| 6 | Rod End Bearing | 1 |

*Figure 34: Exploded view of mount assembly*

The final design for the mounting function is composed of a wrist guard, a curved beam termed the underhand mount to mount the gooseneck, and a nylon rod end bearing where the gooseneck will be seated (seen in Figure 35). The wrist guard was a Dakine model, the straps elastic fabric, the curved beam was originally made of ABS plastic then of aluminum, and the rod end bearing made of nylon. Analysis was done for the underhand mount and the maximum force it should see was 0.95lbf. For ABS plastic the beam has an approximate deflection of 0.015" which decreased to approximately 0.0001" for aluminum. Detailed information regarding the calculations used to determine these values can be found in Appendix E. The straps and nylon rod end bearings will be purchased from McMaster-Carr and the bracer will be purchased from Amazon.com. The curved beam will be manufactured in house on a Haas VF3. A rendering can be seen below in Figure 35.

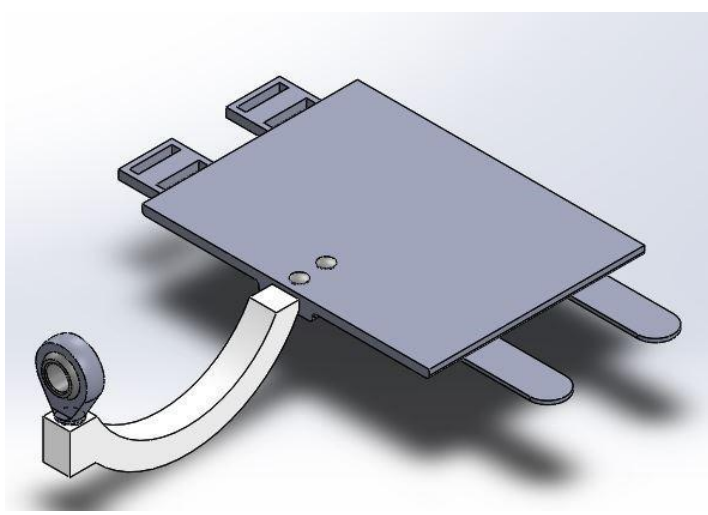


*Figure 35: Mounting Assembly*

## Full Assembly

The final design for the full system can be seen in Figure 36. The camera is seated underneath the bracer and run along the gooseneck tubing. It is seated slightly under the claw to ensure proper viewing of the task and so that it does not interfere with the claw. The flex shaft is inside the gooseneck and it pulls the claw open when the user pulls on the control wheel. It actuates the claw by compressing a spring inside the claw as seen in Figure 37.

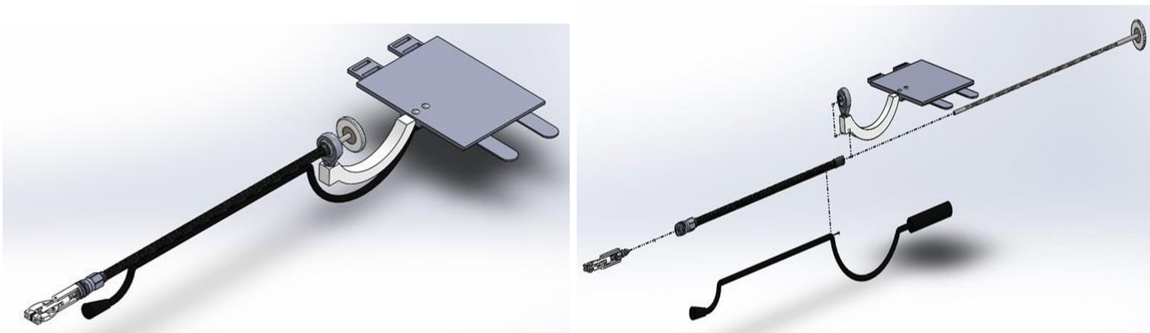


*Figure 36: Assembled and exploded views of full assembly*

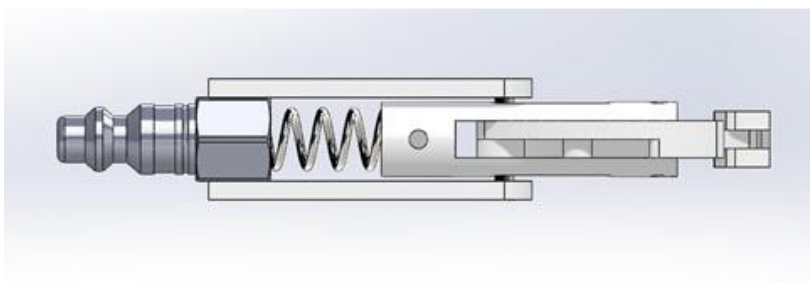
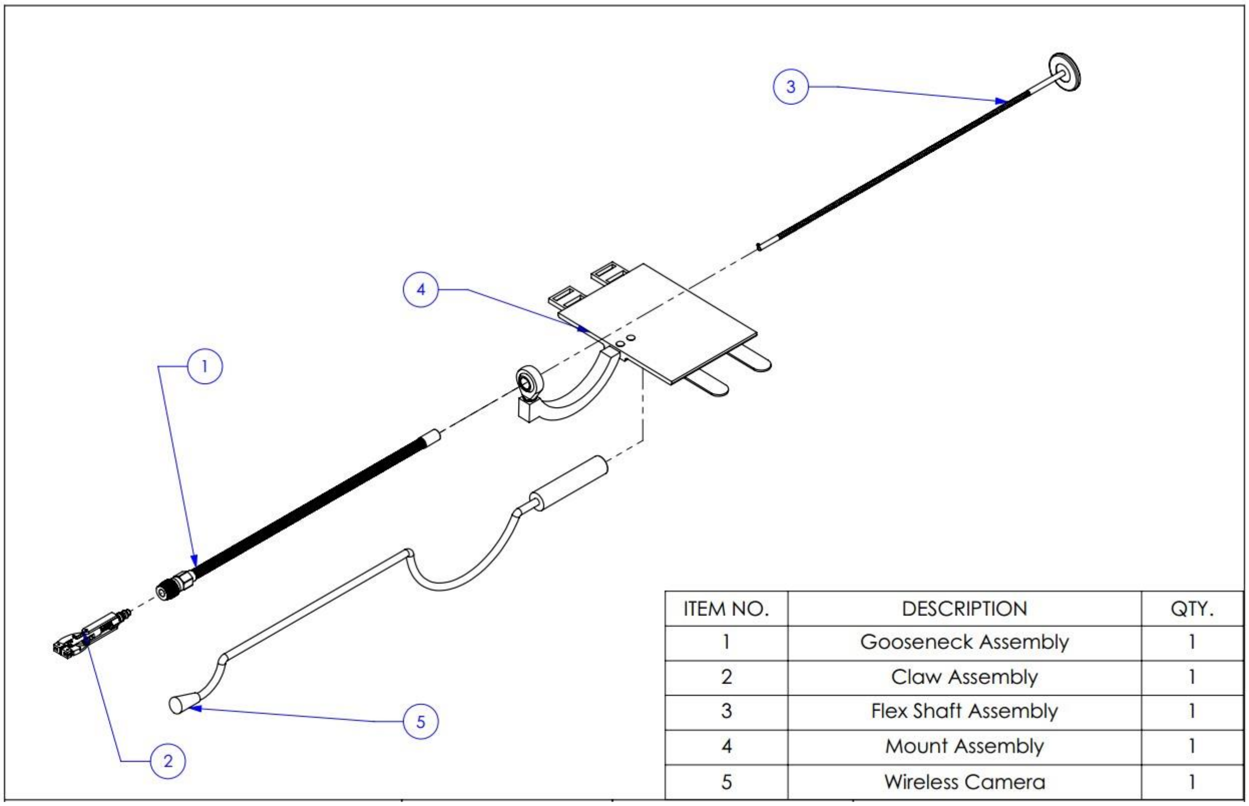


*Figure 37: Side view of claw showing compression spring*

With this final concept, the user should be able to achieve most of the requirements. Only one hand is required to use the device. The device's length is 23.5" which is within the range of specification of 12" to 24". The overall weight of the device is around 1.5 pounds, significantly lower than the original 3-5 pound target. Since this system is mechanically driven, the rotation requirement of 20 rpm and torque requirement of 10 in-lbf have been met because the user can control them directly. With the two-fingered claw design, the device will be able to grip different sizes and shapes of objects. To ensure orthogonality of the extension to the work surface, the feet of the claw are held in place by a pin which allows the claw to grab the object squarely. The maximum opening of the claw is 1.8" when engaging a 0.75" part. This will allow the device to be able to pass through a 2" diameter hole. Parts that are larger than 0.75" will not need to be removed from the machine. The feet of the claw are made of silicone rubber to provide for better grip. A thin magnet was added to the claw feet for magnetic retention of small parts. With the gooseneck, the device is able to bend at least 180 degrees within a three inch radius. The camera system for the device will be strapped under the arm mount to allow for removal when needed. The quick disconnects allowed for interchangeable tool heads while providing the necessary axial support and allowing rotational motion. A detailed drawing of the final assembly can be seen below in Figure 38.




| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Gooseneck Assembly | 1 |
| 2 | Claw Assembly | 1 |
| 3 | Flex Shaft Assembly | 1 |
| 4 | Mount Assembly | 1 |
| 5 | Wireless Camera | 1 |

*Figure 38: Exploded view of the full assembly of the device*

For this prototype, many parts were purchased through a vendor. To see a complete list of vendors and prices for the prototype, see Appendix C. The cost for the first prototype was $318.92. Although the bulk of the cost is from the camera system, we did not consider the cost for the gooseneck because it was part of a sample order. The production cost should be $234.48 per unit for 1000 units. Manufacturing the claw via injection molding instead of 3D printing will be a significantly cheaper alternative. For a complete list of vendors and prices for production, see Appendix C.

## Safety Considerations

When designing a device, it is imperative to design with safety in mind because products may not be used for the intended purpose. There are some safety considerations for our device because the user may be required to exert abnormal effort and/or use the device in an unusual position. It should be noted that the device should not be used on humans because injury could conceivably occur. The intended use of this device is to aid technicians in servicing equipment where access is restricted or limited so caution should be exercised when using the device since the use of one hand will be restricted by the device.

## Maintenance Issues

There should not be any maintenance concerns with this device. Should the end effector be lost or broken, a replacement part can be produced.

# Chapter 5: Product Realization

## Description of Manufacturing Processes

This chapter provides documentation of the prototyping phase, addresses the challenges we encountered, the improvements we made on our design, and recommendations for manufacturing a future product. Recommendations for design changes and future iterations will be discussed in Chapter 7 (Conclusions and Recommendations). We made our way through three iterations of the design and then added a new feature to our third iteration. These iterations, pictured in Figures 39-42, are described below, as are the manufacturing processes for each of them.

*Figure 39: SolidWorks model of Final Design*

*Figure 40: Claw design of Iteration #1*

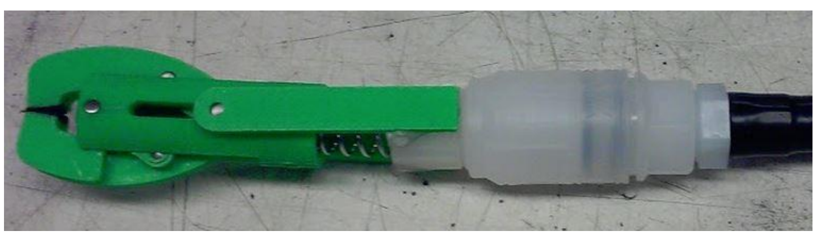


*Figure 41: Claw design of Iteration #2*

*Figure 42: Claw design of Final Iteration*

## Iteration #1

Iteration #1 was much like the description of the final design, which can be seen in Figure 39. The claw was 3D printed on campus in an "ABS-like" plastic. The main feature of this claw design is the pivoting claw foot which allowed the claw to adjust to the contour of the surface it was gripping. This claw was assembled using stainless steel pins cut to length with bolt cutters then ground to have rounded ends. The pins were then pressed into place and held well without the use of an adhesive. Another feature of the first claw was the 1/16" thick adhesive-backed foam padding glued to the end of the pivoting foot. The foam padding deforms to the shape of the object in a fashion similar to the human finger, allowing for better grip and part retention. The two arms or fingers for the claw from Iteration #1 are pictured below in Figure 43.

*Figure 43: Assembled arms for claw for Iteration #1*

The claw was attached to the gooseneck tubing via a quick disconnect coupling for an air-line. The claw was glued to the plug end of the connector. This adapter also allowed for multiple tools if needed by establishing a common interfacing method. The coupling allowed the claw to be rotated while still maintaining a fixed axial length.

An ABS control wheel turned on a manual lathe was used at the end of the flex shaft to allow for better control of the flex shaft and make the interface more user-friendly. It was manufactured to have a thickness of 0.25" and a 2.00" outer diameter with a 1.00" diameter relief for center placement of the flex shaft and knurled on the sides for improved grip. The flex shaft had a ⅛" diameter hole drilled in the end ferrule so it could be bolted to the claw. Once it was glued to the control wheel it was fed through the gooseneck, which was glued to rod end bearing threaded into the underhand mount.

The underhand mount was used to support the system. It was made of ABS plastic. The underhand mount was cut from bar stock with a bandsaw after the initial attempt with the laser cutter failed to provide the desired result. The attempt with the laser led to a much wider kerf than anticipated and much of the plastic near the edge of the part was melted; this is what led to using the bandsaw instead. Holes were drilled for the binding posts used to attach the mount to the wrist guard and one was drilled and tapped for the rod end bearing. Holes were also drilled in the aluminum support inside the wrist guard to accept the barrels of the binding posts. A subassembly of the mounting system is seen below in Figure 44.

*Figure 44: Subassembly of mounting system.*

### Iteration #2

The first iteration revealed a number of flaws with the device, detailed in Chapter 6 (Design Verification Plan and Testing), so we moved on to Iteration #2. The changes between the iterations are organized by the part of the device to which they relate.

#### Claw

Several changes were made to the claw for Iteration #2. The dimensions of the claw were updated to allow for larger holes for the pins because the resolution of the 3D printer was ten thousandths of an inch but the desired clearance was only six thousandths. This led to interference between some components of the claw which was solved by filing the components until they fit together as desired. The pivoting feet on the end of the claw were removed because their ability to rotate freely prevented them from applying the desired gripping force. This issue was addressed in Iteration #2 by integrating the feet into the claw arms. Magnetic retention was also incorporated into Iteration #2 by gluing magnets into reliefs in the claw then gluing the foam over them. This feature allowed for better retention of small nuts and bolts. We had originally planned to use custom bought springs, but we decided to use springs salvaged from the quick disconnects since we would get them for free with each one we bought. These springs were slightly larger than the springs we designed for, so the pull bar was enlarged and a relief was added so that the springs would seat properly. The main claw, the support bars, and the pins were all widened accordingly.

#### Mounting System

There was a small but significant change to the dimensions of the underhand mount. A radius was added at the critical point, seen in Figure 45 below, to minimize the chance of a failure where the underhand mount is attached to the wrist guard.

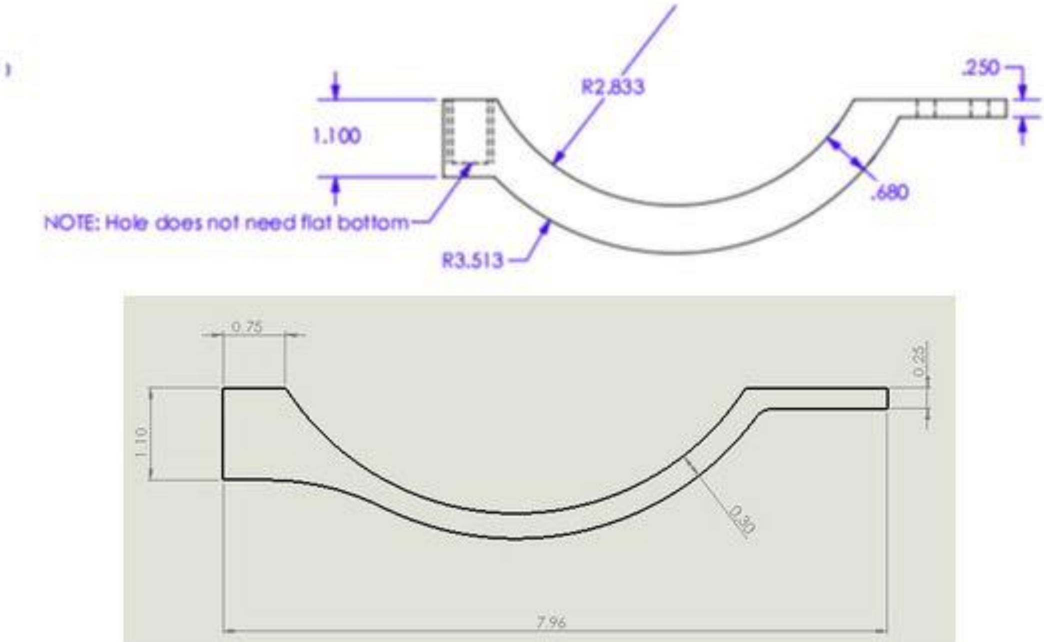



*Figure 45: The original underhand mount (top) and the changes made for Iteration #2 (bottom)*

The material of the underhand mount was updated to be 6061-T6 aluminum because of its higher strength and better machinability than ABS. We used the Haas VF3 milling machine to cut the underhand mount for Iteration #2 due to the number of curves and radii involved with the piece.

Testing on Iteration #1 revealed that the underhand mount was not ergonomic when aligned linearly with the mount. Additional testing with a mock-up model determined an optimum angle of 15.5 degrees and an optimum length of 5.2 inches. The underhand mount was modified to accommodate this new length by adding more mounting holes and the wrist guard hole pattern was modified to accommodate the new angle by rotating the hole pattern. The last change we made to Iteration #2 was altering the rod end bearing. The original rod end bearing did not provide the static friction necessary to support the weight of the gooseneck tubing so we added a setscrew in to hold the inner race in place once the user has positioned it where they desire.

## Iteration #3 Changes (Final Iteration)

The final iteration incorporated changes to resolve issues we encountered during our testing of Iteration #2 discussed in the next chapter. The changes we made are again broken into their appropriate subsystems.

### Claw

The major issue we encountered with Iteration #2 was maneuvering it inside the test box. The root cause of this difficulty was the rigid section from the end of the gooseneck to the end of the claw prohibited fine adjustments anywhere near the hardware we were trying to handle. This was resolved by replacing the quick disconnect with a double shielded ball bearing, reducing the length of the rigid section by about 2.5 inches. The inner race of the bearing was glued to the ferrule of the gooseneck and the outer race was glued to the claw. The supports holding the claw were modified to accommodate this change by combining the two separate support bars via a circular mount approximately the same diameter as the bearing that was epoxied to the outer race of the bearing. A detail of this new mount can be seen in Figure 46 below.

*Figure 46. Support bars for Iteration #3 of claw*

There was an issue during assembly with the epoxy not adhering to the bearing properly, so an ABS washer with an outer diameter approximately ⅛" larger than the bearing was machined, and a bead of epoxy was laid around the circumference of the joint in addition to the area between the two pieces. This extra bead increased the surface area the glue covered, thereby increasing the strength of the joint. New springs were used for this iteration, since it wouldn't be practical to keep salvaging them from the now-unused quick disconnect. The relief for the spring in the pull bar and claw support were adjusted accordingly when reprinting the claw assembly.

The other issue with the claw was it had trouble holding a ½-13 cap nut. This was due to the distance between the claws and the pull bar being too short to accommodate the extra length of the cap and the magnets having insufficient strength to hold onto a larger part through the foam. The claw dimensions were adjusted to provide a little more clearance and larger reliefs were added to fit larger magnets.

### Flex Shaft

In order to compensate for the shortened overall device length, the flex shaft had to be shortened. Also, the shorter length caused the end ferrule to be partially inside of the gooseneck, making it unable to turn, so this was also cut shorter. Bolt cutters were used to trim the flex shaft, then it was ground flat and welded back together. The ferrules were also trimmed and welded in place so that they would not interfere with the gooseneck.

## Vision and Lighting system

We discovered a significant challenge with the vision and lighting system. Since the camera wand is attached below the gooseneck tubing, the camera wand would be under the end effector. Due to the position of the camera wand and the restrictive 2" requirement, it was difficult to see the end effector and the surrounding areas at the same time. To accommodate for this we incorporated an attachable mirror and adjusted the camera wand angle to compensate. This temporarily addressed the issues, but in turn led to new complications. The images from the camera feed were flipped so the user would need to mentally reverse what they were seeing in order to move the device in the direction they desired. Another issue that we encountered was the camera wand needing readjustment very often to keep the end effector in view. We noticed that the camera tubing would rotate with the gooseneck tubing when the camera wand was adjusted or when the gooseneck was bent. To mitigate this problem we tried to use heatshrink to hold the two components together but the variety we purchased was too large. Due to time constraints, we used electrical tape to wrap the camera and gooseneck together to minimize their movements relative to each other as pictured in Figure 47 below.

*Figure 47. Camera and gooseneck taped together to restrict relative movement*

Table 20 below summarizes the changes made to the device with each iteration. These changes are organized by the component of the device to which they apply.

*Table 20: Summary of changes between device iterations.*

| Component | Iteration #1 | Iteration #2 | Final Iteration |
|---|---|---|---|
| Claw | • Pivoting feet<br>• Separate support bars<br>• Salvaged spring | • Integrated feet<br>• Changed claw dimensions<br>• Incorporated magnets | • Single piece support bar<br>• Changed claw dimensions<br>• Relief for cap nut<br>• Larger magnets |
| Attachment between claw and gooseneck | Quick disconnect | Quick disconnect | Bearing |
| Gooseneck tubing | 0.460-L Vinyl wrapped | No changes | No changes |
| Flex shaft | Welded custom length flex shaft | Welded custom length flex shaft | Adjusted length |
| Underhand mount | Underhand mount material: ABS | • Updated underhand mount dimensions<br>• Changed underhand mount material to Aluminum | No changes |
| Wrist guard | Holes for binding posts aligned with axis of wrist | Shifted hole pattern to be more comfortable | No changes |
| Control Wheel | ABS wheel with relief for mounting | No changes | • Removed center relief<br>• Knurled edge |
| Vision/Camera System | Wireless Snake cam | No changes | Attached mirror to end of camera wand |

## Discrepancies between Prototype and Planned Design

One of the differences is the way in which the camera is attached to the gooseneck. The prototype demonstrated and presented at the Senior Project Expo had the gooseneck and the camera tubing attached by wrapping them together with electrical tape since the heat shrink purchased earlier was too loose to hold them together adequately. Another is the inclusion of a “washer” between the outer race of the bearing and the rearmost face of the support bar for the claw. This was used to avoid gluing the bearing in place while trying to glue it to the claw. Fixturing could be produced to make the gluing process go smoother and easier, thus eliminating the need for the washer. Additionally, we had to weld the flex shaft we used to our desired length. Ordering a flex shaft in the proper length, once finalized, would be the preferred option so that there were no “soft spots” or inflexible areas in the flex shaft.

The most important difference between the prototype and the design is the nature of the claw itself.  The claw used in our prototype was made of “ABS-like” material using a 3D printer while the design calls for an injection-molded ABS claw.  The printed claw is made by stacking 2D planes on top of one another to get a 3D shape, which essentially creates predetermined failure points in the part. We discovered this (to our dismay) during testing, but this inherent fragility will not be an issue with a molded part as is called for in the design.

The final dimensioned detail drawings of all parts in the R.E.A.C.H. device are included in Appendix G and an operator’s manual for the final prototype can be found in Appendix H.

## Recommendations for Future Manufacturing of the Design

Several parts of our final prototype were manufactured differently than they should be in the case that the device sees a production run, and some should even be changed for future prototype iterations.  One of the important changes in manufacturing should be ensuring that the correct size of flex shaft is procured from the supplier, including adjusted ferrule lengths.  Having to weld the flex shaft for our prototype caused areas of reduced flexibility that led to occasional binding.  It also caused a lot of extra work for us during manufacturing that could have been avoided by ordering the proper size of part.

The methodology for gluing the claw to the bearing should also be refined.  Having a jig of some variety or a way to shield the bearing components would be highly desirable.  We ended up using a custom made washer in lieu of a fixture but believe that a fixture would be a faster and more reliable method to glue the parts together.  The claw assembly should be injection molded to avoid the issues associated with failures between the 3D printed layers.

# Chapter 6: Design Verification Plan and Testing

## Test Descriptions

The testing of the R.E.A.C.H. device focused on how well it allowed the operators to complete their tasks within the confines of the machinery. To this end, our sponsor provided us with a test box that has a series of paths the device will have to navigate and a representative sample of the tasks it will need to complete, such as threading a nut onto a bolt or carrying a bolt through a two inch hole. There were also some simpler, less demanding tests, such as weighing and measuring the device that ensured that we have met our weight and length criteria. The criteria for success for these two types of tests came from the engineering specifications and our QFD in Appendix B. Our full FMEA and DVP&R are available in Appendix F.

The quantifiable testing will came from analyzing the device's main functions: reach extension/bending, grabbing, vision, and fit/control. These were all tested and verified to ensure the device performed adequately. The reach extension and bending function has many required characteristics: it must reach far enough, the extension must support the weight of the end effector with or without object engagement, and the device must bend at 180 degrees within six inches of itself. All of these characteristics were tested through simple measurements. The device had a final reach extension of 22.25", which fits within the required 18" to 24" length specification. From our theoretical analysis, the max deflection of the gooseneck would be 0.0001" when a point load of 0.085 lbf is applied on the end. While under operation, the gooseneck tubing did not deflect at all. The gooseneck tubing behaved as we expected, it did not deflect until the maximum force was applied, then the whole tubing would give and deflect - the deflection is completely inelastic. The gooseneck tubing we ordered was designed to bend 180 degrees within a 6 inch diameter and measuring its behavior verified that this gooseneck met our specified requirements.

The grabbing function is mechanically driven by linkages and springs. The end effector is closed by default and a spring loaded control wheel must be pulled to cause the end effector to open. This grabber must be able to hold items, open large enough to grab the desired object, and fit through the two inch hole while holding an object. All of these requirements were tested experimentally. With the addition of fingertip magnets, the claw is able to hold our magnetic parts very well - to the point where the claw's magnets will still hold the parts when the claw is fully open. The claw was specifically designed to be able to hold our largest part, a ½-13 cap nut, and our testing verified that it was able to properly hold this part. The maximum diameter of the claw while holding our part was less than 2 inches, as designed, and testing showed that the claw was able to enter the 2 inch hole with very few difficulties while holding any of our specified parts. While the magnets were able to assist the claw in grabbing our parts, they did not help with the transmission of torque between the claw and the nut or bolt. This revealed itself in the fact that the claw had the tendency to slip off of the nut or bolt it was trying to turn when a large amount of torque was required. From this, our testing showed that the foam claw tips did not provide a high enough coefficient of static friction with the metal and a much "stickier" tip material would greatly improve our claw's capabilities to transmit torque.

The vision and lighting function is an inspection camera with a wireless monitor. This function is tasked with giving the user the ability to navigate in the dark confined space as well as allowing the user to view their angle of approach to the part they want to engage. We tested the resolution of the camera at various distances from various sizes of nuts and bolts. We discovered that the angle of the camera placement did not reduce the field of view. The range of view was 2"x 2" at a distance of 3" from the object, indicating that the user would be able to see their entire working area. Most importantly, we tested the device inside of the dark and confined test box. The device does an excellent job of illuminating the dark working space as well as allowing the user to see the target work area.

The mounting function is a compression sleeve or wrist guard with and adjustable strap that is attached to the underhand mount with binding posts. Calculations showed a theoretical max deflection of 0.010" under maximum load (the point where the gooseneck tubing will deflect). In our testing, we saw that the underhand mount performed perfectly and showed no visible deflection. However, there is some play between the wrist guard and the underhand mount, causing the device to not be completely rigid in its attachment to the user. We believe this is due to the metal brace inside of the wrist guard not being held rigidly enough. It is shifting slightly and causing the underhand mount to sway relative to the mount. This does not behave as well as expected, but does not make the device unusable.

The most challenging and important test is introducing the device to the end-user. Can they use the device effectively with little training? Is the device user-friendly? Can they perform their maintenance faster than their current servicing method? Can they wear the device comfortably for a prescribed time? From our testing, the device is intuitive to use as long as the user can see the entire device and does not rely on the vision system to see. However, once this is introduced and the user must completely rely on the camera for navigation, the device becomes more difficult to use due to difficulties maintaining a fixed frame of reference while bending the gooseneck tubing and camera and feeding it through the test box. While this iteration does a good job at showing the concept of the device, additional work will be needed to improve its usability.

## Detailed Results

The main goal of the R.E.A.C.H. device is to be able to perform the required tasks in a constrained environment faster than the current method. To test this, we used the R.E.A.C.H. device in a test box that Lam Research provided to us. The most challenging thing that we tested for was how user-friendly the device was because we anticipated users to have varying levels comfort and capability. This section contains details of our tests for the following categories: reach extension/bending, grabbing, vision, fit/control, types and number of parts removed and threaded, and the time to remove and thread a part.

### Iteration #1

The main testing for Iteration #1 was testing for usability of the device and functionality of the claw. To test for this we slipped on the wrist guard and tried manipulating the control wheel. We found that it was very difficult to manipulate the control wheel because the user had to angle their hand to the right to get a better grip of the control wheel. This would then allow us to manipulate the control wheel with our thumb and index finger but it was not a position easily maintained for a long time. The wrist guard and the underhand mount were attached with no angular offset as seen in Figure 48 below.

*Figure 48: Bottom view of underhand mount and wrist guard attachment*

To find the most comfortable angle to mount the wrist guard to the underhand mount we experimented by putting on the wrist guard and using a mockup of the underhand mount to determine which angle felt the best for each member of the team. From this we discovered the most comfortable angle to offset the wrist guard to be 15.5 degrees. We also tested for the ideal distance from the wrist guard to the rod end bearing at an angle of 15.5 degrees. This value varied for each member of the team so we decided to make the underhand mount adjustable. The average length was 5.2 inches but we added the ability to adjust that distance an inch in either direction.

We also tested the functionality of the claw. We tested this by attaching the claw to the flex shaft and feeding it through the gooseneck then trying to pick up, thread, and remove different sizes of nuts and bolts. We found that the pivoting feet did not perform as expected in that they hindered our ability to hold the hardware securely instead of helping it. We anticipated that the pivoting feet would adjust to the contour of the surface they were gripping, but we instead found that the ability to rotate freely did not provide sufficient gripping force to hold the parts. This discovery lead to an inclusion of magnets beneath the foam padding to keep the parts held closer to the center of the contact pads.

For this iteration we were not able to test inside the test box, so we were not able to test the reach extension/bending function, and vision/camera system.

### Iteration #2

Having improved on Iteration #1, we were able to produce Iteration #2 and test the functionality and usability of the device inside the test box. The full assembly of the device also incorporated the camera, which we attached beneath the gooseneck tubing via zip ties. To test for the fit/control we had each member of the team try on the device. Having the wrist guard at 15.5 degrees offset to the underhand mount and the distance at 5.2 inches allowed better manipulation of the control wheel.

Testing for the reach extension and bending was done outside and inside the test box. To test for the reach extension we measured the reach extension of the device and ensured that the device was between 12” to 24”. The length of the reach extension for Iteration #2 was 22.25 inches. We also tested to see if the extension was able to support the weight of the end-effector with and without it holding an object. To do this we tested how much weight the gooseneck was able to carry before failing or bending. We tested this by clamping down one end of the gooseneck in a vise and loaded the other end of the gooseneck with a spring scale until the gooseneck deflected. The failure mode of the gooseneck was not incremental bending as previously assumed, but rather full bending instantaneously. From the manufacturer's spec sheet the maximum weight that the gooseneck is able to hold is 5.1 oz, and the gooseneck deflected when we applied just shy of 5 ounces in our testing.  Since the heaviest part the device has to lift weighs about 0.6 oz, the device passed this test.

To test for the bending we bent the gooseneck tubing back onto itself and observed if it was able to bend 180 degrees within six inches of itself.  It complied without any problems, but the rigid length at the end effector made it challenging to fit tight bends inside the test box. This made it difficult to engage nuts and bolts that are at a right angle to the access port in the test box.  To test inside the test box we had to bend the gooseneck before inserting it into the test box to be able to maneuver into the restricted 2" opening and then remove the device and adjust it accordingly for each nut and bolt that we wanted to remove. The gooseneck was able to do this inside and outside the box but maintaining the required degree of precision was challenging. We also tested the ability of the of flex shaft to transmit rotation and torque by manipulating the control wheel; the flex shaft passed this test.

Testing for grabbing was done inside and outside the test box. We tested how well the claw was able to grab various sizes of nuts and bolts, and maintain contact with the objects. To do this we clamped various nuts and bolts in a vise as seen in Figure 49. With the new rigid feet, the claw was able to grip the objects with more force than the pivoting feet and this allowed the claw to maintain contact with the objects and remove them successfully. We also tested the magnetic retention of the claw. We did this by picking up the ½-13 nut and found that one magnet was not strong enough to hold it alone, so we increased the size of the magnets for Iteration #3. After more testing we discovered that the 0.0625" foam padding deformed and did not allow for proper gripping. Overall, the claw still performed as expected outside the test box despite some minor setbacks.

*Figure 49: Testing the grabbing function outside the box.*

The vision and light system was tested inside the test box. The camera system was attached below the gooseneck tubing with zip ties. This would allow the camera wand to be positioned to allow the user to view the claw while keeping the profile of the device slim. We found that the camera wand had to be bent in a recurve pattern to allow for adequate viewing of the claw which was challenging to accomplish while keeping the device small enough to fit through the 2” opening. We also found that while the LEDs on the camera sufficiently lit up the viewed area, the field of view was very limited due mostly to the compact size requirement and proximity of the camera to the end effector. The vision and lighting system passed the test but there was certainly room for improvement.

The test for ease of use was more subjective since each individual had different levels of experience with using hand tools. We found that it was challenging to maneuver the device into the test box because the gooseneck had to be bent at a certain angle before entering the test box, which meant the user had to approach the test box from an awkward position to get inside the 2” opening. The device also needed further adjustment after the first insertion and this uncomfortable entry procedure had to be repeated after every adjustment. Overall, the device did not perform as well as we had hoped inside the test box because it took longer and was difficult to use.

None of the members successfully removed a fastener from the test box with Iteration #2 due to the complications from the length of the rigid end of the device. The team spent several hours attempting to remove even a single fastener to no avail, which was an indication that we needed to move on to another iteration. Table 21 below summarizes the outcome of our testing with Iteration #2 on system by system basis. Note that while the Reach extension/bending system passed our criteria, it did not provide the functionality to meet the demands of the test box.

*Table 21: Summary of Iteration #2 results*

| System | Result |
|---|---|
| Fit/Control | Pass |
| Reach Extension/Bending | Reach Extension- Pass<br>Bending- Fail |
| Grabbing | Pass |
| Vision and Light system | Pass |

## Final Iteration

Several changes made to the device for the Final Iteration to improve its usability and functionality. We attached the camera by wrapping it to the gooseneck tubing with electrical tape rather than heat shrink to bind them together better. This step was necessary because in earlier iterations the two would not move in unison and misalignment during adjustment was a common problem.

For this iteration the wrist guard was mounted 15.5 degrees offset to the left of the wrist mount and the finger reach length was optimized to 5.2”. To test for the fit/control, we tested how comfortable the wrist guard would fit different size hands and how well we were able to manipulate the control wheel. We found that it was easy to manipulate the control wheel because the user did not have to angle their hand uncomfortably to maintain solid control of the device. The new wrist mount and underhand mount can be seen in Figure 50 below. Overall, this iteration passed the fit/control test.

*Figure 50: Underhand mount with 15.5 degree offset and optimized length of 5.2 inches*

For this iteration the quick disconnect was removed to allow for more flexibility at the end effector. The quick disconnect was replaced with a single double shielded ball bearing. While this shortened the length of the device, this was not a cause for concern since the reach extension was still well within the requirements. The new reach extension length was approximately 22.25 inches. The bending test did not need to be repeated since the gooseneck was unmodified, but the change from a quick disconnect to a bearing allowed the device to bend closer to the end effector which enabled more precise control of the position of the end effector.

Testing inside the test box was still challenging but became easier with the reduced length of the rigid end effector. The device still had to be adjusted while outside the test box and this was still a tedious process, but the user had more precise control over the position of the end effector. We also tested the ability of the of flex shaft to transmit rotation and torque by manipulating the control wheel and we found that there was some resistance and the end effector did not rotate as freely as before. This was likely due to the shortened ferrules on the flex shaft providing a shorter bearing surface and therefore allowing for a little axial misalignment. The bending radius of the gooseneck was still a little too large to have very much success in the test box even after replacing the quick disconnect with the bearing. Despite meeting the numerical specifications, the gooseneck still failed in the test box.

For this iteration, we added larger magnets to allow one finger of the claw to hold on to a ½- 13 nut. The claw dimensions were updated slightly to account for the bearing and the larger magnet. We repeated the grabbing tests with the new claw and learned that the two-finger claw was still not as effective at picking up round objects as we would have liked. To allow for multiple attachments we adapted a ¼" drive socket wrench to be compatible with the same bolt used to hold the claw in place. To test this we used different socket adapters to remove and thread a few bolts. While this socket wrench attachment did not have magnetic part retention built in, several magnetized driver bits and sockets are on the market and are compatible with the socket wrench.  Both attachments can successfully remove fasteners from inside the test box, meaning that the end effectors pass their tests.

For the vision system we added a mirror attachment that came with the camera to aid with viewing the claw while maintaining a smaller overall diameter. To test for vision and lighting effectiveness we observed how well were able to see the claw while still maintaining enough visibility to see where the device was pointed. The mirror provided an adequate view of the claw but the quality of the image was rather poor. It also took longer than anticipated to adjust the image of the claw into the field of view of the mirror due to frequent misalignment between the two components. This step alone took more than ten minutes to achieve an adequate image of the claw in the mirror. Additionally, that the images on the mirror were flipped which meant the user had to reverse what they were seeing mentally in order to determine the correct direction to move the device when aligning it.  While the vision and lighting system passed the test, it did not perform as well as we had hoped.

For our hardware removal time test, not every member had success in removing components from the test box using the device.  All members were able to remove hardware from the box with their hands using the 5" access port with a time in the 15-25 second range.  One member was able to remove a fastener in just under three minutes after about half an hour of practicing with the device.  The sponsors were able to remove and then re-thread a nut within half an hour of first trying the device, which was an encouraging result indicating that the device was rather successful.  The general experience of both the sponsors and the team members was that the time cost of the device was largely in the setup time.  Team members voiced their concerns with keeping the camera and gooseneck aligned and the difficulty of approaching the test box and inserting the device, saying that these faults were some of the more time consuming parts of the process.

We discovered that the device performed to the specifications outside the test box, but the test box was more demanding than the specifications alone.  To see how the other people felt about our device we allowed attendees of the Senior Expo to use the device to try to remove a component from the test box. We were glad to see that some participants were able to remove and re-insert some hardware in under thirty minutes with the device. We also learned that a lot of participants faced the same challenges that we did while testing the device. Most participants said that the device took a little bit of time to learn and get used to operating but did not find it uncomfortable or extraordinarily frustrating.  They also raised many other areas where the device would have applications outside of repairing the equipment at Lam Research. The device passes the usability test in that someone new to the device was able to successfully operate it but it falls short in terms of the speed with which a user can accomplish the desired task.

The results of our tests with the Final Iteration are contained in Table 22 below.  As with Iteration #2, the device passed all of the numerical tests but still struggled with some of the more subjective tests.

*Table 22: Summary of final iteration specification results*

| System | Result |
|---|---|
| Fit/Control | Pass |
| Reach extension/bending | Reach Extension- Pass<br>Bending- Pass |
| Grabbing | Pass |
| Vision and Light system | Vision- Pass<br>Light- Pass |

## Specification Verification Checklist

Table 23 below details the performance of our Final Iteration as compared to both the required and desired specifications. Table 24 on the following page shows the tolerances and requirements used to determine the verdicts in Table 23.

*Table 23. Required and desired specifications, respectively.*

| **Length 12" to 24"** | **One-handed operation** | **Grip various nuts, bolts, and oddly-shaped objects** | **End effector passes through 2" hole** | **Extension bends 180 degrees within 3" radius** | **Vision and lighting system** |
|---|---|---|---|---|---|
| 22.25" | Yes | Yes | Yes | Yes | Yes |

| **Interchangeable tool heads** | **Articulating wrist motion** | **Magnetic retention** | **Ensured orthogonality to work surface** | **Verification of proper thread engagement** |
|---|---|---|---|---|
| Yes | No | Yes | No | No |

*Table 24. Initial requirements, goals, and metrics for R.E.A.C.H. device.*

| Spec # | Parameter Description | Requirement or Target | Tolerance | Risk | Compliance | Pass/Fail |
|---|---|---|---|---|---|---|
| 1 | Length | 18” | ±6” | L | A, T, I | Pass |
| 2 | Hands Required for Operation | 1 | max | M | T | Pass |
| 3 | Weight | 5 lbf | max | H | A, T | Pass |
| 4 | Torque | 10 in-lbf | max | L | T | Pass |
| 5 | Rotation Speed | 20 rpm | min | L | T | Pass |
| 6 | Grip Capabilities | Able to grip #4 to ¼-20 socket head cap screws, #6-32 to ½-13 nuts | min | M | T | Pass |
| 7 | End Effector Diameter | 2 in | max | H | I, T | Pass |
| 8 | Bending Angle | 180° | min | L | I, T | Pass |
| 9 | Bend Radius | 6 in | max | M | A, I, T | Pass |
| 10 | Battery Life (operating time) | 1 hour | min | L | A, T | Pass |
| 11 | Vision and Lighting System | Operator can observe part manipulation | N/A | M | T | Pass |
| 12 | Instruction Level Required for Use | 10 minutes | Max | M | T, I | Pass |
| 13 | Tool Interface | Equipped | N/A | L | I, T | Pass |
| 14 | Magnetized Part Retention | Equipped | N/A | L | I, T | Pass |
| 15 | Force Feedback | Equipped | N/A | M | A, I, T | Pass |

# Chapter 7: Conclusion and Recommendations

This project has provided an exciting and challenging task for team R.E.A.C.H. over the course of the past several months. While the project had no shortage of challenges, we feel that we were successful in our endeavor to realize an idea and bring the R.E.A.C.H. device to life in a functional prototype. We were able to iterate a number of times but still feel that there is room for improvement in future iterations.

Some of the more important improvements that could be made relate to the functionality of the device. For the claw, a third finger would be a welcome and significant improvement. While having two opposed fingers allows for a lot of functionality, it is challenging to securely hold anything with a round cross section. Having three points of contact would grip round parts better and reduce the chance that a part would twist. The gooseneck, while being almost exactly what we were looking for with the reach extension and bending requirement, has too large of a bending radius to allow for precise positioning within the confines of the operating space. Additionally, it bends in a coupled fashion where it deflects in a direction perpendicular to the direction in which it is being bent intentionally. Replacing the gooseneck with a series of independent pieces or joints, similar to those used in Loc-Line, would not only solve the issue of coupled bending but also allow for finer positioning along the length of the extension.

Designing a more rigid replacement for the wrist guard would improve the stability of the device but at the cost of the excellent ergonomics the current wrist guard provides. This is left up to Lam to be pursued or ignored at their discretion. The flex shaft performed well but tended to twist under high torsional loading since it was effectively a long coil spring at full compression. A series of rigid links connected with u-joints or a similar connection would likely solve the twisting problem but would require a larger diameter of extension to guide it. This would also increase the weight of the device, which is an important parameter to monitor to maintain ease of use. The camera works reasonably well but the depth perception is lacking and the off-axis alignment and continually changing reference frame are difficult to account for using the wireless monitor. An external camera with a fixed reference frame or a camera mounted coaxially with the extension would likely improve the ease of use of the device.

Regarding future iterations of the product, we recommend that Lam Research invest in further design work and/or optimization in several areas. The first area of interest would be the underhand mount. While the current support design is functional and robust enough, the aesthetics could be improved. A geometry with more curves and soft edges, and maybe a taper running away from the user, would be more appealing and marketable while also appearing more robust. The mount could benefit from some ergonomic considerations and biometric data on user comfort regarding hand position and wrist motion range. The ideal solution would be a combined mount/support that had a path for routing the camera through them both.

We also recommend that Lam pursues the development of more tool heads. The tool attachment system is simple and versatile, meaning that other tools can easily be integrated into the device. The inclusion of a ¼" drive socket wrench also helps expand the utility of the device. There exists a tremendous opportunity to broaden the scope of the device with the addition of the proper tools and we feel this is an opportunity that should be seized to the fullest.

# Appendices

Appendix A: Bibliography
Appendix B: QFD House of Quality
Appendix C: Vendor Information
Appendix D: Purchased Component Information
Appendix E: Supporting Analysis
Appendix F: Analysis Plan, FMEA, and DVP&R
Appendix G: Drawing Packet
Appendix H: Pugh Matrices
Appendix I: Operator's Manual

## Appendix A: Bibliography

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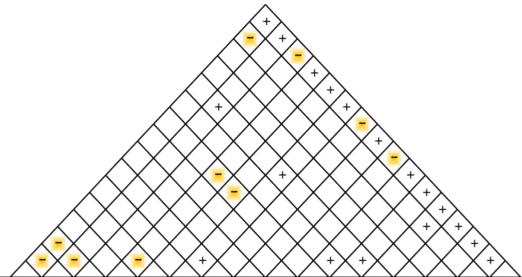
# Appendix B: QFD House of Quality

QFD: House of Quality
Project: Mini-Hand Extension
Revision: 1.0
Date: 10/15/2014

| Correlations | |
|---|---|
| Positive | + |
| Negative | − |
| No Correlation | |

| Relationships | |
|---|---|
| Strong | ● |
| Moderate | ○ |
| Weak | ▽ |

| Direction of Improvement | |
|---|---|
| Maximize | ▲ |
| Target | ◇ |
| Minimize | ▼ |



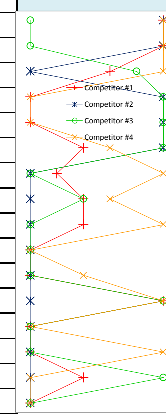
WHO: Customers

NOW: Current Product Assesment - Customer Requirements

HOW: Engineering Specifications

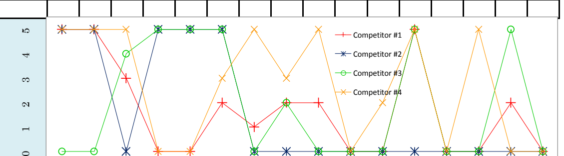
| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction of Improvement | ▲ | ▼ | ◇ | | | | | | | | | | | | | |
| HOW: Engineering Specifications | Device meets length requirement | Operable with one hand | Maximum weight (carry and use) | Maximum torque | Rotates | Adaptive grip capability | Diametral size of effector | Specific bending angle | Max bend radius | Energized | Digital vision/lighting system | Requires minimal instruction | Standardized tool interface | Magnetized/magnetizable | Touch feedback/force sensing | Reduction in repair time |

| Row # | Weight Chart | Relative Weight | Al Schoepp | Technicians | | | Maximum Relationship | WHAT: Customer Requirements (explicit & implicit) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Competitor #1: Trigger-Operated Grabber | Competitor #2:Robotic Arm | Competitor #3: Manual Disassembly/Repair | Competitor #4: Multi-prong pick-up tool | | Row # |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 6% | 10 | 7 | | | 9 | 12 <Device Length <24* | ● | | ○ | | | | ▽ | | | | ▽ | | | | | ○ | 5 | 5 | 0 | 5 | | 1 |
| 2 | | 7% | 10 | 8 | | | 9 | One-handed operation* | | ● | ○ | ▽ | ▽ | | | | | | | ▽ | | | ○ | | 5 | 5 | 0 | 5 | | 2 |
| 3 | | 7% | 10 | 10 | | | 9 | Lightweight/Portable* | ○ | ○ | ● | | | | ▽ | | | ○ | | | | | | | 3 | 0 | 4 | 5 | | 3 |
| 4 | | 7% | 10 | 8 | | | 9 | Can deliver 10in-#s of torque* | | | | ● | ○ | | | | | ○ | | | | | | | 0 | 5 | 5 | 0 | | 4 |
| 5 | | 6% | 10 | 7 | | | 9 | Rotates at 20 RPM* | | | | ○ | ● | | | | | ○ | | | | | | | 0 | 5 | 5 | 0 | | 5 |
| 6 | | 7% | 10 | 9 | | | 3 | Able to grip appropriate hardware and odd objects* | | | ▽ | | ▽ | ○ | ▽ | | | | | | ○ | | ○ | | 2 | 5 | 5 | 3 | | 6 |
| 7 | | 7% | 10 | 10 | | | 9 | Fits through a 2" diameter hole* | | | ○ | | | | ● | | | | | ○ | ○ | | | ○ | 1 | 0 | 0 | 5 | | 7 |
| 8 | | 7% | 10 | 8 | | | 9 | Can bend 180 degrees* | ▽ | | | | | | | ● | ○ | | ▽ | | | | | ○ | 2 | 0 | 2 | 3 | | 8 |
| 9 | | 6% | 10 | 7 | | | 9 | Has maximum bend radius of 3"* | | | | | | | | | ● | | ○ | | | | | ○ | 2 | 0 | 0 | 5 | | 9 |
| 10 | | 4% | 7 | 5 | | | 9 | Battery powered* | | | ▽ | ▽ | ▽ | | | | | ● | ○ | | | ▽ | ▽ | | 0 | 0 | 0 | 0 | | 10 |
| 11 | | 7% | 10 | 9 | | | 9 | Vision/lighting system* | | | ▽ | | | | | | | ○ | ● | ○ | | | | ○ | 0 | 0 | 0 | 2 | | 11 |
| 12 | | 6% | 7 | 8 | | | 9 | Ease of use* | | ○ | ○ | | | ○ | | | | ▽ | ○ | ○ | ▽ | ▽ | ▽ | ● | 5 | 0 | 5 | 5 | | 12 |
| 13 | | 6% | 9 | 7 | | | 3 | Interchangeable tool heads* | ○ | | ▽ | ○ | ○ | ○ | ○ | | | ▽ | ▽ | ○ | ○ | ▽ | ▽ | ○ | 0 | 0 | 0 | 0 | | 13 |
| 14 | | 4% | 6 | 5 | | | 3 | Magnetic retention of small parts | | | | | | ▽ | | | | ▽ | | | ▽ | ○ | | | 0 | 0 | 0 | 5 | | 14 |
| 15 | | 6% | 8 | 7 | | | 9 | Touch feedback/force sensing | | | | | | | | | | ○ | | ○ | | | ● | | 2 | 0 | 5 | 0 | | 15 |
| 16 | | 7% | 10 | 10 | | | 9 | Faster than current procedure | | | | | | | | | | | | ▽ | | | | ● | 0 | 0 | 0 | 0 | | 16 |




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HOW MUCH: Target | 12-24 inches | Y/N | 5 pounds | 10 in-lbs | Rotates at ≥20 RPM | #4-1/2-13 nuts, oddly shaped objects (provided by Lam Research?) | 2" | 180° | ≤ 3 inches | Y/N | Y/N | 5 minutes training or 10 mnutes reading a manual | Y/N | Y/N | Y/N | Y/N |
| Max Relationship | 9 | 9 | 9 | 9 | 9 | 3 | 9 | 9 | 9 | 9 | 9 | 3 | 3 | 3 | 9 | 9 |
| Technical Importance Rating | 102.2 | 98.36 | 168.2 | 106.6 | 111.2 | 59.37 | 104.8 | 59.41 | 75.62 | 153.1 | 130.2 | 108.1 | 70.41 | 27.95 | 106.3 | 234.6 |
| Relative Weight | 6% | 6% | 10% | 6% | 6% | 3% | 6% | 3% | 4% | 9% | 8% | 6% | 4% | 2% | 6% | 14% |
| Weight Chart | | | | | | | | | | | | | | | | |
| Competitor #1: Trigger-Operated Grabber | 5 | 5 | 3 | 0 | 0 | 2 | 1 | 2 | 2 | 0 | 0 | 5 | 0 | 0 | 2 | 0 |
| Competitor #2:Robotic Arm | 5 | 5 | 0 | 5 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Competitor #3: Manual Disassembly/Repair | 0 | 0 | 4 | 5 | 5 | 5 | 0 | 2 | 0 | 0 | 0 | 5 | 0 | 0 | 5 | 0 |
| Competitor #4: Multi-prong pick-up tool | 5 | 5 | 5 | 0 | 0 | 3 | 5 | 3 | 5 | 0 | 2 | 5 | 0 | 5 | 0 | 0 |

Current Product Assesment - Engineering Specifications




| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

Template Revision: 0.9 Date: 4/23/2010
Christopher Battles

# Appendix C: Vendors, Contact info, Pricing

## Prototype

| Function | Part Name | Model Number | Quote | Quantity | Taxes | Shipping Cost | Total Cost | Shipping From | Shipping to | Delivery Method | Delivery Time | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Vision and Lighting* | *Wireless V-snake viewer with Color Monitor* | 70920 | 119.99 | 1 | 8.25% | 13.99 | 133.98 | Elgin, IL | San luis Obispo, CA | Economy | 2 Weeks | Autobodytoolmart |
| *Reach Extension and Bending* | *Ullman Flexible Spring Claw No.16* | 5681A14 | 8.20 | 1 | *included | *included | 8.20 | Santa Fe Springs, CA | San luis Obispo, CA | Next day | 1 Day | McMaster-Carr |
| | *Gooseneck - 18''* | 0.460-L | 15 | 1 | 0 | 13 | 28 | Terryville, CT | San luis Obispo, CA | Economy | 2 Weeks | flexible-gooseneck.com |
| | *Nylon-Tip Set Screws* | 90291A533 | 7.05 | 1 | *included | *included | 7.05 | Santa Fe Springs, CA | San Luis Obispo, CA | Next Day | 1 Day | McMaster-Carr |
| *Mounting* | *BInding Posts* | 99024A339 | 12.96 | 2 | *included | *included | 12.96 | Santa Fe Springs, CA | San Luis Obispo, CA | Next Day | 1 Day | McMaster-Carr |
| | *Nylon Rod End Bearing* | 1064K571 | 12.25 | 1 | *included | *Included | 12.25 | Santa Fe Springs, CA | San luis Obispo, CA | Next Day | 1 Day | McMaster-Carr |
| | *Bearing* | 6384K46 | 11.02 | 1 | *included | *Included | 11.02 | Santa Fe Springs, CA | San luis Obispo, CA | Next Day | 1 Day | McMaster-Carr |
| | *Arm Mount* | W 1500800 | 15.00 | 1 Pair | 8.25% | *Included | 16.24 | CA | San luis Obispo, CA | 2-Day | 2-Day | Amazon |
| | *Aluminum Stock* | 8975K237 | 37.22 | 1 | *included | *Included | 37.22 | Santa Fe Springs, CA | San luis Obispo, CA | Next Day | 1 Day | McMaster-Carr |
| *Grabbing* | *3D Claw* | --- | 65.00 | 1 | *included | 0 | 65.00 | San Luis Obispo, CA | San Luis Obispo, CA | Pick-up | -- | ME Department |
| | *1/8" Drive Shaft* | 1327K39 | 7.23 | 1 | *included | *included | 7.23 | Santa Fe Springs, CA | San Luis Obispo, CA | Next Day | 1 Day | McMaster-Carr |
| | *Springs* | --- | 0 | 1 | 0 | 0 | 0 | Norwalk, CA | San luis Obispo, CA | Economy | -- | Argo Spring |
| | *ABS Stock* | 8587K9 | 23.66 | 1 | *included | *included | 23.66 | Santa Fe Springs, CA | San Luis Obispo, CA | Next Day | 1 Day | McMaster-Carr |

**Appendix D: Purchased Component Information**

## Specification Datasheet

### Wireless V-snake view with color monitor

The Wireless V-Snake Viewer provides high resolution color remote video inspection allowing the user to view real time images from the camera wand. The wireless camera wand allows unlimited access to inspection areas and maximum control of the camera. Ideal for automotive, industrial, electrical, construction, plumbing, building maintenance and pest inspection.

#### Inspection Camera

- Wireless camera wand allows unlimited access to inspection areas and precise camera orientation at all times.
- High resolution auto focus camera.
- 10 meter / 30' wireless inspection range.
- 4 channel wireless selection on camera wand to prevent interference.
- 10mm camera with internal LED lighting and dimmer control on wand.
- Flexible 700mm / 28" camera wand.
- 90 degree mirror attachment.
- Magnetic pick up attachment
- Rechargeable internal lithium battery.

#### Wireless Standard Monitor

- 2.4" full color viewing monitor.
- Rechargeable internal lithium battery.
- 4 channel wireless selection on monitor to prevent interference.
- Universal charging adapter for camera wand and monitor.
- Hanging hook and fold out monitor stand.
- Protective silicone monitor cover.
- AV Output
- All components in custom blow mold case.

**Appendix D: Purchased Component Information**

## Ullman Flexible Spring Claw No. 16 (Flex Shaft)


**Brand Name**: Ullman
**Material**: Steel
**Length**: 23 ½ ''
**Opening width**: 1''
**UPC**: 032513100717

**Appendix D: Purchased Component Information**

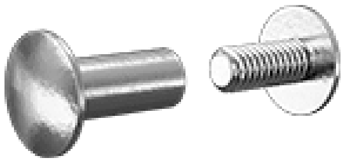
## Gooseneck

| Items | <br>0.460-L | <br>0.460-M | <br>0.460-H | <br>0.585-M | <br>0.585-H |
|---|---|---|---|---|---|
| **Size (O.D.)** | 0.460 Inch<br>11.68 mm | 0.460 Inch<br>11.68 mm | 0.460 Inch<br>11.68 mm | 0.585 Inch<br>14.9 mm | 0.585 Inch<br>14.9 mm |
| **Spring Dia.** | 0.091 Inch | 0.105 Inch | 0.113 Inch | 0.135 Inch | 0.148 Inch |
| **I.D.** | 0.265 Inch | 0.230 Inch | 0.220 Inch | 0.280 Inch | 0.255 Inch |
| **Stiffness** | Light | Medium | Heavy | Medium | Heavy |
| **Min. Bend Dia.** | 2.50 Inch | 3.00 Inch | 3.50 Inch | 4.50 Inch | 4.75 Inch |
| **Ferrule Thread** | 1/8-27 I.P.S Male<br>1/8-27 I.P.S Female<br>5/8-27 UNS Male<br>5/8-27 UNS Female<br>1/4-20 Male<br>1/4-20 Female | 1/8-27 I.P.S Male<br>1/8-27 I.P.S Female<br>5/8-27 UNS Male<br>5/8-27 UNS Female<br>1/4-20 Male<br>1/4-20 Female | 1/8-27 I.P.S Male<br>1/8-27 I.P.S Female<br>5/8-27 UNS Male<br>5/8-27 UNS Female<br>1/4-20 Male<br>1/4-20 Female | 1/8-27 I.P.S Male<br>1/8-27 I.P.S Female<br>1/4-18 I.P.S Male<br>1/4-18 I.P.S Female<br>3/8-18 I.P.S Male<br>3/8-18 I.P.S Female<br>5/8-27 UNS Male<br>5/8-27 UNS Female<br>1/4-20 Male<br>5/8-27 UNS with Side Outlet | 1/8-27 I.P.S Male<br>1/8-27 I.P.S Female<br>1/4-18 I.P.S Male<br>1/4-18 I.P.S Female<br>3/8-18 I.P.S Male<br>3/8-18 I.P.S Female<br>5/8-27 UNS Male<br>5/8-27 UNS Female<br>1/4-20 Male<br>5/8-27 UNS with Side Outlet |
| **Weight Supported Horizontally at Distance 6"** | 32.0 oz | 44.0 oz | 48.0 oz | 64.0 oz | 144.0 oz |
| **Weight Supported Horizontally at Distance 12"** | 10.5 oz | 20.0 oz | 24.0 oz | 31.0 oz | 52.0 oz |
| **Weight Supported Horizontally at Distance 18"** | 5.1 oz | 11.0 oz | 12.6 oz | 17.5 oz | 31.0 oz |
| **Weight Supported Horizontally at Distance 24"** | 2.3 oz | 5.9 oz | 8.0 oz | 11.6 oz | 18.8 oz |
| **Finishes** | Baked epoxy paint<br>Brass plated<br>Chrome plated<br>Copper plated<br>Galvanized<br>Micrometer<br>Nickel plated<br>Satin chrome plated<br>Unfinished<br>Vinyl-clad (colors) (white, black,red) | | | | |

*Length of Gooseneck is 18 in and finishes for the gooseneck tubing are Vinyl-clad (black)

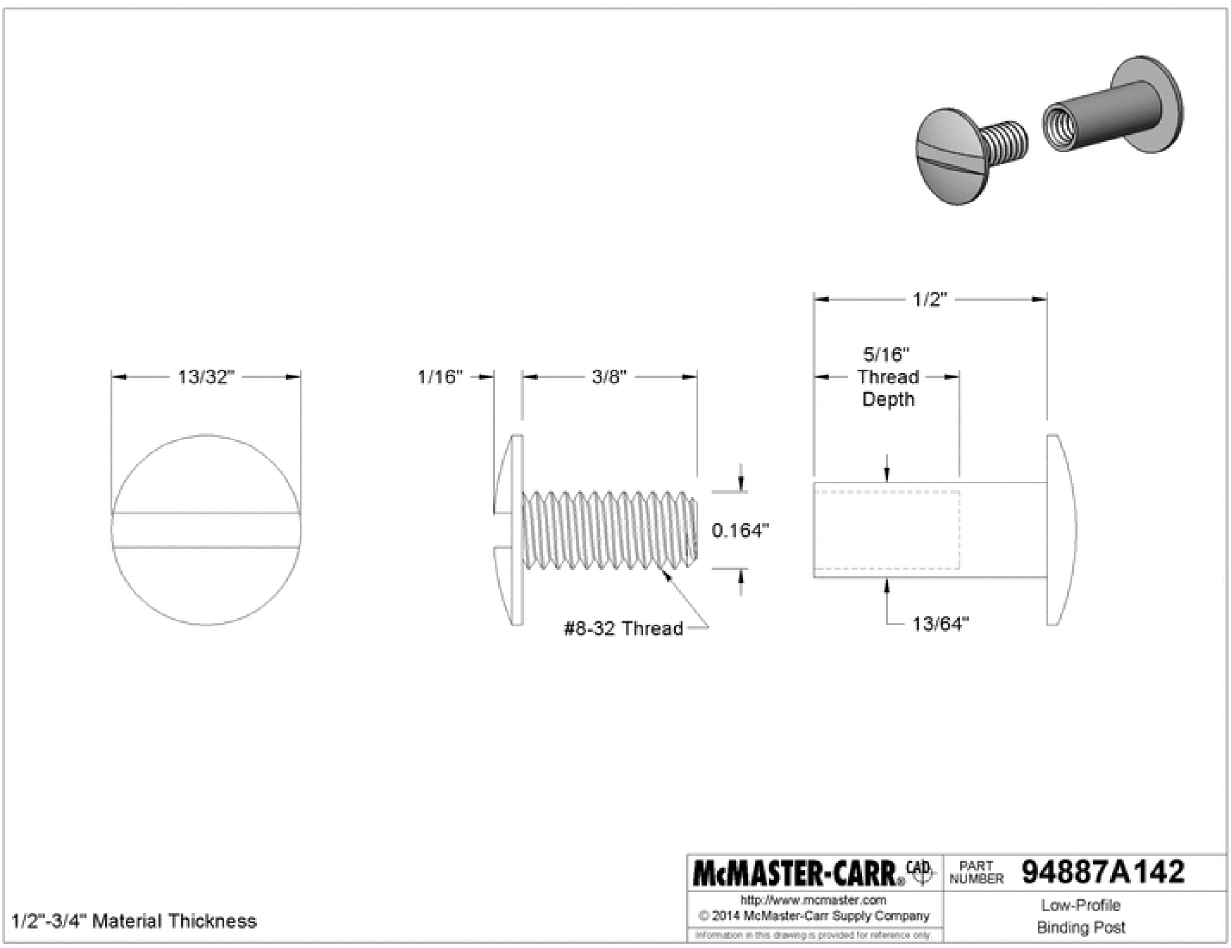
**Appendix D: Purchased Component Information**

## Stainless Steel Low-Profile Binding Post (Binding Posts for Mount)



94887A142

| | |
|---|---|
| Drive Style | Slotted |
| Thread Size | 8-32 |
| For Material Thickness | |
| Minimum | 1/2" |
| Maximum | 3/4" |
| Length | 1/2" |
| Barrel Diameter | 13/64" |
| Material | 18-8 Stainless Steel |

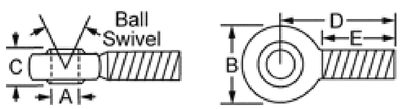


**Appendix D: Purchased Component Information**

## Corrosion- Resistant Nylon Ball Joint Rod End (Nylon Rod End Bearing)

### Corrosion-Resistant Nylon Ball Joint Rod End

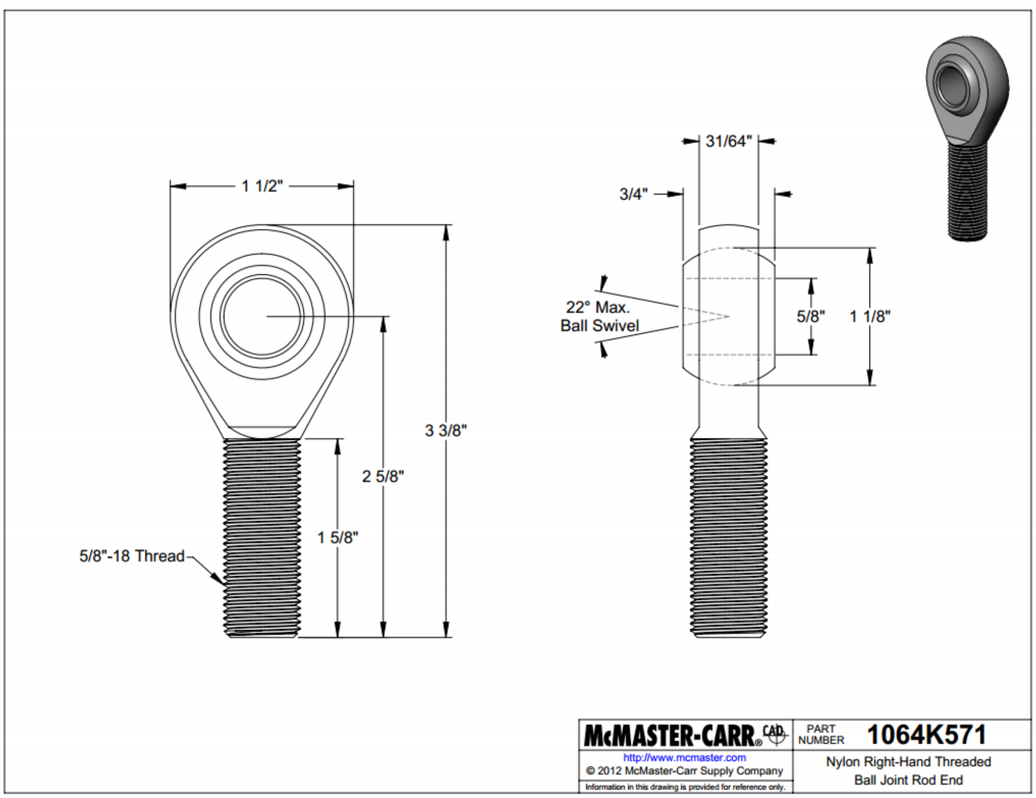
5/8"-18 RH Male Shank, 5/8" Ball ID, 1-5/8" Long Thread




1064K571

| | |
|---|---|
| Shank Thread Direction | Right-Hand Threads |
| Shank Type | Male-Threaded |
| Shank Thread Size | 5/8"-18 |
| Ball ID (A) | 5/8" |
| Maximum Ball Swivel | 22° |
| Overall Width (B) | 1 1/2" |
| Overall Thickness (C) | 3/4" |
| (D) | 2 5/8" |
| Thread Length (E) | 1 5/8" |
| Static Radial Load Capacity | 134 lbs. |
| RoHS | Compliant |

Made of an impact-resistant nylon composite, these rod ends withstand corrosion as well as fuels, lyes, and weak acids. They are also 80% lighter than steel. A self-lubricating nylon ball ensures low friction and maximum abrasion resistance. Temperature range is –22° to +176° F.

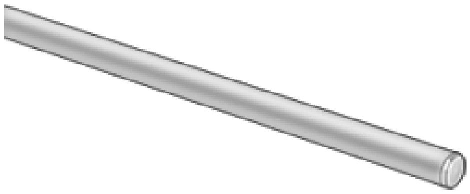


**Appendix D: Purchased Component Information**

## Miniature 12L14 Drive Shaft (1/8" Drive Shaft)

### Miniature 12L14 Drive Steel Shaft

1/8" OD, 12" Length

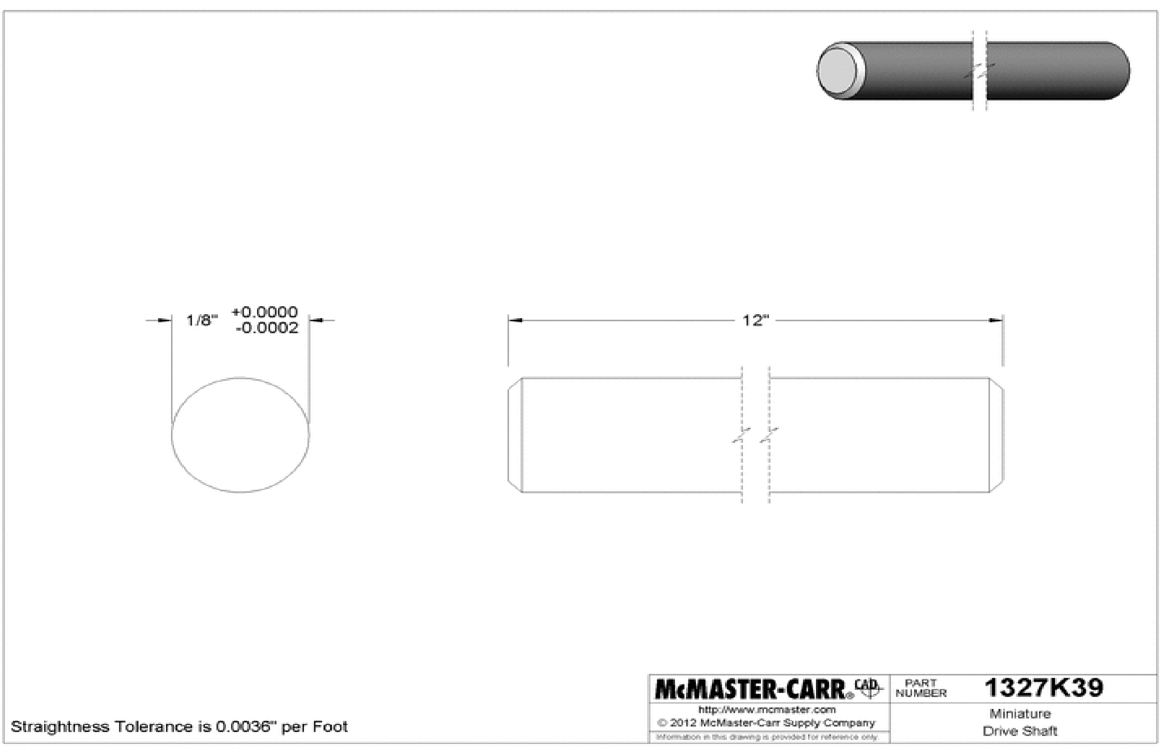


1327K39

| | |
|---|---|
| Material | 12L14 Steel |
| Diameter | 1/8" |
| Diameter Tolerance | -0.0002" to 0" |
| Length | 12" |
| Straightness Tolerance | 0.0036" per ft. |
| RoHS | Compliant |

Diameters are sized for miniature rotary applications. These shafts also work well with miniature sprockets, pulleys, and gears. Ends are beveled on 1/8" and larger diameters and on 2.5 mm and larger diameters.

Steel Shafts—Made of 12L14 steel, these shafts are stronger than stainless steel shafts but are less corrosion resistant. Hardness is Brinell 167.



**Appendix D: Purchased Component Information**

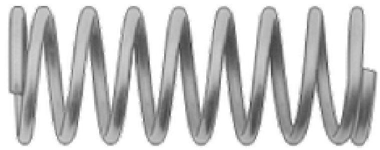
## Dakine Men’s Wrist Guard

Color: **Black**

- 100% Neoprene
- Imported
- Low profile design for use inside gloves
- Lightweight internal aluminum stay
- Neoprene stretch body for maximum comfort
- Adjustable hook and loop wrist cinch

**Appendix D: Purchased Component Information**

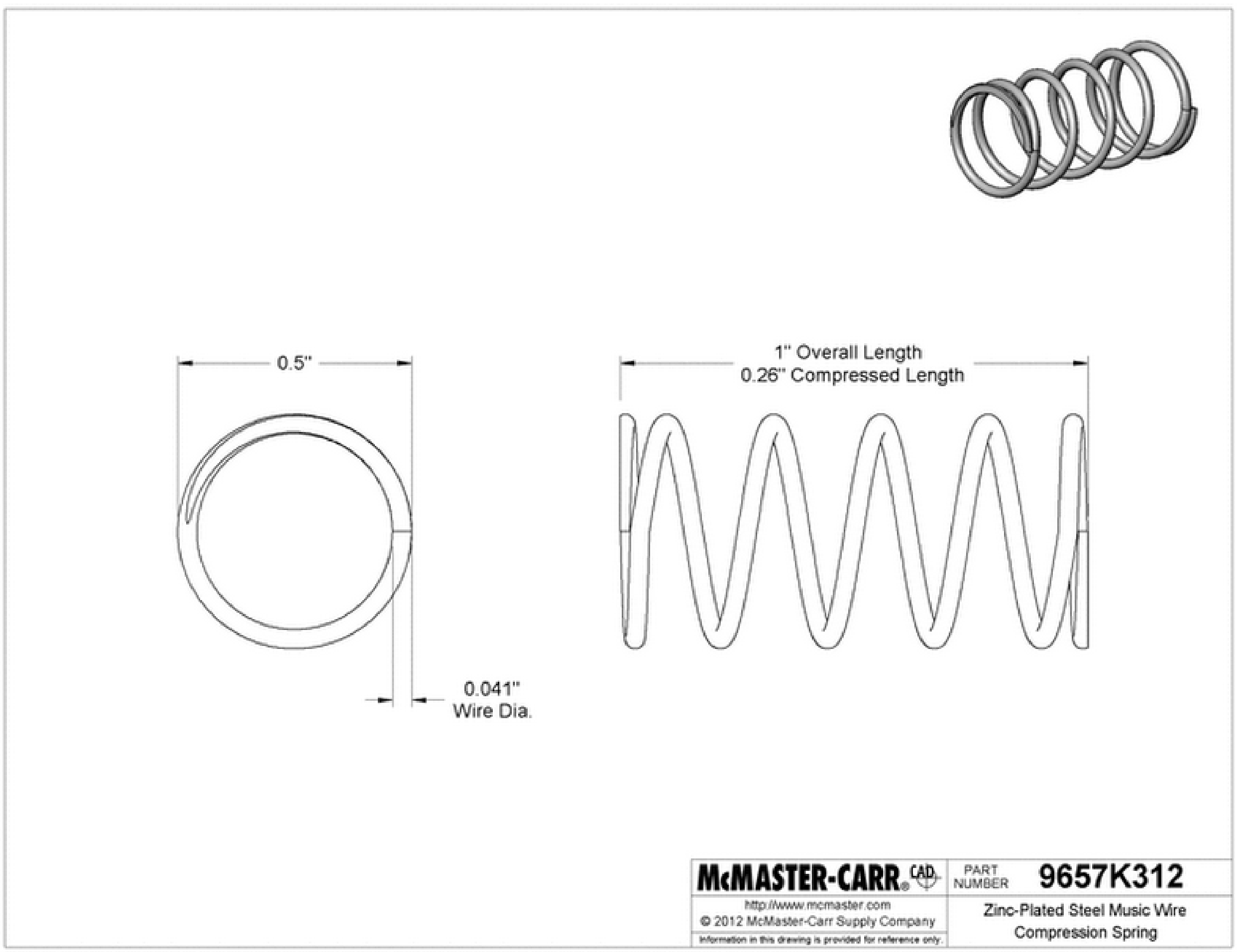
## Steel Compression Spring



9657K312

| | |
|---|---|
| Spring OD | 0.5" |
| Wire Diameter | 0.041" |
| Compressed Length | 0.26" |
| Maximum Load | 7.37 lbs. |
| Rate | 9.90 lbs./inch |
| Additional Specifications | Zinc-Plated Steel Music Wire—Closed and Ground Flat Ends<br>1" Overall Length |
| RoHS | Compliant |

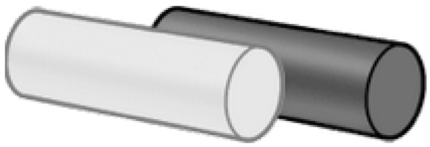
Choose steel music wire for strength; spring-tempered steel for heat resistance; brass for durability and heat resistance; or phosphor bronze for strength, heat resistance, and corrosion resistance.



**Appendix D: Purchased Component Information**

## ABS Rod (Control Wheel)

### Easy-to-Machine ABS Rod
2" Diameter



Length, ft.
1

8587K9

Color

- Black

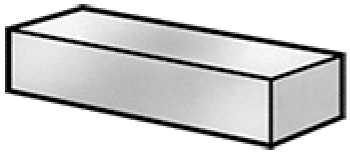
| | |
|---|---|
| Diameter | 2" |
| Diameter Tolerance | +0.005" |
| Color | Beige or black |
| Maximum Temperature | 160° F |
| Tensile Strength | Good |
| Impact Strength | Excellent |
| Additional Specifications | Rods |
| RoHS | Compliant |

ABS resists breaking upon impact and is often used in protective applications, such as equipment housings and machine guards. Its rigid surface won't slow down cutting tools.

All rods meet UL 94HB for flame retardance and ASTM D4673. Beige rods are made with FDA-compliant resin.

**Appendix D: Purchased Component Information**

## Square 6061 Aluminum Rod (Underhand Mount)



8975K237

| | |
|---|---|
| Alloy | 6061 |
| Shape | Rectangular Bar |
| Finish | Unpolished |
| Thickness | 1" |
| Thickness Tolerance | ±0.012" |
| Width | 2" |
| Width Tolerance | ±0.034" |
| Yield Strength | 35,000 psi |
| Hardness | Soft (80 Brinell) |
| Material Condition | Heat Treated |
| Temper | T6511 |
| Specifications Met | ASTM B221 |
| Material Composition | |
| Silicon | 0.4-0.8% |
| Iron | 0-0.7% |
| Copper | 0.05-0.4% |
| Manganese | 0-0.15% |
| Magnesium | 0.8-1.2% |
| Chromium | 0.4-0.8% |
| Nickel | 0-0.05% |
| Zinc | 0-0.25% |
| Titanium | 0-0.15% |
| Zirconium | 0-0.25% |
| Other | 0.15% |
| Aluminum | 95.1-98.2% |
| Nominal Density | 0.097-0.1 lbs./cu. in. |
| Modulus of Elasticity | 10.0 ksi × $10^3$ |
| Elongation | 8-17% |
| Melting Range | 1,080° to 1,205° F |
| Thermal Conductivity | 1390 Btu/hr × in./sq.ft. @ 75° to 77° F |
| Electrical Resistivity | 24 Ohm-Cir. Mil/ft. @ 68° F |
| Length Tolerance | ±1" |

**Appendix D: Purchased Component Information**

## Steel Ball Bearing

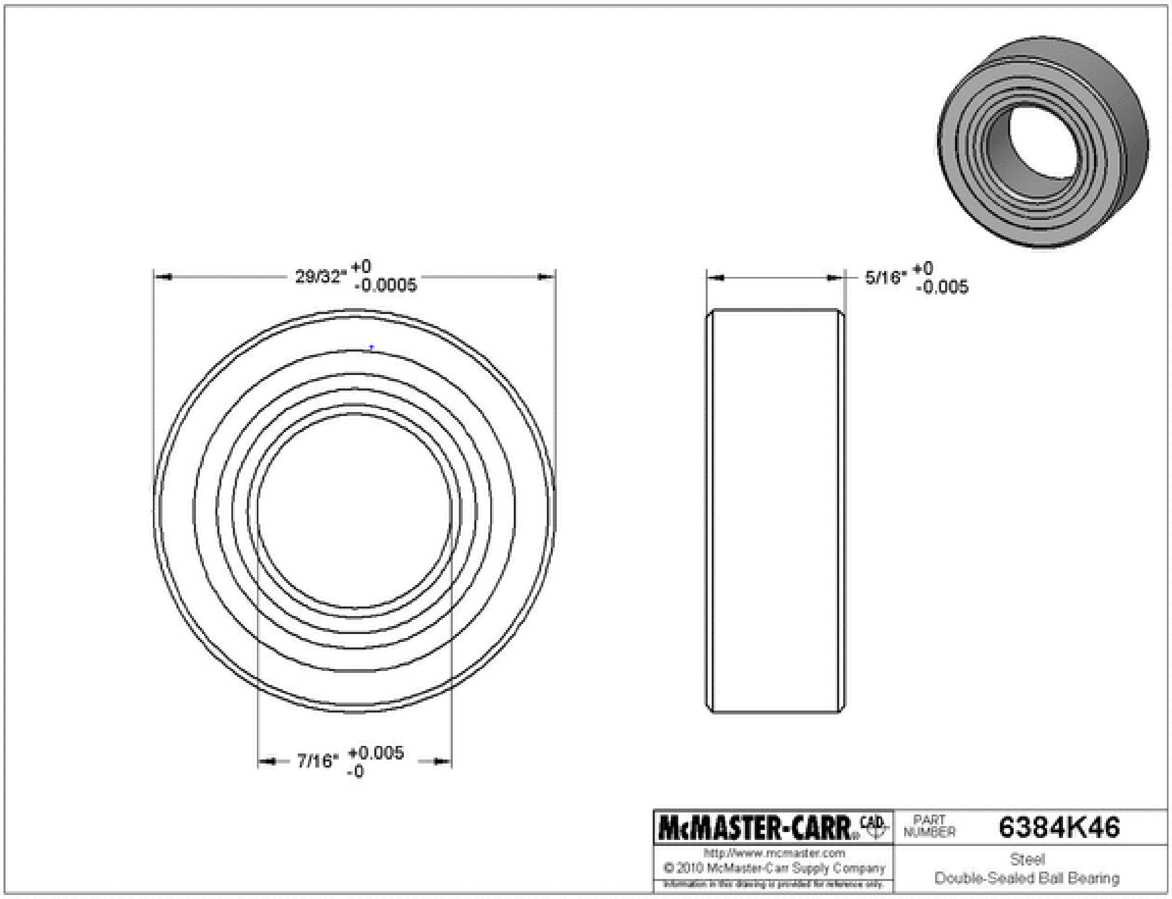
6384K46

| | |
|---|---|
| Bearing Type | Ball |
| Ball Bearing Style | Double Sealed |
| Bearing Material | Steel |
| Seal Material | Buna-N |
| Temperature Range | -20° to 250° F |
| For Shaft Diameter | 7/16" |
| For Shaft Diameter Tolerance | -0" to +0.005" |
| OD | 29/32" |
| OD Tolerance | -0.0005" to +0" |
| Width | 5/16" |
| Width Tolerance | -0.005" to +0" |
| Dynamic Load Capacity | 350 lbs. |
| Maximum rpm | 2,500 |
| RoHS | Compliant |

Count on solid performance from these steel ball bearings. Temperature range is –20° to 250° F. Maximum speed is 1200 rpm for open bearings; 2500 rpm for all others. These bearings are not ABEC rated.

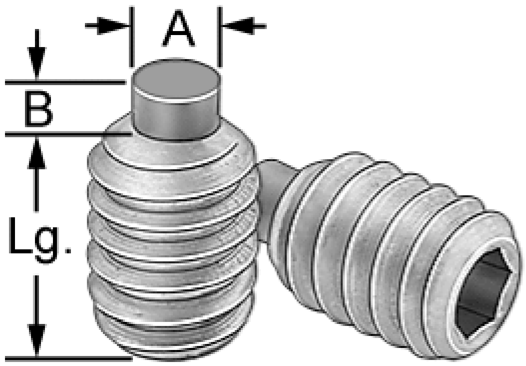
Double-sealed bearings have Buna-N seals that block out dirt, preserve lubricants, and reduce noise. They come greased.

**Appendix D: Purchased Component Information**



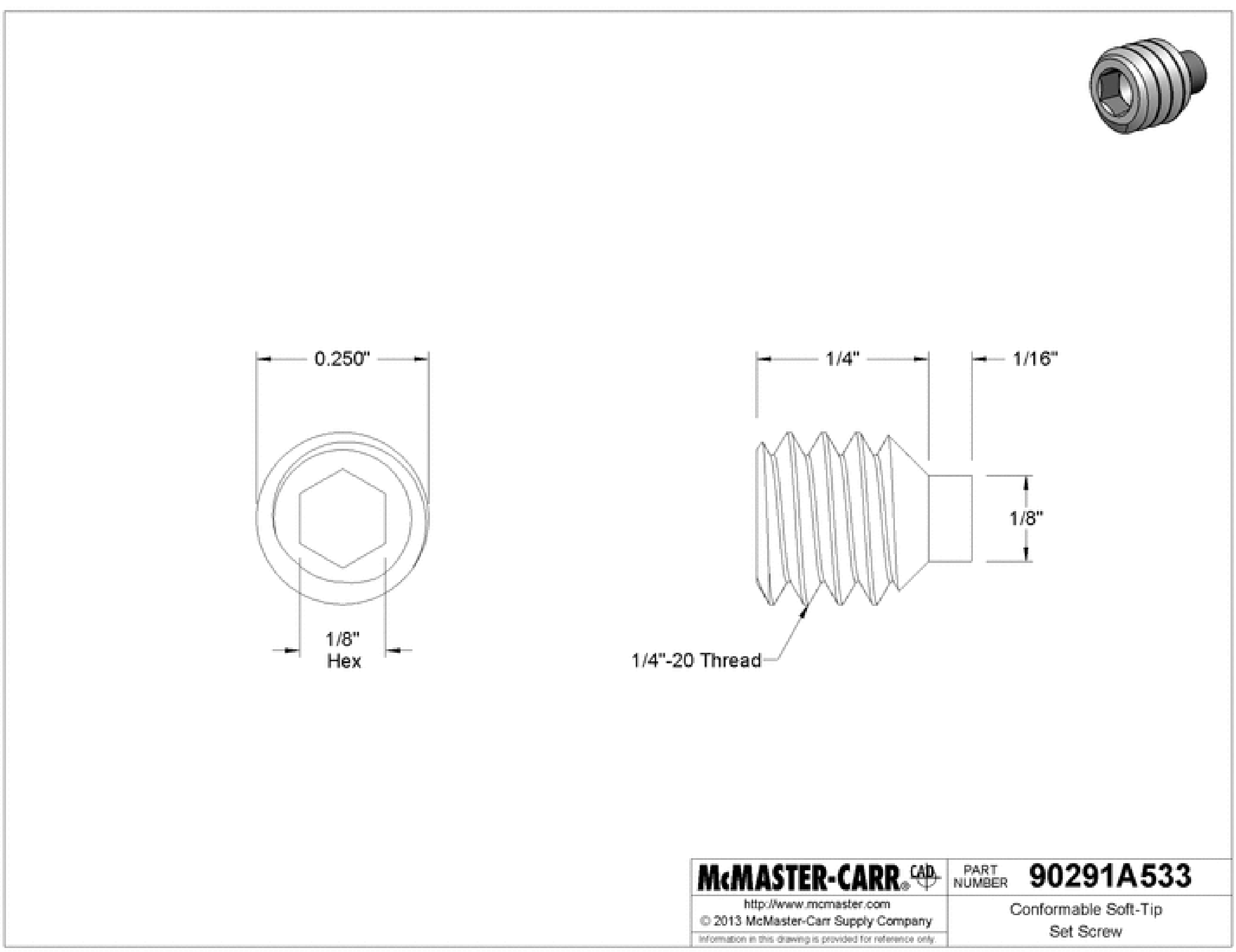
**Appendix D: Purchased Component Information**

## Conformable Soft Nylon-Tip Set Screws




90291A533

| | |
|---|---|
| Material | 18-8 Stainless Steel |
| Tip Material | Nylon |
| Thread Size | 1/4"-20 |
| Screw Size | 1/4" (0.250") |
| Length | 1/4" |
| Drive Style | Hex Socket |
| Hex Size | 1/8" |
| (A) | 1/8" |
| (B) | 1/16" |
| RoHS | Compliant |

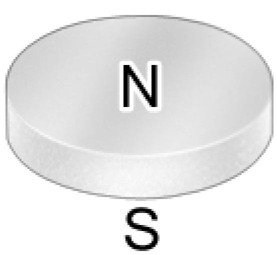


**Appendix D: Purchased Component Information**

## ¼” Drive Universal Joint

| Model # | H4DUNIV |
|---|---|
| Depth | 0.98 in. |
| Height | 4.49 in. |
| Width | 1.77 in. |

## Neodymium Disc Magnet

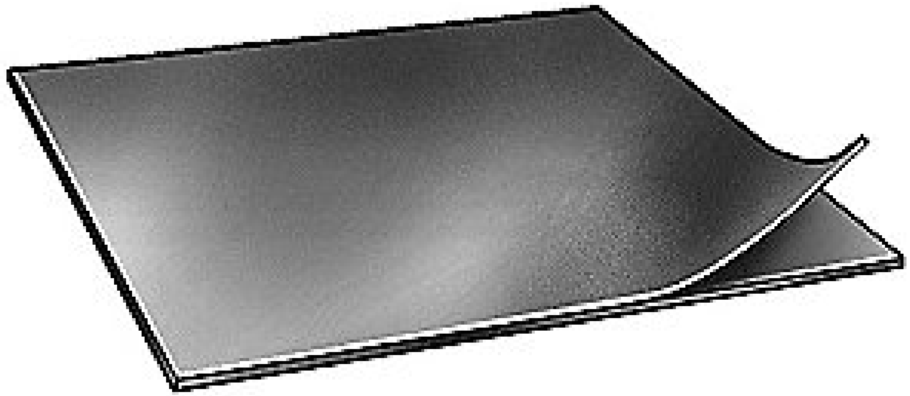



5862K79

| | |
|---|---|
| Shape | Disc |
| Diameter | 1/4" |
| Thickness | 0.06" |
| Maximum Pull | 1.3 lbs. |
| Finish | Nickel Plated |
| RoHS | Compliant |
| Shipping | Regulated by the U.S. Department of Transportation |

**Appendix D: Purchased Component Information**

## Neoprene Rubber Sheet



Item # 1DXC5

### Technical Specs

| | | | |
|---|---|---|---|
| Item | Rubber Sheet | Finish | Smooth |
| Application | General Purpose | Backing Type | Adhesive |
| Type | Commercial Grade | Min. Temp. Rating (Deg. F) | -20 |
| Material | Neoprene Rubber | Max. Temp. (F) | 170 |
| Thickness | 1/16" | Durometer | 30A |
| Width | 12" | Elongation | 350% |
| Length | 12" | Tensile Strength (PSI) | 1000 |
| Color | Black | Standards | ASTM D2000 BC |

| Gooseneck Deflection Analysis | |
|---|---|
| Point load weight of claw assembly and heaviest manipulated part (lbf) | 0.0875 |
| Extension length of gooseneck tubing (in) | 18 |
| Weight of gooseneck tubing (lbf/in) | 0.048 |
| E of steel (psi) | 2.90E+07 |
| I of tube ($in^4$) | 1.30E-01 |
| Average length of human arm (in) | 25 |
| Total Deflection of Gooseneck (in) | 0.0001 |
| Equiv. weight felt by user (lbf) | 1.33 |

| Underhand Curved Beam Deflection Analysis | |
|---|---|
| Total point load on end of beam (lbf) | 0.952 |
| Length of curved beam (in) | 7.89 |
| Beam Thickness (in) | 0.68 |
| Density of ABS ($lbf/in^3$) | 0.0376 |
| Beam Width (in) | 0.75 |
| Weight of Beam (lbf/in) | 0.019 |
| E of ABS (psi) | 3.20E+05 |
| I of Curved Beam ($in^4$) | 1.97E-02 |
| Total Deflection of curved beam (in) | 0.0146 |

| Stress calculations for claw | | | |
|---|---|---|---|
| **Claw Specs** | | **Curved Beam Stress Calculations** | |
| Inner Radius (in) | 1.25 | Eccentricity (in) | 0.37 |
| Outer Radius (in) | 1.625 | Cross Sectional Area ($in^2$) | 0.05 |
| Base Peg Diameter (in) | 0.125 | $r_n$ (in) | 1.43 |
| Claw Length (in) | 1.5 | $c_i$ (in) | 0.18 |
| Claw Width (in) | 0.375 | $c_o$ (in) | 0.20 |
| Claw Thickness (in) | 0.125 | Moment (in*lb) | 6.00 |
| Max Torque (in*lb) | 10 | $\sigma_o$ (psi) | 42.02 |
| Max Spring Force (lb) | 4 | $\sigma_i$ (psi) | 135.39 |
| Claw Max Opening (in) | 1.8 | | |
| | | **Shear From Torque** | |
| | | Shear Force (lb) | 9.00 |
| **Axial Stress around base peg** | | Statical Moment of Area ($in^3$) | 0.00 |
| Effective Cross Section ($in^2$) | 0.03125 | Moment of Inertia ($in^4$) | 0.00 |
| Stress Concentration Factor | 5 | $\tau$ (psi) | 864.00 |
| Axial Stress(psi) | 640 | | |
| | | **Principal Stresses** | |
| Yield Strenght of ABS (psi) | 6000 | $\sigma_1$ (psi) | -798.95 |
| Factor of Safety | 9.375 | $\sigma_2$ (psi) | 934.34 |
| | | $\sigma_1$- $\sigma_2$ (psi) | 1733.30 |
| | | | |
| | | Yield Strength of ABS (psi) | 6000.00 |
| | | Factor of Safety | 3.46 |

Calculation done using a conservative approach

Axial stress was added to the inner moment stress in the curved beam calculations

Stress concentration factor gotten from *Shigley's Mechanical Engineering Design*

C.F.

| | |
|---|---|
| Point load weight (lbf) | 1.875 |
| Extension length (in) | 18 |
| rod weight (lbf/in) | 0.003833333 |
| E (psi) | 34000000 |
| I (in^4) | 0.017338242 |
| Arm length (in) | 25 |
| Total Deflection (in) | 0.006097876 |
| Equiv. Weight (lbf) | 3.31884 |

Gooseneck

| | |
|---|---|
| Point load weight (lbf) | 0.0875 |
| Extension length (in) | 18 |
| rod weight (lbf/in) | 0.048 |
| E (psi) | 29000000 |
| I (in^4) | 0.13030682 |
| Arm length (in) | 25 |
| Total Deflection (in) | 1.01E-04 |
| Equiv. Weight (lbf) | 1.32554 |

Gooseneck Deflection Analysis

| | |
|---|---|
| Point load weight of claw assembly and heaviest manipulated part (lbf) | 0.0875 |
| Extension length of gooseneck tubing (in) | 18 |
| Weight of gooseneck tubing (lbf/in) | 0.048 |
| E of steel (psi) | 2.90E+07 |
| I of tube (in^4) | 1.30E-01 |
| Average length of human arm (in) | 25 |
| Total Deflection of Gooseneck (in) | 0.0001 |
| Equiv. weight felt by user (lbf) | 1.33 |

| | Curved Beam | ABS | |
|---|---|---|---|
| Point load weight (lbf) | 0.9515 | | |
| Extension length (in) | 7.886 | | |
| Beam Thickness (in) | 0.68 | | 0.027824 |
| Beam Width (in) | 0.75 | | |
| Weight of Beam (lbf/in) | 0.019176 | | |
| E (psi) | 320000 | | |
| I (in^4) | 1.97E-02 | | |
| Total Deflection (in) | 0.0146 | | |

Curved Beam Deflection Analysis

| | | |
|---|---|---|
| Point load weight produced by claw assembly, heaviest manipulated part, and gooseneck tubing (lbf) | 0.952 | |
| Length of curved beam (in) | 7.89 | lbf/in^3 |
| Beam Thickness (in) | 0.68 | |
| Density of ABS (lbf/in^3) | 0.0376 | |
| Beam Width (in) | 0.75 | |
| Weight of Beam (lbf/in) | 0.019 | |
| E of ABS (psi) | 3.20E+05 | |
| I of Curved Beam (in^4) | 1.97E-02 | |
| Total Deflection of curved beam (in) | 0.0146 | |

| Inner Radius | Outer Radius | Torque | Gripper Length | Force | Gripper Width | d | max width | Tensile strength |
|---|---|---|---|---|---|---|---|---|
| in | in | in*lb | in | lb | in | in | in | psi |
| 1.5 | 1.875 | 10 | 1.5 | 4.5 | 2 | 1 | 3.5 | 6500 |

| Moment |
|---|
| in*lb |
| 4.5 |

| width | thickness | eccentricity | cross section | r_n | c_i | c_o |
|---|---|---|---|---|---|---|
| in | in | in | in^2 | in | in | in |
| 0.125 | 0.5 | 1.002322485 | 0.0625 | 0.560178 | -0.939822485 | 1.314822485 |

| sigma_o | sigma_i |
|---|---|
| psi | psi |
| 50.37219475 | 2.993048688 |

| V | Q | I |
|---|---|---|
| lb | in^3 | in^4 |
| 5.714285714 | 0.00390625 | 0.001302083 |

| tau |
|---|
| psi |
| 34.28571429 |

| principal stress | | |
|---|---|---|
| sigma 1 | sigma 2 | s2-s1 |
| -32.82183502 | 35.8148837 | 68.63671872 |

| force | thickness | width | hole size | eff width | Area | h/w | d/w | kt_est |
|---|---|---|---|---|---|---|---|---|
| 4.5 | 0.0625 | 0.25 | 0.1875 | 0.0625 | 0.003906 | 0.125 | 0.75 | 2.3 |
| | | | | | | | | |
| 2649.6 | | | | | | | | |
| | | | | | | | | |
| 7948.8 | | | | | | | | |

## Appendix F: Analysis Plan, FMEA, and DVP&R

*Table 1: Analysis plan for REACH device*

| Functions | Option | What to test for | How to test | Due Date |
|---|---|---|---|---|
| **Reach Extension and Bending** | Gooseneck Tubing | • Size of Gooseneck Tubing<br>• Length of Gooseneck Tubing | • stress analysis<br>• Stability of Reach Extension<br>• weight of Reach Extension | 2/3/15 |
| **Grabbing Function** | Independent Fingers | • Number of fingers | • adequate grip strength and capability | 2/3/15 |
| **Mounting** | Bracer | • Stability | • Stress analysis | 2/3/15 |
| **Vision and Lighting** | Borescope | • Brightness<br>• Resolution | • visibility | 12/5/14 |

***Potential***
**Failure Mode and Effect Analysis**
**(Design FMEA)**

**___ System** REACH Device
**___ Subsystem** ----
**___ Component** -----

**FMEA Number:**

**Design Responsibility:**

**Key Date:**

**Prepared By: Team REACH**

**Core Team:** Aulivia Bounchaleun, Haden Cory, Scott Onsum, Zack Phillips

**FMEA Date (Orig.) 30 NOV 2014 (Rev.)**

| | | | | | | | | | Action Results | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item / Function** | **Potential Failure Mode** | **Potential Effect(s) of Failure** | **Sev** | **Potential Cause(s) / Mechanism(s) of Failure** | **Occur** | **Crit** | **Recommended Action(s)** | **Responsibility & Target Completion Date** | **Actions Taken** | **Sev** | **Occur** | **Crit** |
| Device must extend reach 12" to 24" | Device does not extend reach far enough | Can not reach far enough into machine | 7 | End effector might be too heavy | 8 | 56 | optimize cross section and/or material selection | S. Onsum - 5/6/15 | End effector light enough to avoid deflection | 7 | 1 | |
| | | | 7 | Reaching length might be out of device's scope | 1 | 7 | make device's reach longer | S. Onsum - 5/6/15 | Device is long enough | 7 | 1 | |
| | Extension cannot support weight of end effector | Becomes unstable | 8 | End effector might be too heavy | 8 | 64 | redesign end effector geometry and/or material selection | S. Onsum - 5/6/15 | Device is sufficiently stable | 8 | 1 | |
| | | | 8 | Moment arm may be too long | 4 | 32 | analysis to find appropirate length of moment arm | S. Onsum - 5/6/15 | Device does not deflect | 8 | 1 | |
| Device must grab #4 to 1/4" socket head screws, 6-32 nuts to 1/2-13 nuts, and oddly shapped parts while | End effector cannot hold items | Drops stuff | 8 | Insufficient grabbing force | 7 | 56 | better springs and/or design grippier tip | S. Onsum - 5/6/15 | Integrated feet into arms, improved grabbing | 8 | 1 | |
| | End effector cannot open large enough to grab desired object | End effector does not get big enough to get around desired object | 7 | Grabbing linkages not long enough | 4 | 28 | redesign holder geometry | S. Onsum - 5/6/15 | Claw is sufficiently large for required items | 7 | 1 | |
| | End effector cannot fit through 2" hole | Device cannot get into machine | 8 | Incorrect measurements of end effector's dimensions when fully closed or | 5 | 40 | redesign end effector geometry | S. Onsum - 5/6/15 | End effector fits through hole | 7 | 1 | |
| Device must have vision system with light to operate in dark areas | Vision system does not allow operator to see in dark areas | Can't operate device effectively in dark areas | 7 | Incorrect routing of wires through device | 1 | 7 | Color Coding wires for different functions | S. Onsum - 1/10/15 | Operator can see in dark areas | 7 | 1 | |
| | | | 7 | Light becomes broken/cracked | 1 | 7 | replace vision system | S. Onsum - 1/10/15 | Light maintained integrity | 7 | 1 | |

***Potential***
**Failure Mode and Effect Analysis**
**(Design FMEA)**

**___ System** **REACH Device**
**___ Subsystem** **----**
**___ Component** **-----**

**FMEA Number:**

**Design Responsibility:**

**Key Date:**

**Prepared By: Team REACH**

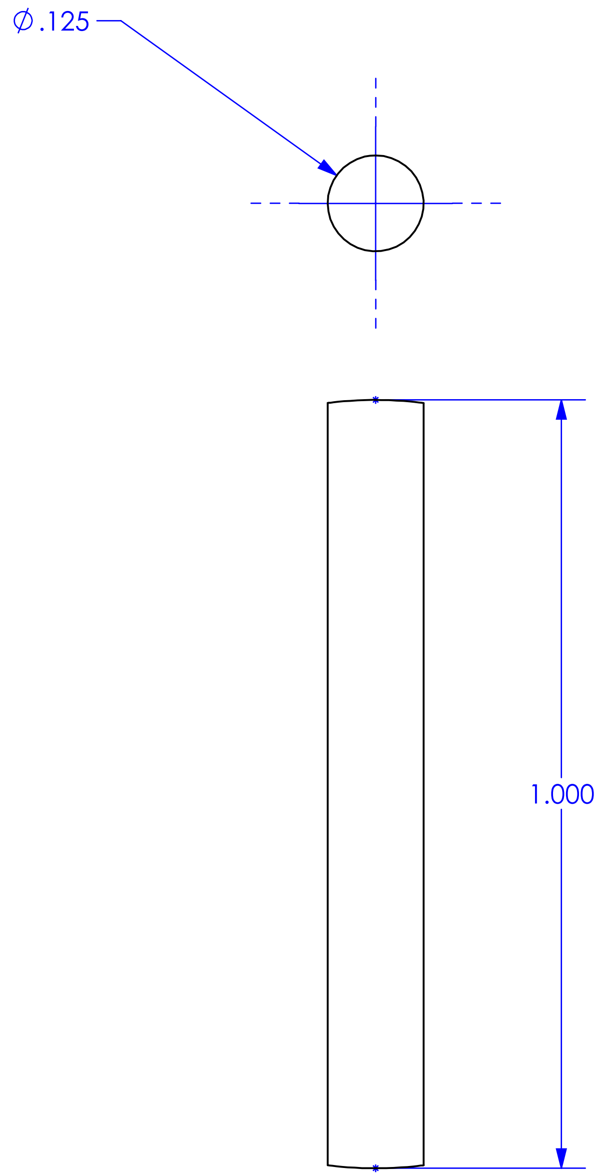
**Core Team:** **Aulivia Bounchaleun, Haden Cory, Scott Onsum, Zack Phillips**

**FMEA Date (Orig.) 30 NOV 2014 (Rev.)**

| | | | | | | | | | Action Results | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item / Function** | **Potential Failure Mode** | **Potential Effect(s) of Failure** | **Sev** | **Potential Cause(s) / Mechanism(s) of Failure** | **Occur** | **Crit** | **Recommended Action(s)** | **Responsibility & Target Completion Date** | **Actions Taken** | **Sev** | **Occur** | **Crit** |
| | | | 7 | Inadequate wiring contact | 1 | 7 | rebuild connections | S. Onsum - 1/10/15 | Camera functioned correctly | 7 | 1 | |
| | | | 7 | Poor placment of vision system on end effector | 4 | 28 | adjust positions of vision system | S. Onsum - 5/6/15 | Offset camera from extension | 7 | 1 | |
| Device must bend at least 180 degrees within six inches of itself | Device cannot bend at least 180 degrees | Device does not bend back on itself | 6 | Shaft might be too rigid | 6 | 36 | Material Selection or optimization of shaft design | S. Onsum - 5/6/15 | Device bends sufficiently | 6 | 1 | |
| | Device cannot bend within six inches of itself | Does not allow work in confined areas | 6 | Device is not flexible enough | 6 | 36 | Material Selection or optimization of shaft design | S. Onsum - 5/6/15 | Bend radius is small enough | 6 | 1 | |
| | Device cannot bend 180 degrees within six inches of itself | Takes too much space to bend around backwards | 6 | Shaft might be too rigid | 6 | 36 | Material Selection or optimization of shaft design | S. Onsum - 5/6/15 | Device meets specification | 6 | 1 | |
| Mount/Interface | Device is too heavy to use with one hand | Cannot operate with one hand | 7 | End effector might be too heavy | 8 | 56 | Material Selection and optimization of geometry/design | S. Onsum - 5/6/15 | Device is light enough to use with one hand | 7 | 1 | |
| | Interface does not allow operator to control end effector | Device is to hard to use | 5 | Interface is poorly designed | 7 | 35 | Testing of natural control methods | S. Onsum - 5/6/15 | Operator can effectively control device | 5 | 1 | |

# ME428 DVP&R Format

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Report Date | | 2014-12-01 | Sponsor | Al Schoepp, Lam Research | | | | | Component/Assembly | | REACH Device | REPORTING ENGINEER: | Team REACH |
| TEST PLAN | | | | | | | | | | TEST REPORT | | | |
| Item No | Specification or Clause Reference | Test Description | Acceptance Criteria | Test Responsibility | Test Stage | SAMPLES TESTED | | TIMING | | TEST RESULTS | | | NOTES |
| | | | | | | Quantity | Type | Start date | Finish date | Test Result | Quantity Pass | Quantity Fail | |
| 1 | Reach Extension | Linear Measurement | 12"<length<24" | S. Onsum | DV | 1 | Prototype | 2014-12-04 | 2015-05-06 | 22.25" | 1 | 0 | |
| 2 | Reach Extension | Stiffness | Supports End Effector w/o Impactful Deflection | S. Onsum | DV | 1 | Prototype | 2015-01-05 | 2015-05-06 | Success | 1 | 0 | |
| 3 | End Effector | Grip Strength | Capable of holding parts supplied by Lam Research | S. Onsum | PV | 1 | Prototype | 2015-03-30 | 2015-05-06 | Device can hold all hardware | 1 | 0 | |
| 4 | End Effector | Grabber Maximum Opening Diameter | Capable of enclosing parts supplied by Lam Research | S. Onsum | DV | 1 | Prototype | 2015-01-05 | 2015-05-06 | Device can hold all hardware | 1 | 0 | |
| 5 | End Effector | Grabber Fits Through Access Point | Yes | S. Onsum | PV | 1 | Prototype | 2015-03-30 | 2015-05-06 | Yes | 1 | 0 | |
| 6 | Vision System | Operator can see in dark areas | Yes | S. Onsum | PV | 1 | Prototype | 2014-12-04 | 2014-12-15 | Operator can see 2" range at 3" from object | 1 | 0 | |
| 7 | Extension Bending | Device bends | at least 180 degrees | S. Onsum | PV | 1 | Prototype | 2015-03-30 | 2015-05-06 | Yes | 1 | 0 | |
| 8 | Extension Bending | Device has small enough bend radius | No more than 3" | S. Onsum | PV | 1 | Prototype | 2015-03-30 | 2015-05-06 | Yes | 1 | 0 | |
| 9 | Mount/Interface | Device weight | Device is light enough to comfortably be used by operator | S. Onsum | PV | 1 | Prototype | 2015-03-30 | 2015-05-06 | Yes | 1 | 0 | |
| 10 | Mount/Interface | Operator can successfully operate device | Yes | S. Onsum | PV | 1 | Prototype | 2015-03-30 | 2015-05-06 | Difficult, but yes | 1 | 0 | |




| | | | |
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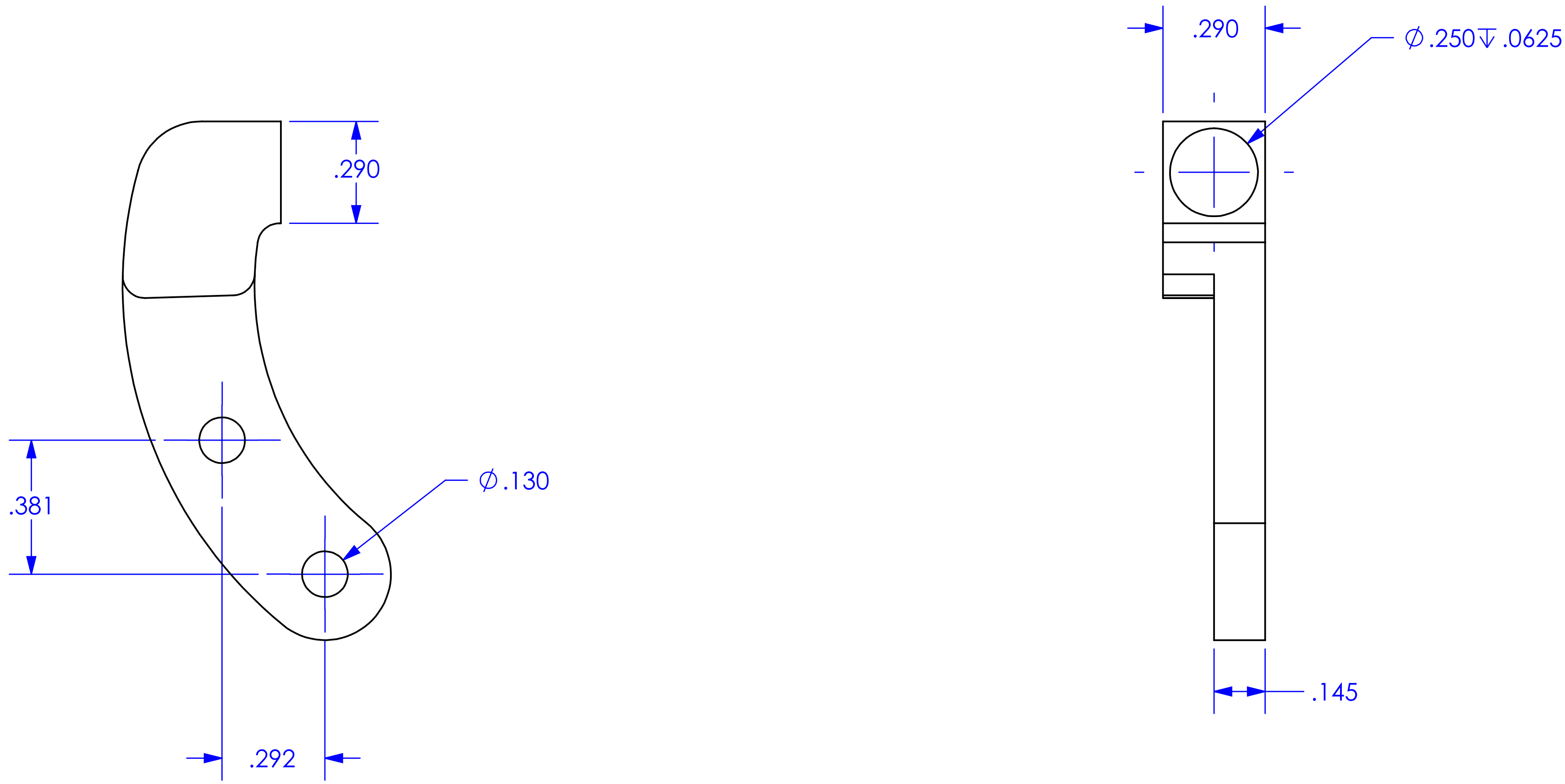
| | | NEXT ASSY: | NAME: ZACK PHILLIPS |
| | | DRAWING #: | SIGNATURE: |




| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: ABS PLASTIC |
| | TOLERANCE: ± 0.002 | SCALE: 2:1 | TITLE: CLAW FINGERS |
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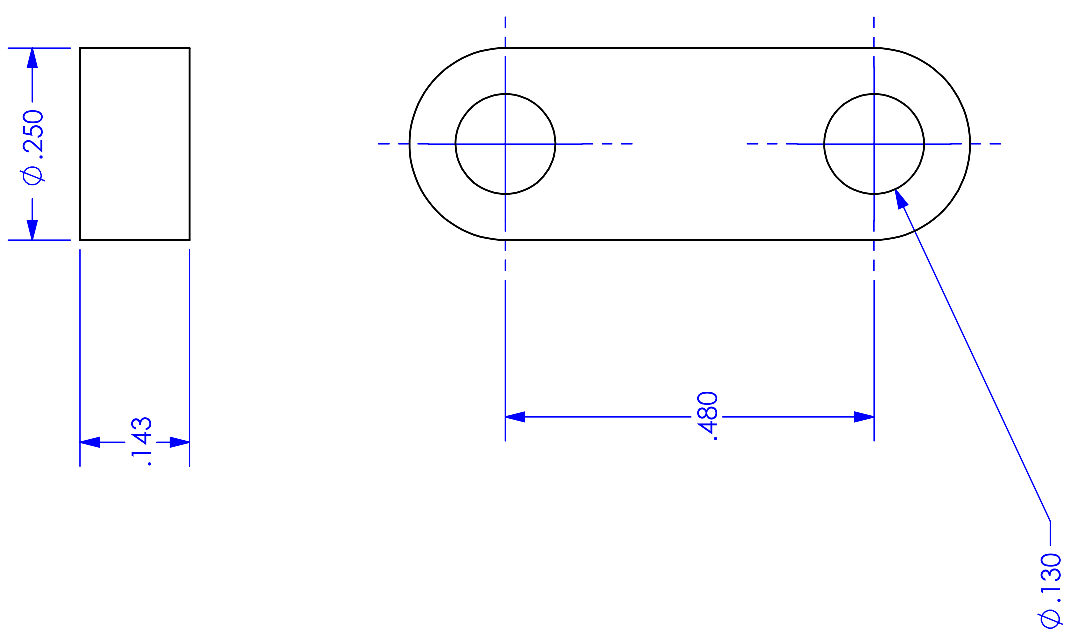
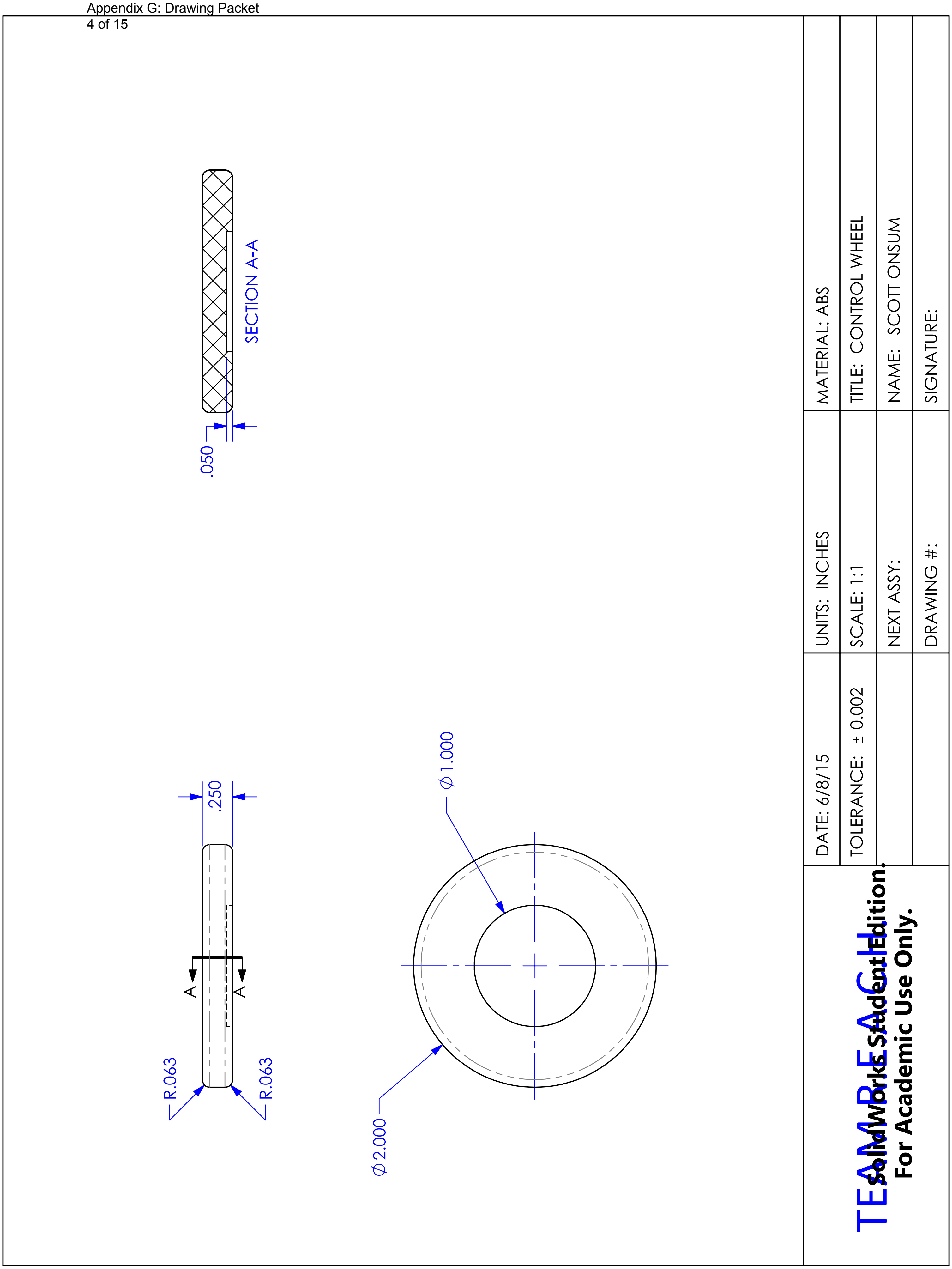
| | | DRAWING #: | SIGNATURE: |




| | | |
|---|---|---|
| MATERIAL: ABS PLASTIC | UNITS: INCHES | DATE: 6/8/15 |
| TITLE: SMALL BAR | SCALE: 4:1 | TOLERANCE: ± 0.002 |
| NAME: ZACK PHILLIPS | NEXT ASSY: | |
| SIGNATURE: | DRAWING #: | |

TEAM R.E.A.C.H.


SECTION A-A
.050
.250
A
A
R.063
R.063
Ø1.000
Ø2.000
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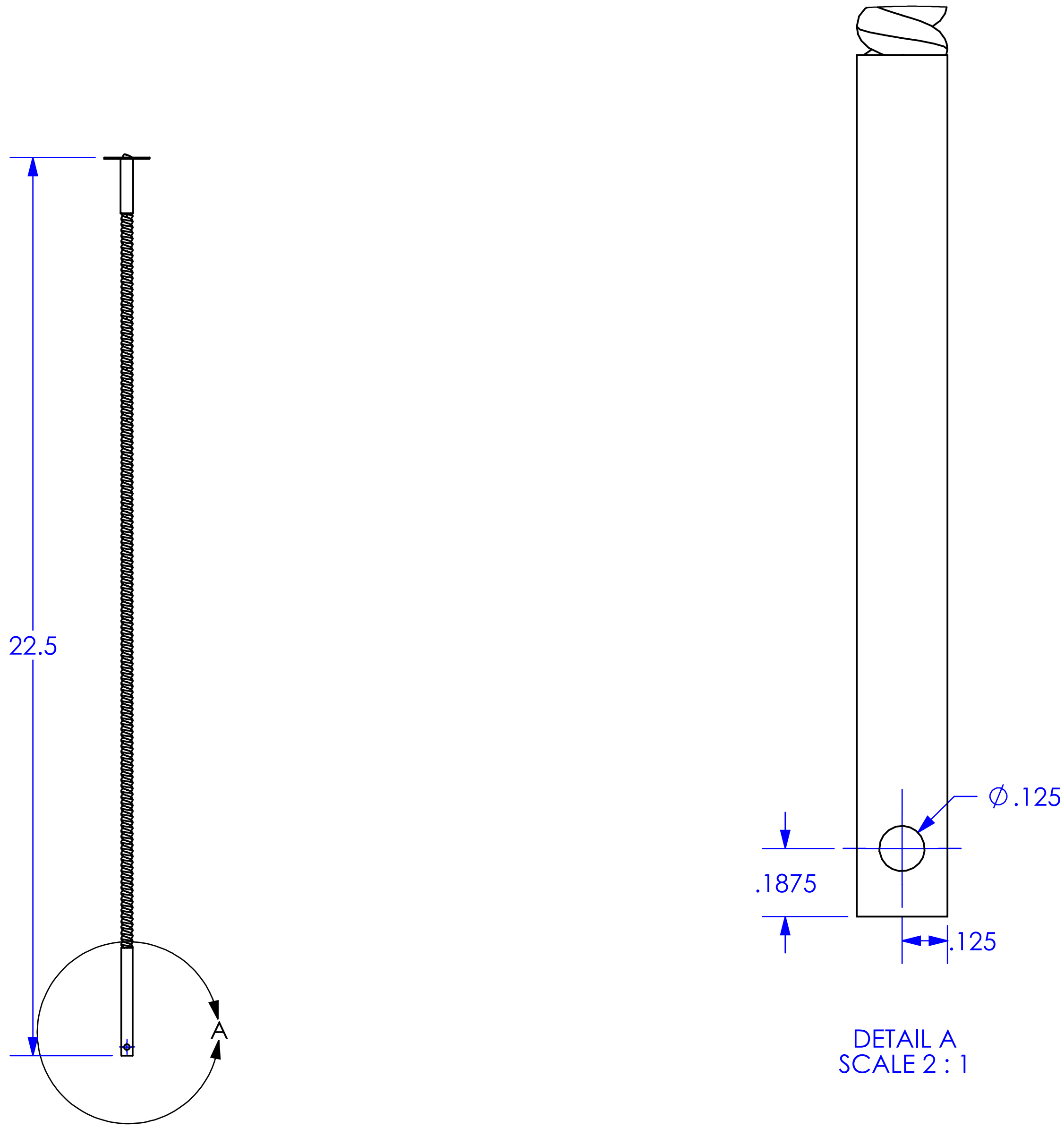
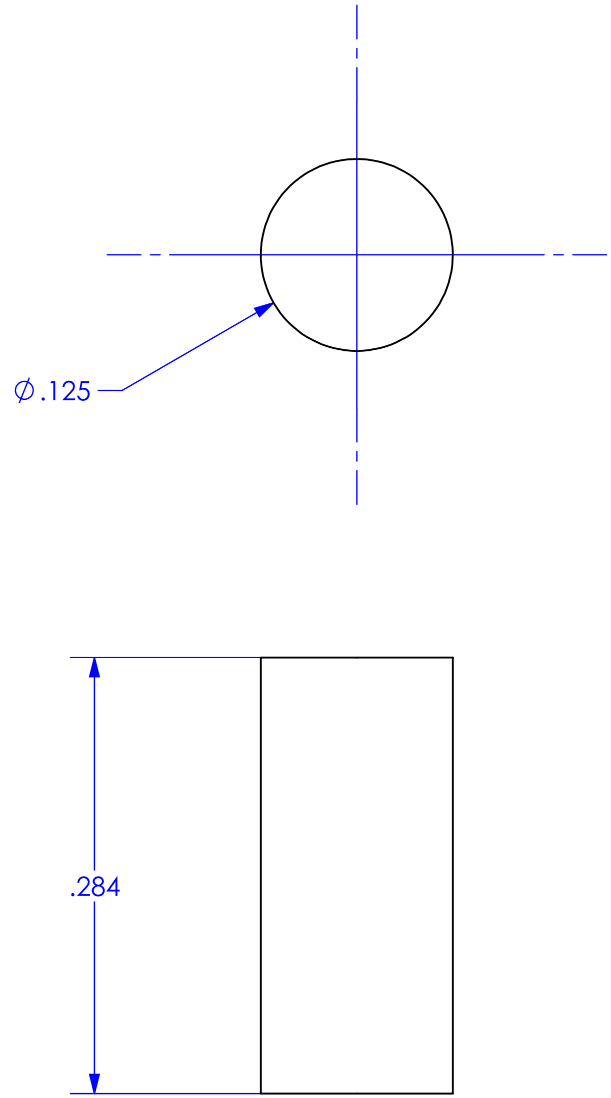
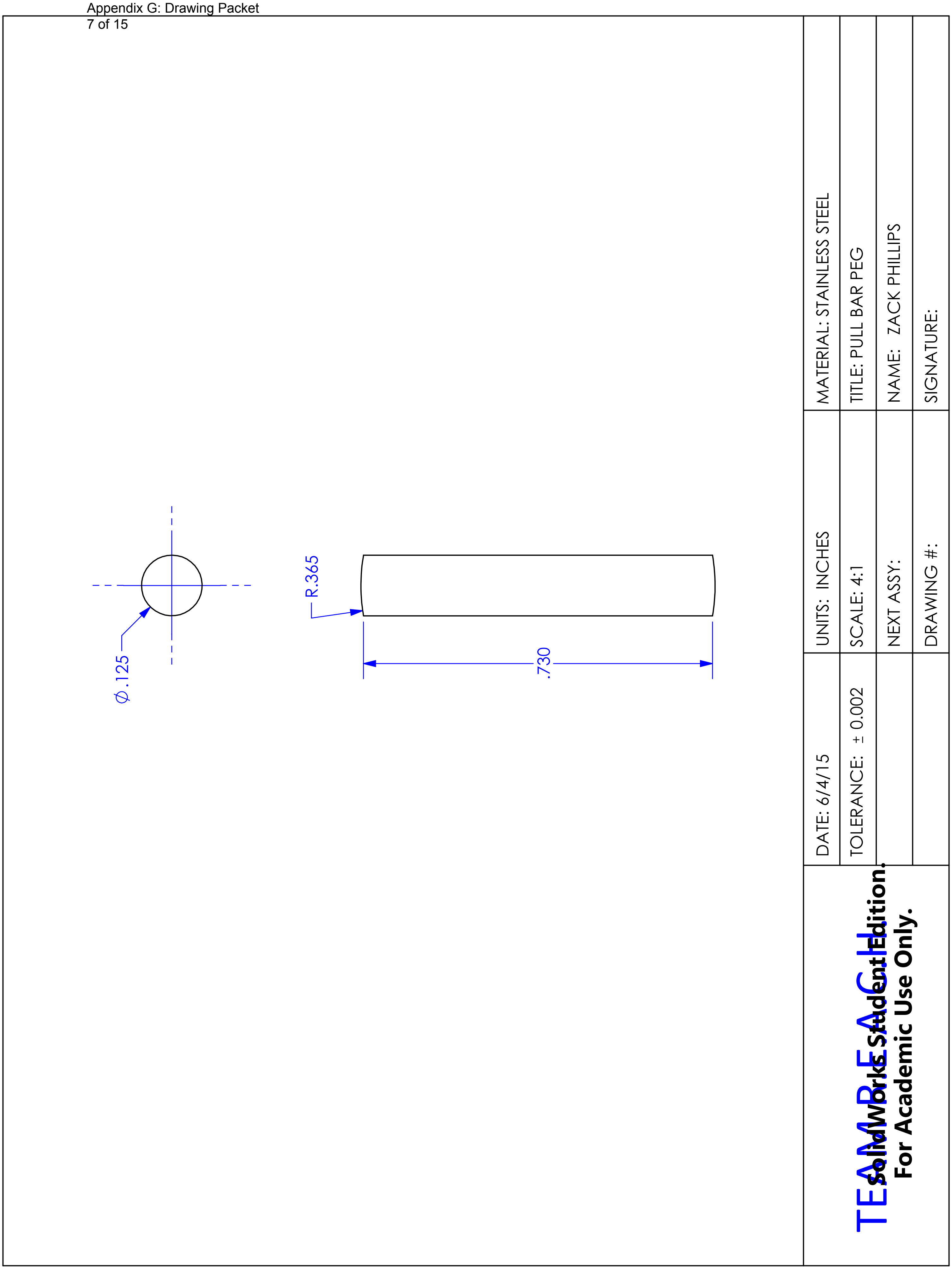
UNITS: INCHES
MATERIAL: ABS
TOLERANCE: ± 0.002
SCALE: 1:1
TITLE: CONTROL WHEEL
NEXT ASSY:
NAME: SCOTT ONSUM
DRAWING #:
SIGNATURE:
TEAM R.E.A.C.H.
SolidWorks Student Edition.
For Academic Use Only.




| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: STEEL |
| | TOLERANCE: ± 0.002 | SCALE: 4:1 | TITLE: FLEX SHAFT |
| | | NEXT ASSY: | NAME: SCOTT ONSUM |
| | | DRAWING #: | SIGNATURE: |




| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/4/15 | UNITS: INCHES | MATERIAL: STAINLESS STEEL |
| | TOLERANCE: ± 0.002 | SCALE: 8:1 | TITLE: BAR-TO-CLAW PEG |
| | | NEXT ASSY: | NAME: ZACK PHILLIPS |
| | | DRAWING #: | SIGNATURE: |


⌀.125
R.365
.730
MATERIAL: STAINLESS STEEL
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NAME: ZACK PHILLIPS
SIGNATURE:
UNITS: INCHES
SCALE: 4:1
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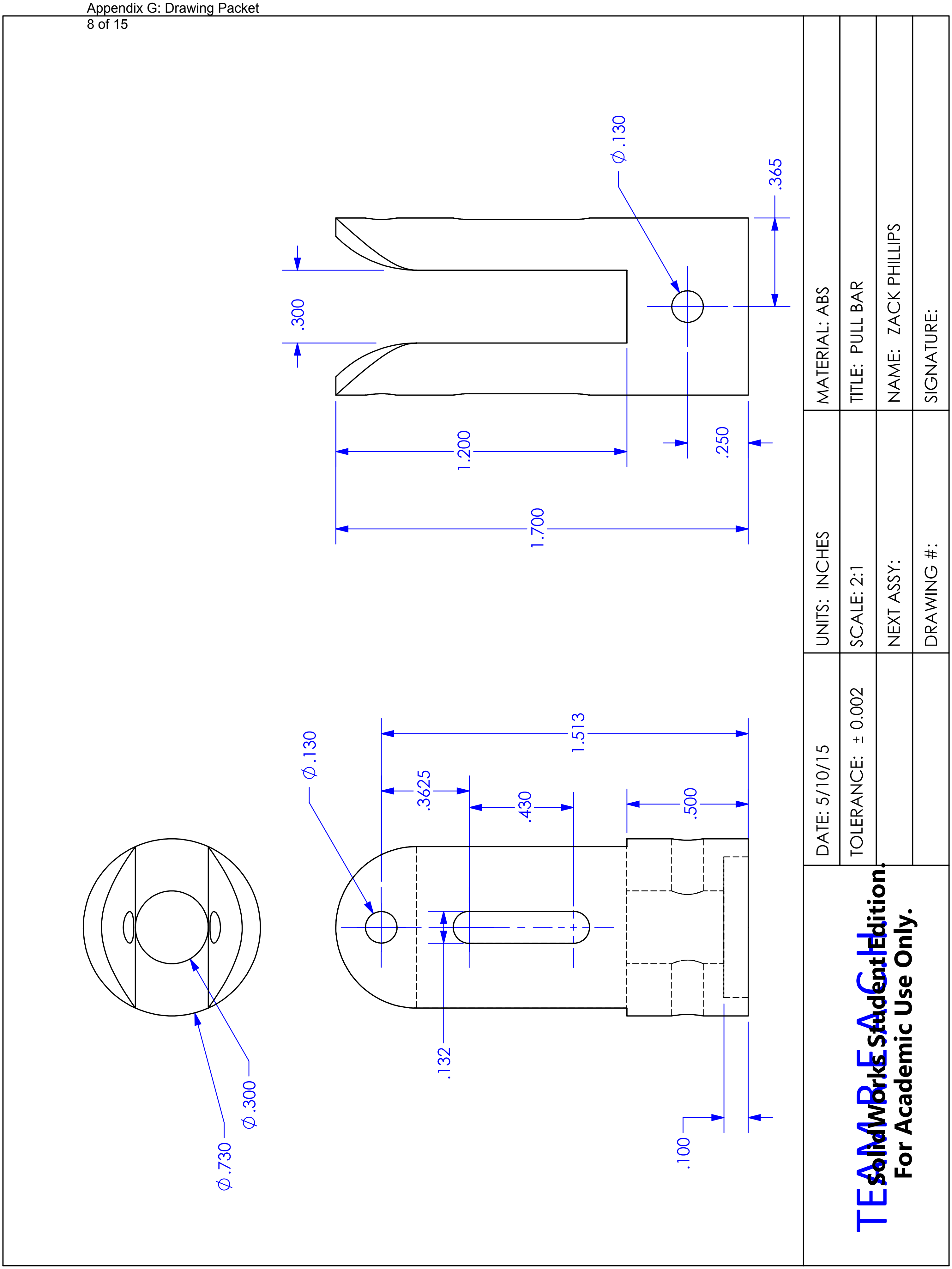
DATE: 6/4/15
TOLERANCE: ± 0.002
TEAM R.E.A.C.H.
SolidWorks Student Edition.
For Academic Use Only.


Ø.130
.365
.300
1.200
.250
1.700
Ø.130
1.513
.3625
.430
.500
.132
.100
Ø.300
Ø.730
MATERIAL: ABS
TITLE: PULL BAR
NAME: ZACK PHILLIPS
SIGNATURE:
UNITS: INCHES
SCALE: 2:1
NEXT ASSY:
DRAWING #:
DATE: 5/10/15
TOLERANCE: ± 0.002
TEAM REACH
SolidWorks Student Edition.
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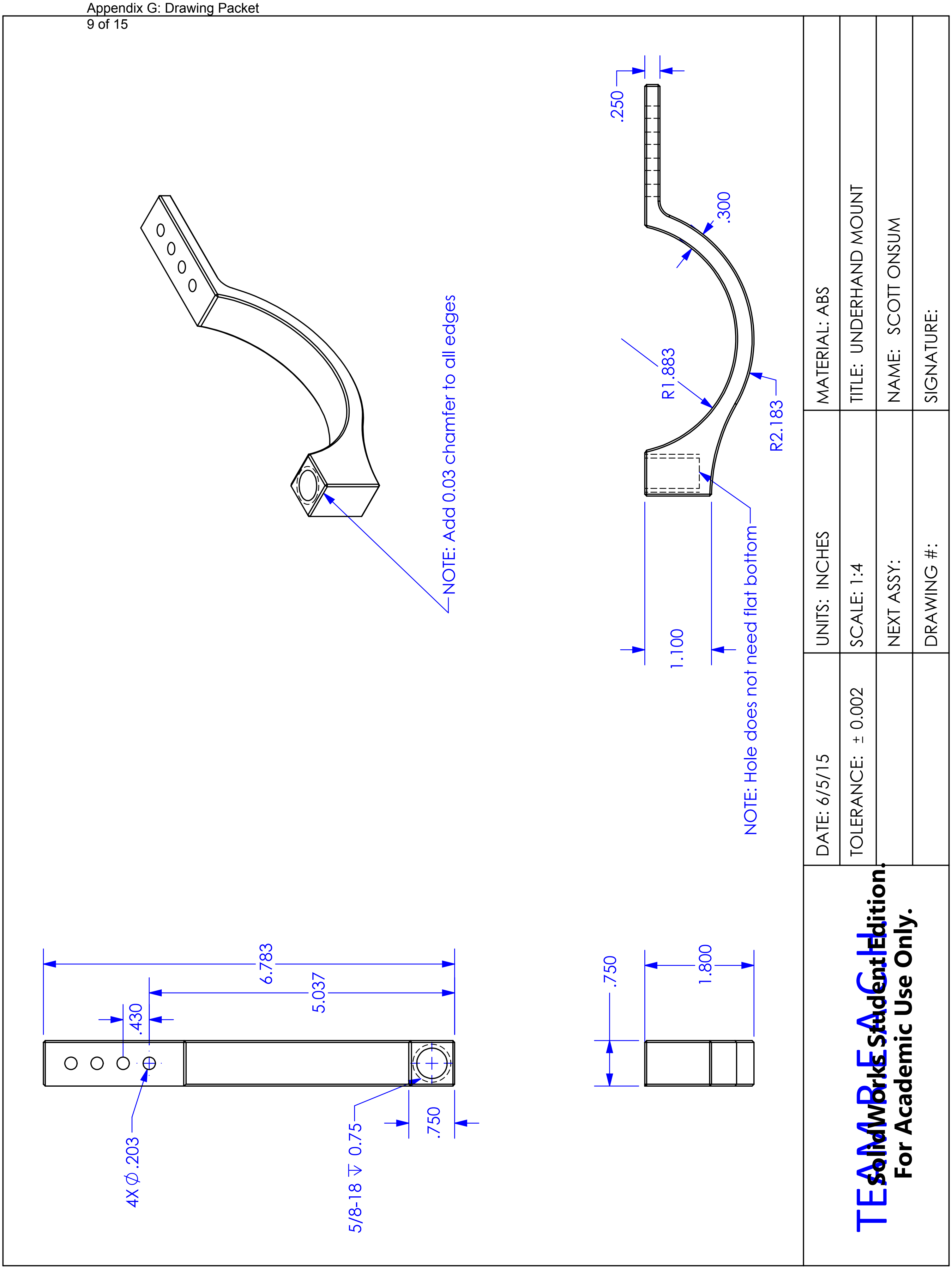
.250
.300
R1.883
R2.183
1.100
NOTE: Hole does not need flat bottom
NOTE: Add 0.03 chamfer to all edges
6.783
5.037
.430
4X ⌀ .203
5/8-18 ↧ 0.75
.750
.750
1.800
DATE: 6/5/15
TOLERANCE: ± 0.002
UNITS: INCHES
SCALE: 1:4
NEXT ASSY:
DRAWING #:
MATERIAL: ABS
TITLE: UNDERHAND MOUNT
NAME: SCOTT ONSUM
SIGNATURE:
TEAM R.E.A.C.H.
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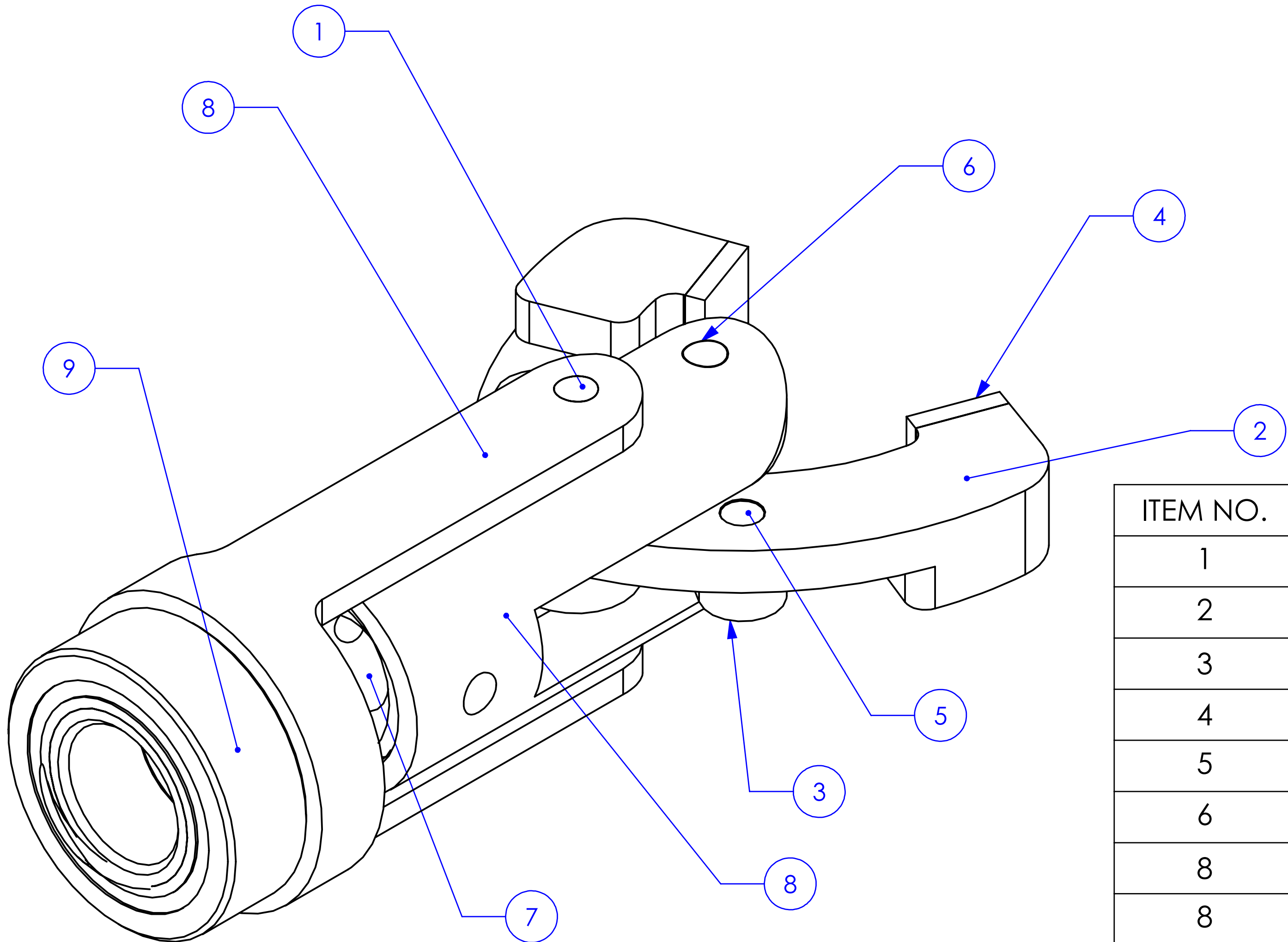
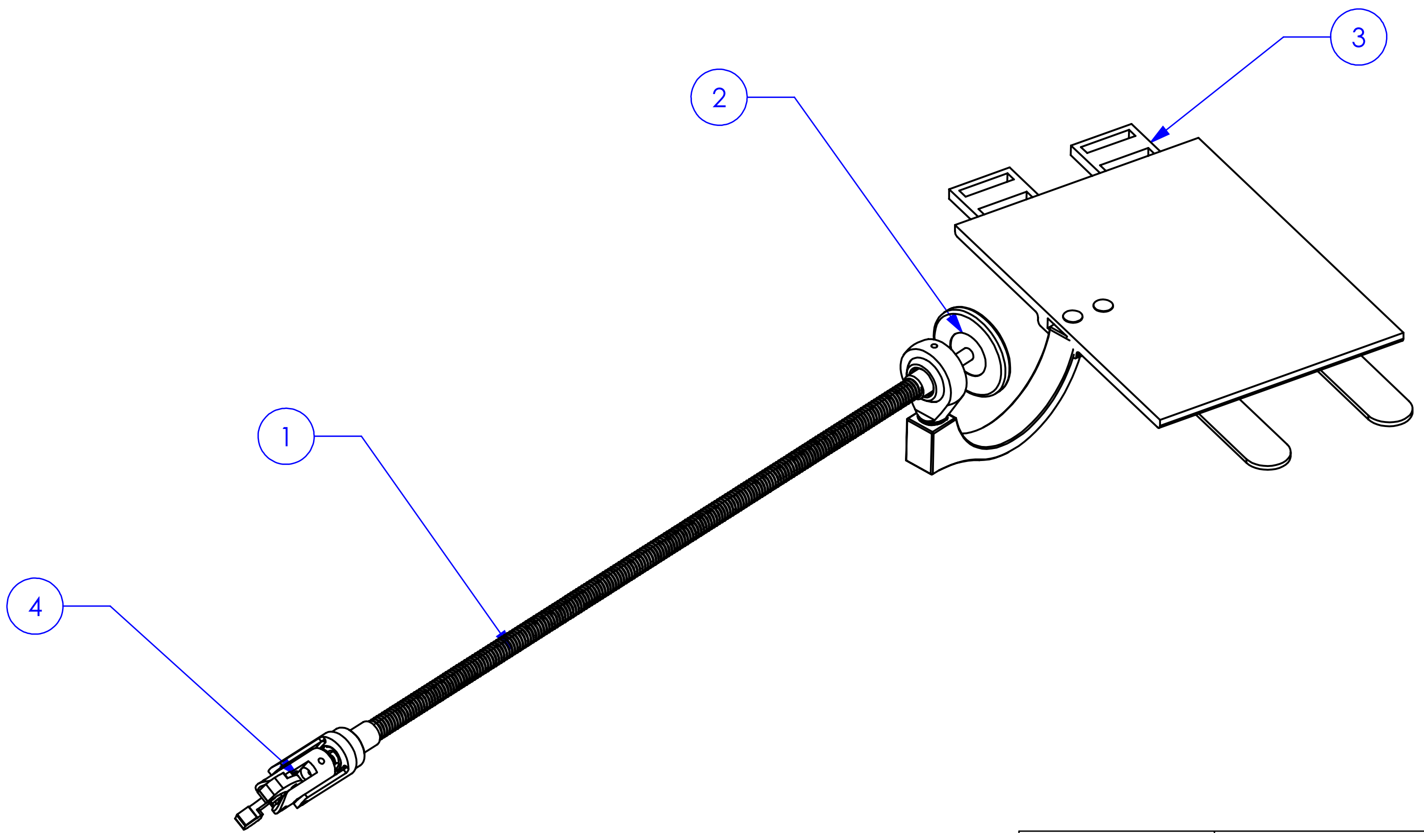


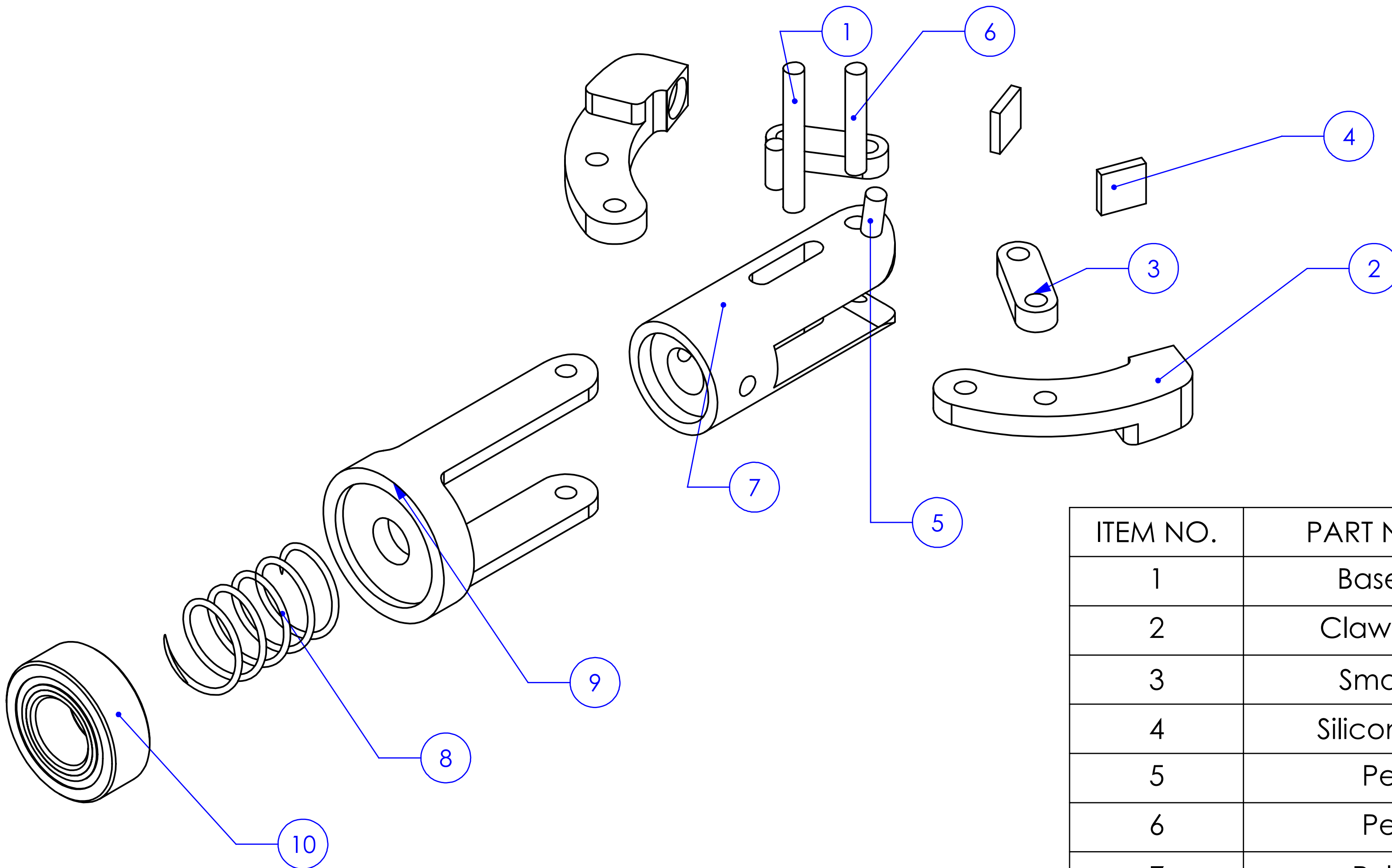

| ITEM NO. | PART NAME | QTY. |
|---|---|---|
| 1 | Base Peg | 1 |
| 2 | Claw Finger | 2 |
| 3 | Small Bar | 2 |
| 4 | Silicone Pad | 2 |
| 5 | Peg 2 | 2 |
| 6 | Peg 3 | 1 |
| 8 | Pull Bar | 1 |
| 8 | Claw Support | 1 |
| 9 | Sealed Ball Bearing | 1 |
| 10 | spring | 1 |

| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: VARIOUS |
| | TOLERANCE: ± 0.002 | SCALE: 2:1 | TITLE: CLAW ASSEMBLY |
| | | NEXT ASSY: | NAME: SCOTT ONSUM |
| | | DRAWING #: | SIGNATURE: |



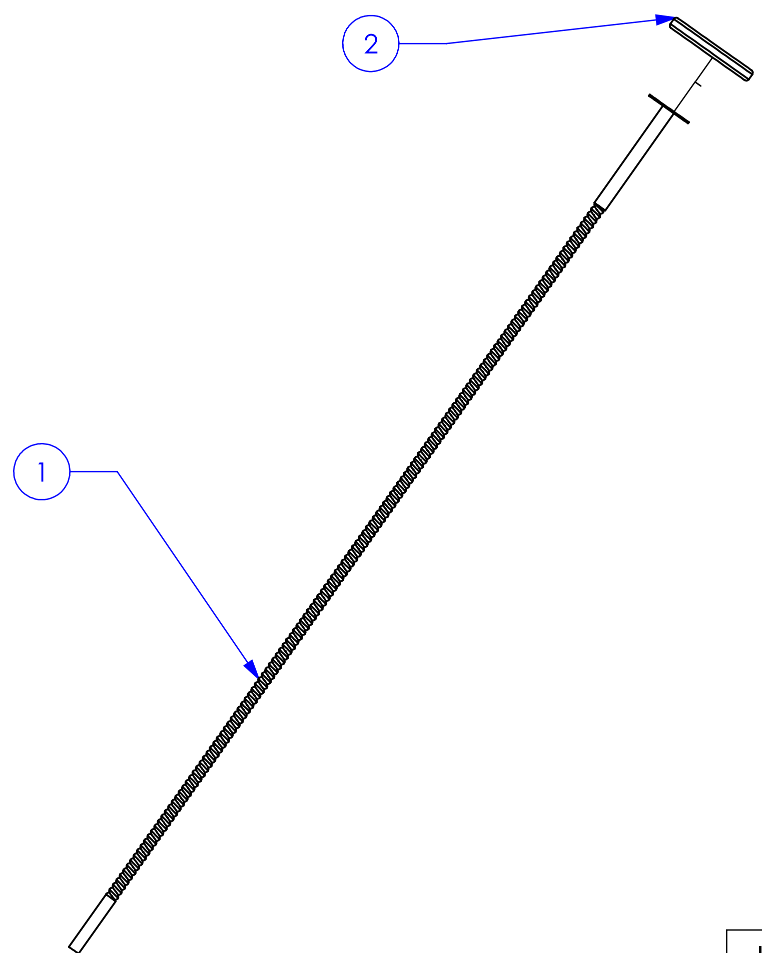

| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Gooseneck Assembly | 1 |
| 2 | Flex Shaft Assembly | 1 |
| 3 | Mount Assembly | 1 |
| 4 | Claw Assembly | 1 |

| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: VARIOUS |
| | TOLERANCE: ± 0.002 | SCALE: 1:4 | TITLE: FULL ASSEMBLY |
| | | NEXT ASSY: | NAME: HADEN CORY |
| | | DRAWING #: | SIGNATURE: |



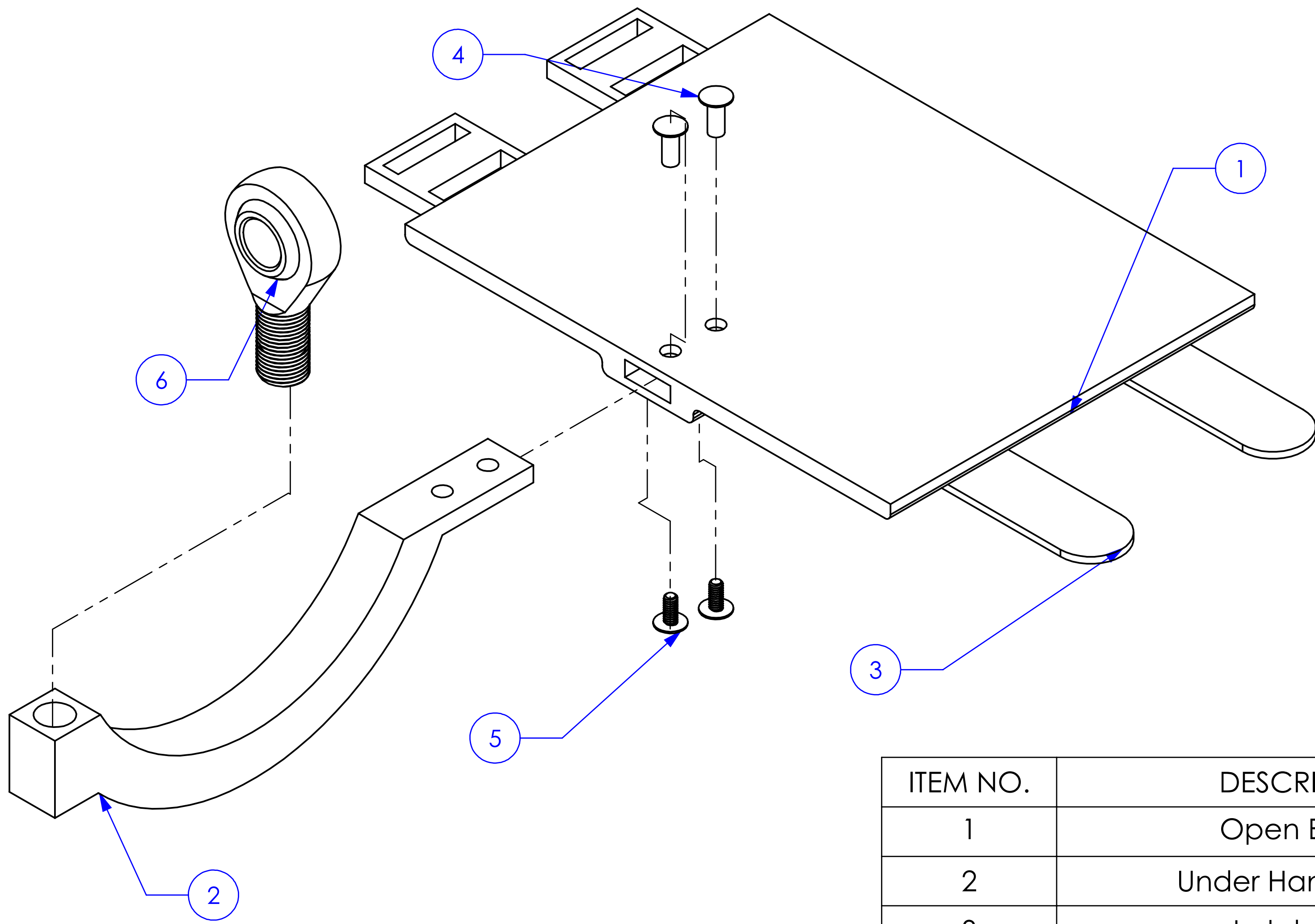

| ITEM NO. | PART NUMBER | QTY. |
| --- | --- | --- |
| 1 | Base Peg | 1 |
| 2 | Claw Finger | 2 |
| 3 | Small Bar | 2 |
| 4 | Silicone Pad | 2 |
| 5 | Peg 2 | 2 |
| 6 | Peg 3 | 1 |
| 7 | Pull Bar | 1 |
| 8 | spring | 1 |
| 9 | Claw Support | 1 |
| 10 | Sealed Ball Bearing | 1 |

| | | | |
| --- | --- | --- | --- |
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: VARIOUS |
| | TOLERANCE: ± 0.002 | SCALE: 1:1 | TITLE: EXPLODED CLAW ASSEMBLY |
| | | NEXT ASSY: | NAME: SCOTT ONSUM |
| | | DRAWING #: | SIGNATURE: |



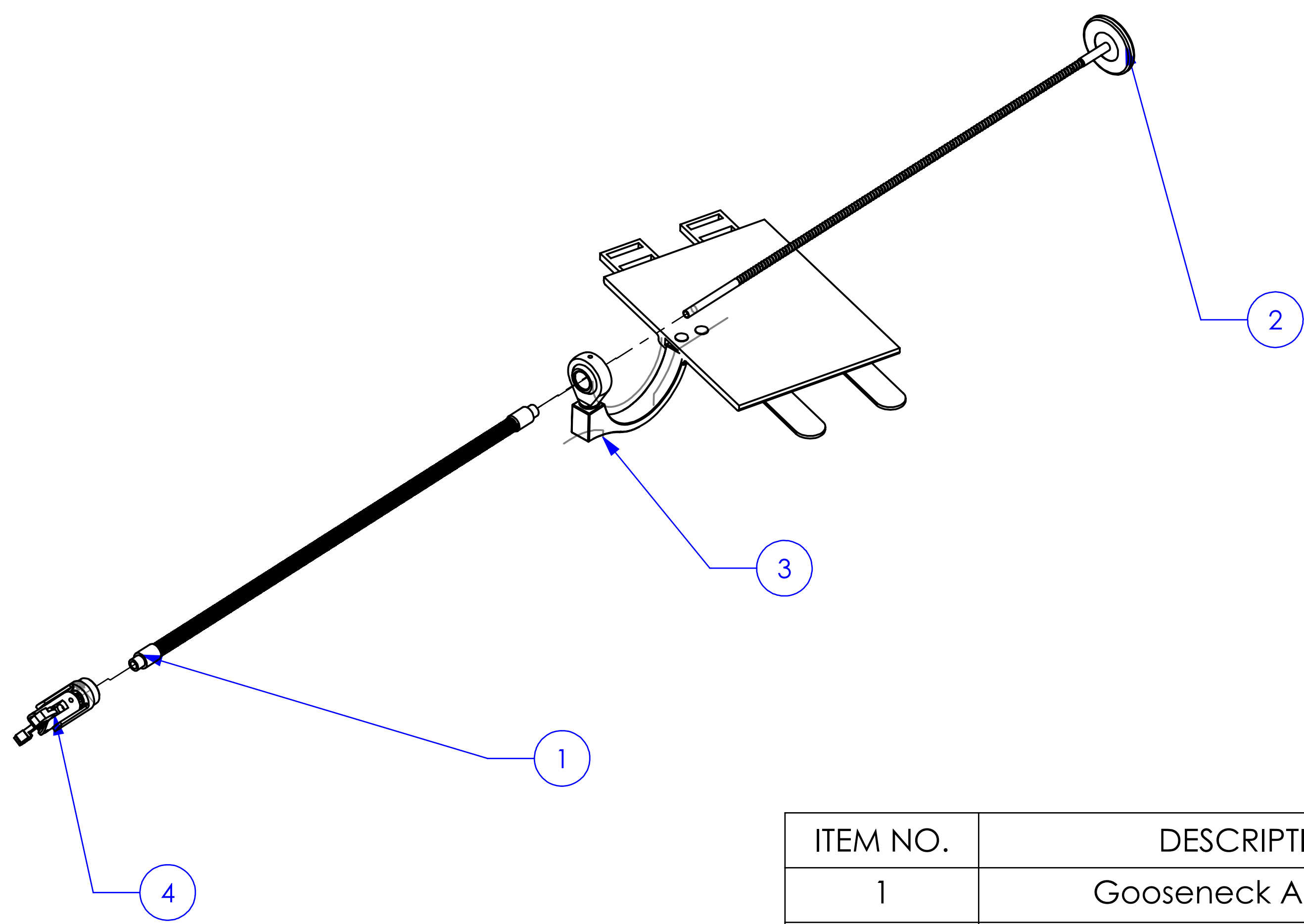

| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Flex Shaft | 1 |
| 2 | Control Wheel | 1 |

| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: ABS, STEEL |
| | TOLERANCE: ± 0.002 | SCALE: 1:4 | TITLE: EXPLODED FLEX SHAFT ASSEMBLY |
| | | NEXT ASSY: | NAME: HADEN CORY |
| | | DRAWING #: | SIGNATURE: |




| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Open Bracer | 1 |
| 2 | Under Hand Mount | 1 |
| 3 | Latch Base | 2 |
| 4 | Binding Post Insert | 2 |
| 5 | Binding Post Screw | 2 |
| 6 | Rod End Bearing | 1 |

| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: VARIOUS |
| | TOLERANCE: ± 0.002 | SCALE: 1:2 | TITLE: MOUNT ASSEMBLY |
| | | NEXT ASSY: | NAME: HADEN CORY |
| | | DRAWING #: | SIGNATURE: |




| ITEM NO. | DESCRIPTION | QTY. |
|---|---|---|
| 1 | Gooseneck Assembly | 1 |
| 2 | Flex Shaft Assembly | 1 |
| 3 | Mount Assembly | 1 |
| 4 | Claw Assembly | 1 |

| | | | |
|---|---|---|---|
| TEAM R.E.A.C.H. | DATE: 6/8/15 | UNITS: INCHES | MATERIAL: VARIOUS |
| | TOLERANCE: ± 0.002 | SCALE: 1:6 | TITLE: EXPLODED ASSEMBLY |
| | | NEXT ASSY: | NAME: SCOTT ONSUM |
| | | DRAWING #: | SIGNATURE: |

Table 1: Reach Extension Pugh Matrix

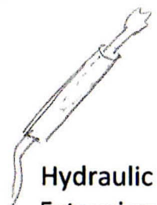
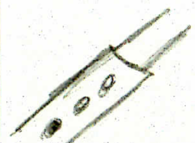
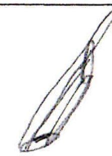
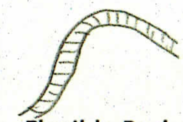
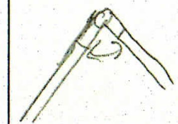
| Concepts/ Criteria |  Solid Pole |  Hydraulic Extension |  Collapsible Pole |  Toggle Linkage |  Flexible Rod (like Borescope) |  Hinge Extension |
|---|---|---|---|---|---|---|
| 12"<Device Length<24" | DATUM | s | s | s | s | s |
| One-Handed Operation | DATUM | s | s | s | s | s |
| Lightweight /Portable | DATUM | - | + | s | s | s |
| Fits through 2" hole | DATUM | s | s | - | s | s |
| Bends | DATUM | s | s | + | + | + |
| Bend 180 degrees with 3" radius | DATUM | s | s | s | + | + |
| Sum of + | DATUM | 0 | 1 | 1 | 2 | 2 |
| Sum of - | DATUM | 1 | 0 | 1 | 0 | 0 |
| Sum of S | DATUM | 5 | 5 | 4 | 4 | 4 |
| Actual Total | | -1 | 1 | 0 | 2 | 2 |
| Total | | 0 | 2 | 1 | 3 | 3 |

Table 2: Grabbing Function Pugh Matrix

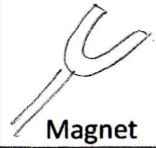
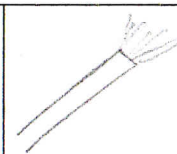
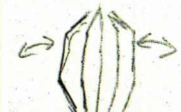
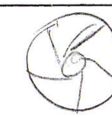
| Concepts/ Criteria |  Human Hand |  Claw |  Independent Fingers (3) |  Magnet |  Vacuum |  Suction Cup |  Deformable Foam |  Expanding Claw |  Aperture Grip |
|---|---|---|---|---|---|---|---|---|---|
| Size | DATUM | + | + | + | - | + | + | + | s |
| Weight and/or Portability | DATUM | + | + | + | - | + | + | + | s |
| Versatility | DATUM | - | - | - | - | - | s | - | s |
| Rotation: 20RPM | DATUM | s | s | - | - | + | - | + | + |
| Torque: 10 in-lbf | DATUM | - | s | - | - | - | - | s | - |
| Fits through 2" hole | DATUM | + | + | + | + | + | + | + | + |
| Magnetic | DATUM | + | + | + | s | s | s | + | + |
| Touch Feedback | DATUM | - | - | - | - | - | - | - | - |
| Sum of + | DATUM | 4 | 4 | 4 | 1 | 4 | 3 | 5 | 3 |
| Sum of - | DATUM | 3 | 2 | 4 | 6 | 3 | 3 | 1 | 2 |
| Sum of S | DATUM | 1 | 2 | 0 | 1 | 1 | 2 | 2 | 3 |
| Actual Total | | 1 | 2 | 0 | -5 | 1 | 0 | 4 | 1 |
| Total | | 6 | 7 | 5 | 0 | 6 | 5 | 9 | 6 |

Table 3: Grabbing Function Pugh Matrix

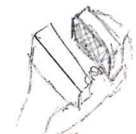
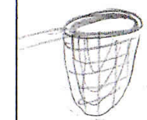
| Concepts/ Criteria |  "Bionic" Wrench |  Pipe Wrench |  Rollers |  Tongs |  Blood Pressure Cuff |  Vise |  Adhesive |  Clothes pins |  Scoop |  Net |
|---|---|---|---|---|---|---|---|---|---|---|
| Size | s | - | s | + | - | - | - | + | + | s |
| Weight and/or Portability | s | - | - | + | + | - | + | + | + | + |
| Versatility | s | - | - | - | - | - | - | - | - | - |
| Rotation: 20RPM | + | + | - | + | - | + | - | s | - | - |
| Torque: 10 in-lbf | s | + | - | - | - | + | - | - | - | - |
| Fits through 2" hole | + | s | s | + | + | + | - | + | + | + |
| Magnetic | + | + | + | + | s | + | s | + | + | s |
| Touch Feedback | - | - | - | - | - | - | - | - | - | - |
| Sum of + | 3 | 3 | 1 | 5 | 2 | 3 | 1 | 4 | 4 | 2 |
| Sum of - | 1 | 4 | 5 | 3 | 5 | 4 | 6 | 3 | 4 | 4 |
| Sum of S | 4 | 1 | 2 | 0 | 1 | 1 | 1 | 1 | 0 | 2 |
| Actual Total | 2 | -1 | -4 | 2 | -3 | -1 | -5 | 1 | 0 | -2 |
| Total | 7 | 4 | 1 | 7 | 2 | 4 | 0 | 6 | 5 | 3 |

Table 4: Maneuvering Around Objects Pugh Matrix

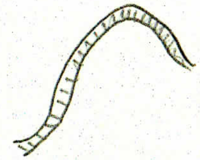
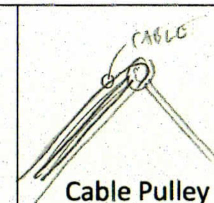
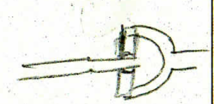
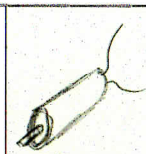
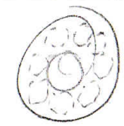
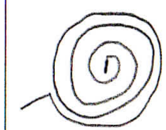
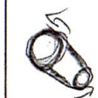
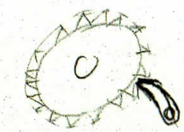
| Concepts/ Criteria |  Solid Pole |  Twist to lock joints |  Flexible Shaft |  Cable Pulley system |  U-Joints |
|---|---|---|---|---|---|
| Fits through 2" hole | DATUM | s | s | - | s |
| Can bend 180 degrees | DATUM | + | + | + | + |
| Maximum 180 bend of radius of 3" | DATUM | + | + | + | + |
| Ease of use | DATUM | - | s | + | s |
| Sum of + | DATUM | 2 | 2 | 3 | 2 |
| Sum of - | DATUM | 1 | 0 | 1 | 0 |
| Sum of S | DATUM | 1 | 2 | 0 | 2 |
| Total | | | 2 | 2 | 2 |

Table 5: Rotation Function Pugh Matrix

| Concepts/ Criteria |  Human Hand |  Claw |  Motor |  Hand Drill Thingy |  Ball Bearings |  Torsional Springs |  Belt Drive |  Sprocket |  Ratchet & Pawl |
|---|---|---|---|---|---|---|---|---|---|
| Weight and/or Portability | DATUM | s | s | - | s | s | - | - | s |
| Rotation: 20RPM | DATUM | + | + | + | + | - | + | + | + |
| Torque: 10 in-lbf | DATUM | - | + | + | - | - | - | + | + |
| Fits through 2" hole | DATUM | + | + | - | + | + | - | - | + |
| Sum of + | DATUM | 2 | 3 | 2 | 2 | 1 | 1 | 2 | 3 |
| Sum of - | DATUM | 1 | 0 | 2 | 1 | 2 | 3 | 2 | 0 |
| Sum of S | DATUM | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 |
| Actual Total | | 1 | 3 | 0 | 1 | -1 | -2 | 0 | 3 |
| Total | | 3 | 5 | 2 | 3 | 1 | 0 | 2 | 5 |

R.E.A.C.H. Device Operator's Manual

This manual is includes pictures placed below each set of instructions to illustrate the included procedures.

Setting up the device

- Insert hand into wrist guard and test distance to control wheel for comfort.

    - If distance comfortable, tighten strap around forearm to secure device.
    - If device needs adjustment, unscrew binding post inserts and shift position of underhand mount relative to wrist guard.  Re-insert binding post inserts and tighten.  Tighten wrist guard to forearm with strap to secure device.

- Bend the gooseneck into the desired position

- Turn on camera and viewing monitor


  - Ensure the camera and monitor are on the same channel
    - Consult bottom of camera wand base to set camera channel


    - Button on face of monitor cycles through channels


  - Adjust LED brightness with arrow-shaped buttons above and below camera wand power button.
- Align camera so that the desired picture is visible on the monitor

    - Ensure the camera is close enough to the gooseneck to fit through available opening
    - Re-align camera as necessary according to any changes in gooseneck position
    - Camera will not always be in the same orientation as the viewing monitor. If possible, orient monitor to reflect the orientation of the camera to improve ease of use.

Operating the device

All inputs to influence rotation and actuation of the claw to the device once it is inside the machine should be performed using the control wheel pictured below. The steps provide instructions on opening and rotating the claw.

- Grabbing
    - Pull back on control wheel to open the jaws of the claw
    - Release control wheel to allow the part to clamp down
    - Ensure that the part is axially aligned with the claw to ensure easier rotation
- Rotation
    - Spin the control wheel in the desired direction, clockwise or counter-clockwise
        - If the part does not engage try readjusting the position of the gooseneck

Changing end effectors

- Remove bolt holding claw assembly to flex shaft

- Remove pin between claw and support bar assembly, then remove claw from support bar assembly
    - Note that support bar for claw will remain attached to bearing. This should not interfere with use of the socket drive end effector.

- Align hole in clevis on 1/4” socket drive with hole in flex shaft and bolt the two parts together.

- Attach desired effector to driver end

  - For socket, a step-up driver may be required
  - For a hex key/Allen wrench, use an adapter to convert from a ¼” socket drive to the appropriately sized receiving end.