Marine Biomass Analyzer

A Senior Project Final Design Report Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Mechanical Engineering at California Polytechnic State University, San Luis Obispo

13 June 2017

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Statement of Disclaimer

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Executive Summary

This report documents the design, fabrication, and testing for a marine biomass analyzer. The goal of the project and constructed system was to determine the validity and efficacy of a process that could flatten benthic macrofauna to a consistent thickness such that a biomass for the collected sample could be accurately determined. The system that was built and tested consists of a drive train that turns a mill subassembly where the organisms are flattened, supply and collection spools that hold the white fabric and clear film used to capture the organisms, a collection zone where the sample is injected, and a superstructure that supports the device for rigidity and positioning of components. Through clever design, we were able to minimize the parts required to locate and tension the spools, allowing them to be removed and resupplied quickly. Additionally, the number of lost organisms that were not captured was minimized to under 5%. All components and fabrication were made using typical equipment found in a machine shop including a manual mill and lathe, laser cutter, 3D printer, and general shop tools. A software package called Matlab was used for image processing to determine sample size and calculate a biomass given the interpreted surface area of the caught sample. Ultimately, we were able to design, build, and test a system and analytical process that could determine the biomass of a sample to within ±10% of its actual value. We consider our proof-of-concept design to be a success and can be further developed upon with new iterations. Eventually, this system could be incorporated into an autonomous underwater rover that simultaneously collects, filters, and scans benthic samples to determine biomass and biodiversity in oceanic environments.

1. Introduction

Current methods of benthic (seafloor) sampling of macrofaunal (animals around 1-2 mm in size) provide limited, discrete point-data for researchers. The process requires manually intensive labor and can often misrepresent patchy animal populations. The goal of this project is to create a proof-of-concept test bed that can continuously capture benthic macrofauna and prepare them for further analysis. Preparation would include storing half of the organisms to be later identified under a microscope and "squishing" the other half to determine the biomass of the sample through an approximation of body volume. The long term vision of this project is to implement the test bed into a benthic rover that will continuously collect organisms on the coastal ocean floor.

Small (ca. 2 mm long) animals living in sub-tidal marine sediments can provide insight to environmental conditions including habitat health, human impacts, and many other research possibilities. These small invertebrate animals, known as macrofauna, are important sediment recyclers, particle processors, and bioturbators supporting the food webs important for many fish, marine mammal, and seabirds. Three groups of animals living in soft sediments are especially important, worms, small crustaceans, and small mollusks. Automating and/or standardizing benthic subtidal macrofaunal investigations allow for better impact assessment and ecological monitoring of marine and coastal developments. The sandy and muddy regions just offshore may look lifeless, however, it is where the most diversity in benthic animals is located. [1]

Individuals and groups who may be interested in this project include: marine biologists, ecologists, benthic researchers, and other individuals/organizations interested in the ocean monitoring. It may be a concern for those in the oil industry, cable layers, and other marine development concerns as a means of identifying and mitigating environmental impacts for continual impacts (e.g. dredging) or pulse impacts (e.g. oil spills) in a more standardized fashion where monitoring costs can be more precisely known and incorporated into project planning.

2. Background

2.1 Customer

The benthic rover will provide biologists, ecologists, and benthic researchers with a continuous data collection platform for researching and understanding animals inhabiting surface layers of the benthos. Currently, no such platform exists to capture and study the benthic macrofauna. Today's methods of sampling involve point-collections by grabbing small areas of the seafloor and thereby giving scattered data, limiting insight to the number and types of benthic organisms known to be found in patches in the nearshore environment. A continuous stream of connected data will help map out population characteristics of macrofauna and allow for closer examination and assessment of the coastal environment by directly measuring animal population gradients with respect to a disturbance.

2.2 Customer Requirements

Dr. Paavo is looking for a mechanical system to be designed that can continuously catch, and flatten macrofauna. The ultimate goal is to implement a similar system into a "benthic rover" to enhance research capabilities in coastal regions.

An optimal system should be able to collect the macrofauna, "squish" half of them, and store all of them for future analysis in an index-able manner. The collection of the system should be continuous and directly correspond to the location of the rover. This means that the location that each sample was taken should be identified and recorded for population mapping.

The crushing process must be able to flatten half of the collected animals, regardless of species, while leaving the other half relatively intact – enough to be identified manually under a microscope. Flattening half of the organisms to a thin layer allows for an imaging system (outside the scope of this project) to estimate their "2-D" area. By multiplying this area by the average thickness and density of the organisms, the biomass of the sample can be estimated. The other half must remain separate and undamaged so they can be identified by a specialist. The combination of flattened and undamaged macrofauna should help researchers identify what, approximately how many, and the biomass of each common species are in the sampled transect.

A belt material must be selected that is "fuzzy" with a small mesh to collect the macrofauna yet permeable enough for water and air to pass through. Water and air are expected to be used to separate the animals from the sediment in an adjunct process (outside the scope of this project). It must be able to operate under tension in a seawater environment and in a 5% ethanol solution. This belt should collect on an easily removable and replaceable spool to allow for inspections during testing runs.

Given that the system will be running on the ocean floor – or submerged in a marine test tank, it must be able to handle grains (< 10 mm diameter) of calcium carbonate shells and small rocks passing through it without jamming. The system should have a drive mechanism that can be easily upgraded to a motor at a future stage in the product. The overall system should be able to fit inside of a 150-liter tank.

As taking measurements in metric is standard in the biology industry, the project sponsor has requested that all specifications are reported in metric units.

2.3 Benthic Sampling Methods

2.3.1 Sampling Size and Location

The design of sampling methods is crucial to assessing the benthic habitats. Benthic populations tend to be extremely patchy in their distribution and their abundance due to natural and anthropogenic disturbances. Natural disturbances include the rolling and crashing of waves, erosion of coastal sediments, large storms, predation, and competition for food and space while anthropogenic disturbances include trawling, dredging, dumping, sewage disposal, and other human related activities. The population densities can vary substantially at distances as small as in tens of meters, making consistent results complicated to obtain. It is therefore important to have a well-defined method of sampling, analyzing, and interpreting the sample data due to this complex benthic variance. [2]

Current benthic sampling techniques involve collecting cores or quadrats of sediment and animals from an identified measurement area. Small benthic animals often organize themselves into scattered clusters (Figure 2.1)**.** This introduces a need to choose an appropriate quadrat size in order to collect enough animals to create a statistical distribution.

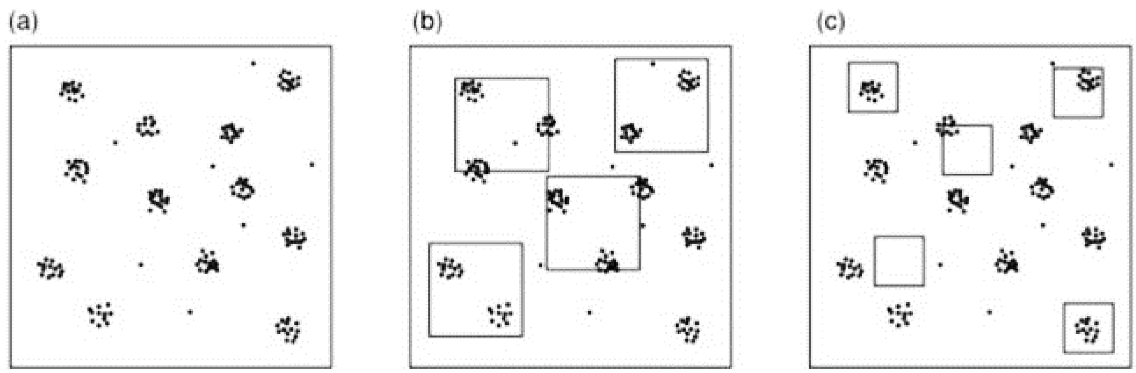


Figure 2.1 ***(a)*** *Top view layout of sampling benthic animals.* ***(b)*** *and* ***(c)*** *show two different quadrat sampling sizes which aim to collect scattered, aggregated groups of benthic animals. [2]*

Although each quadrat size in (b) and (c) will collect animals, the data from each method will suggest different results. The larger quadrat samples from (b) will produce data that suggests a normal distribution of animals in the area. Since the quadrat size is large enough to include multiple population clusters, it will “ignore” the gaps in between them and give a well-defined average population density. On the other hand, the smaller quadrat sizes in (c) will produce data that shows how the clusters are spread apart. The small quadrat data will be sporadic, some samples containing no animals, some with an incredibly high population density, and some with populations somewhere in between. In most cases, a normal distribution is desired to find average population density of the location; however, it does not provide an accurate depiction of the benthic population layout. [2]

This process of selecting a quadrat size is further complicated since the macrofauna are unobservable from above. Marine biologists are unable to easily see the sizes of the clusters as they are shown above (Figure 2.1) and must work out an appropriate quadrat size. If multiple species of different sizes and abundances need to be sampled, nestled quadrats (Figure 2.2) may be used to save time. The larger quadrat can sample the few larger species while the smaller quadrants save time counting the numerous smaller species and better map their population layout.

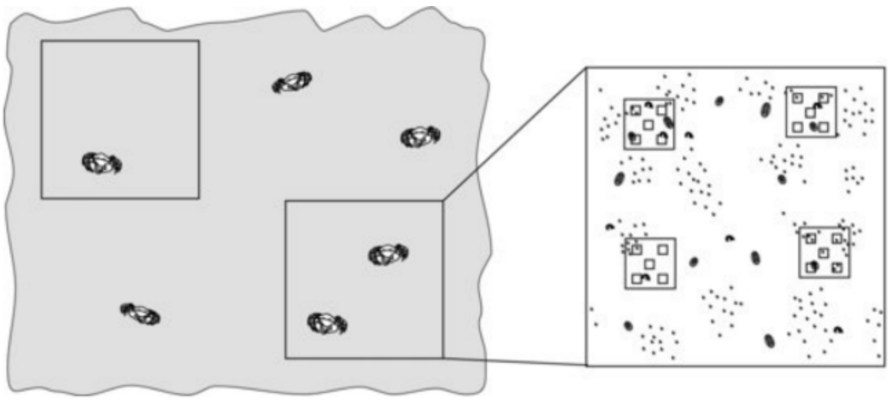


Figure 2.2 *Nestled quadrats allow for multiple species of different sizes and abundances in the same location to be efficiently sampled. [2]*

An unsuitable quadrat/core size will also give incorrect relationships when attempting to measure how species interact with each other. Consider two species that live in abundance together (i.e. both species thriving in a localized environment). Depending on the size and number of samples taken in that area, the correlation between the two species' abundance may be different. Unfortunately, different quadrat sizes can give partial or incorrect information about the species' relationship. Neither of the quadrat sizes can justify a correlation between the two species' populations. The actual pattern is likely due to small-scale environmental variables, and is not clearly seen from the quadrats either (Figure 2.3(e)).

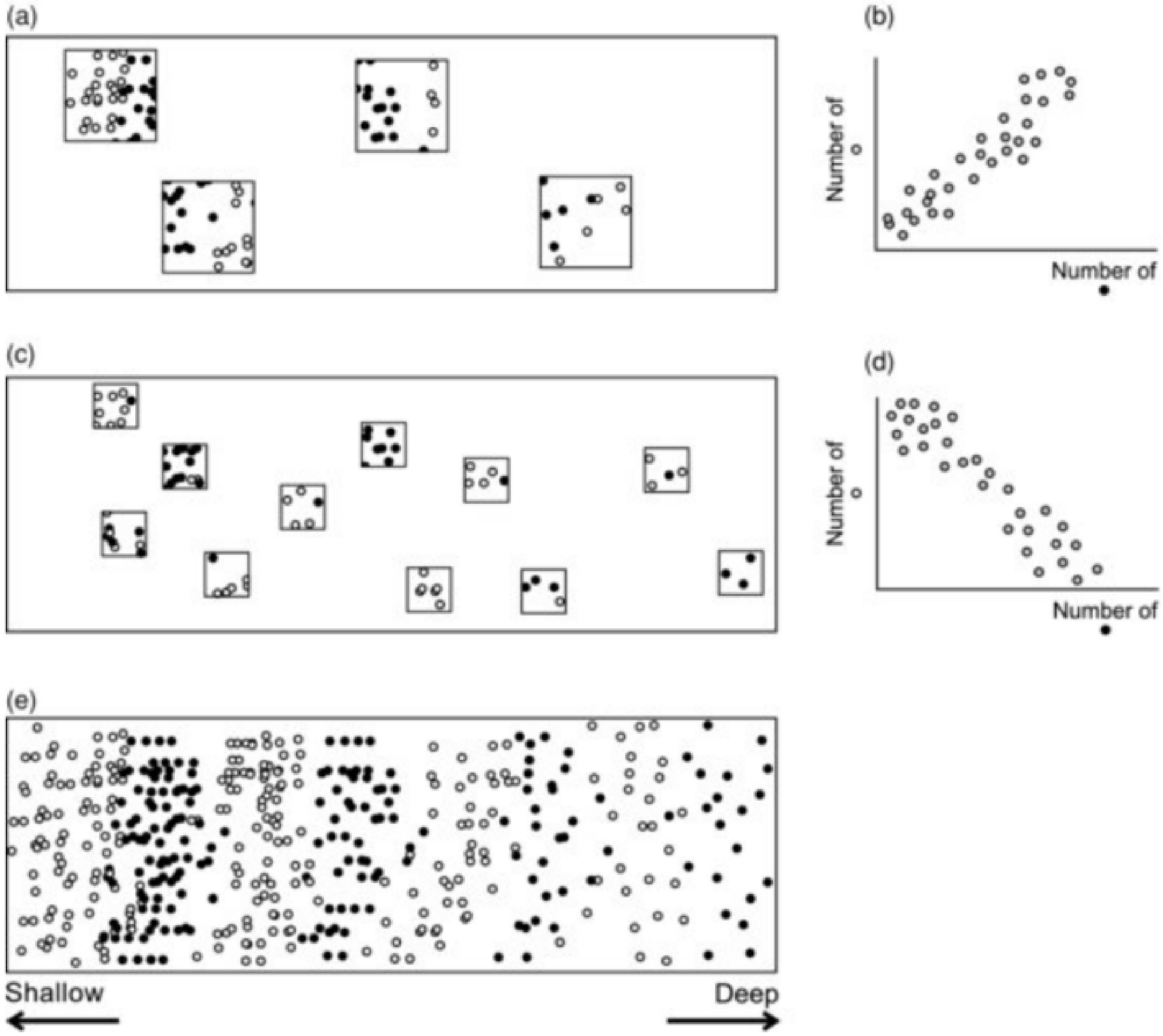


Figure 2.3 ***(a)*** *and* ***(b)*** *show a positive correlation between the two species based on the large quadrat samples. However,* ***(c)*** *and* ***(d)*** *show a negative correlation between the two species from the same location. Neither are correct, as* ***(e)*** *shows that there is no distinct pattern. The change in abundance is likely due to small-scale environmental variables such as water depth. [2]*

It is easier to predict benthic population patterns based for large-scale, specific habitats. For example, around a newly constructed, sewage treatment center, one species might thrive on the new bacteria and nutrients released from the plant while another existing species might die from the changed conditions. A population gradient would potentially form of the two species that would show how each reacted to the new facility. Population gradients of species can help map species' relationship with other large-scale variables such as levels of water salinity, temperature, or benthic topography. However, these large-scale patterns must be balanced against the small-scale samples that they are derived from. Predation, competition, and small currents can create empty patches or aggregated clusters within these gradients and can over represent or underrepresent the population density in the gradient.

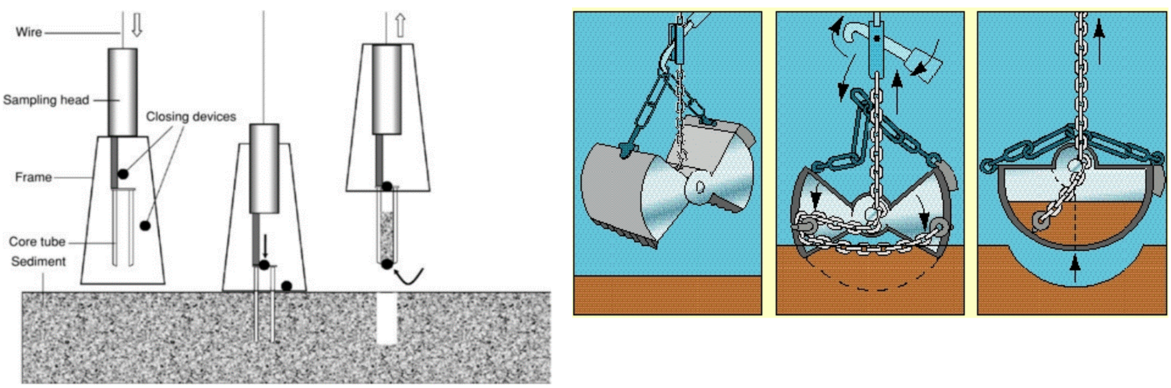
The ability to obtain a continuous stream of data could help alieve the difficulties associated with determining sample sizes and locations. With continuous data, researchers would have a bigger picture of the benthic landscape.

2.3.2 Sampling Gathering Equipment

A wide variety of equipment is used to complete benthic sampling. Most instruments can be categorized into four unique groups: corers, grabs, trawls, and underwater video. [3]

Corers work by boring either a large tube into the sediment, sealing the bottom, and pulling the resulting core out (Figure 2.4(a)). Scientists are able to obtain samples of small organisms as they are found naturally in the sea floor. They minimize injury to possibly delicate organisms and show the depth they are found at.

Grabs are typically downwardly-directed jaws (Figure 2.4(b)). They are unsuitable for coarse sediments due to their claws jamming on rocks, but operate well in finer conditions. While macrofauna are often capable of escaping their grasp, grabs more easily gather samples of the macrofauna in the ocean sediment. The sample area of grabs is sparse, ranging from 0.04 - 0.25 m^2. Grabs also have the issue of mixing sediment, so the depth of the animals are found at is lost.



(a) *(b)*

Figure 2.4 ***(a)*** *A corer in operation [2]*. ***(b)*** *A benthic grab sampler in operation. [4]*

Trawls are used to obtain larger sections of data (Figure 2.5). Trawls can be towed 200 - 800 m and provide manageable sample sizes. Different sized meshes and chains can be used depending on the coarseness of the region being samples. Trawls with mesh sizes of 3 mm or less are used to capture small organisms.

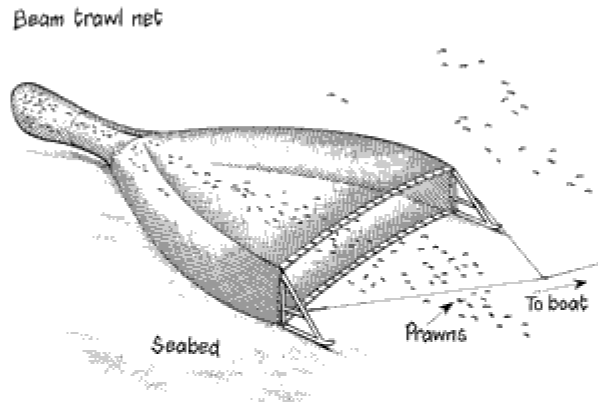


Figure 2.5 *A beam trawl net for collecting small animals dependent on mesh size of trawl. [5]*

Underwater video and photography are valuable as non-destructive evaluation techniques of benthic regions. However, they do not provide high enough resolution for the type of animals the team will be analyzing.

2.3.3 Sampling Evaluation

Once the sample has been obtained from one of the methods above, its volume is estimated and a description of the sediment type is recorded. Then, separation of the sediment and fauna can begin on the ship to reduce the amount of raw material returned to the lab. The sample is run through sieves with a 5 - 10 mm stainless steel mesh. A gentle hose is used to push sediment through without harming any delicate organisms that may be in the sample. Once through the first sieve, the finer sample is washed over a 1 mm mesh sieve, and in rare cases, a 0.5 mm mesh sieve. The sieves are vibrated horizontally as necessary, never vertically, to prevent harming the small organisms falling through. [3]

The container with the finest sample is then lightly agitated to separate the lighter animals from the sediment. By pouring this fine sample back-and-forth between two containers, a froth will develop. The majority of the macrofauna will float to the top of the containers since their hydrophobic skeletons will attach to the air bubbles that form. A piece of paper is placed on top of this froth to pick up the floating animals. Finally, the animals are rinsed off the paper into storage for future analysis. Any heavy shelled animals that remain in the sediment must be picked by hand.

This process of floating the macrofauna to separate them from the sediment is called elutriation. Both a wet weight and a dry weight (once the sample is blotted dry) can be determined to find the biomass of the sample. After a sample has been fully processed, the equipment must be thoroughly washed and cleaned to avoid future cross-contamination.

2.4 Cal Poly Pier Trip

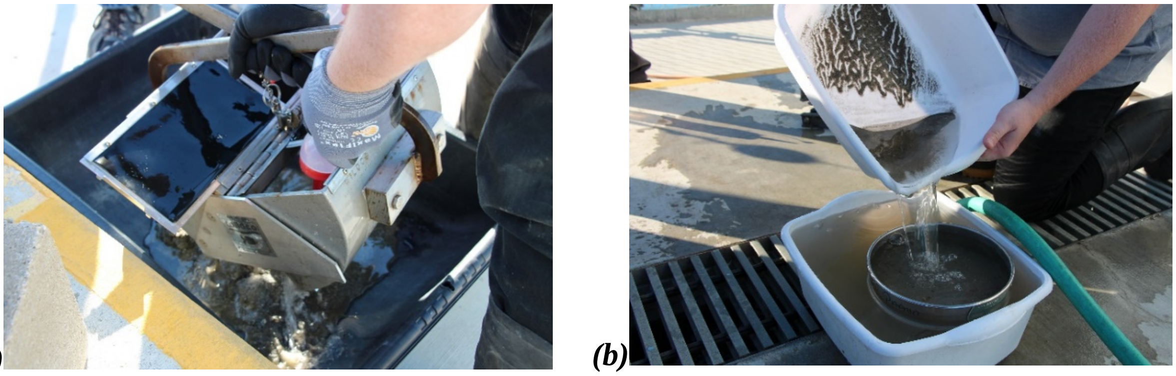
2.4.1 Pier Overview

The team took a trip to the Cal Poly Pier to experience first-hand how Dr. Paavo currently obtains his samples. The team was able to use a small grab built into the pier to take a sample from the sediment. The grab was held open by a pre-loaded spring that was released when it made contact with the sea floor. It was attached to the steel cable on the crane arm. The extended arm was then slowly rotated over the water so that the grab would not swing dramatically and potentially cause the grab to activate. Once the grab was no longer swinging, the team lowered it into the water using an automated winch. The winch was simple to operate, consisting only of a wind/unwind switch. The operator had to wear gloves to protect from burns and splinters from the steel cable. The team lowered the grab for about three minutes until the cable became slack, indicating that the grab had hit the ocean floor. The team then raised the grab without knowing if the grab had actually activated. Once another three minutes had passed to bring the grab above water, the team was pleased to find that the grab had activated and closed. The arm holding the grab was slowly rotated over the pier so the team could check that the grab collected sediment and did not activate too early. By looking through a mesh on the top of the grab, the team found that the grab had fired at the appropriate time on the ocean floor and had collected a large sediment sample.

(a) ***(b)***

Figure 2.6 ***(a)*** *The grab was attached to the steel cable on the crane arm.* ***(b)*** *The arm was slowly rotated over the pier. The winch mechanism can be seen in the lower right-hand corner.*

The team then emptied the contents of the grab into a black, plastic container. The insides of the grab were rinsed off using a wash bottle to ensure that all sediment was emptied into the black container. The team then placed handfuls of sediment into a white container filled with sea water to begin the elutriation process. Normally defined volumes of sediment are placed into the white container to obtain more precise data for statistical analysis, however, the team used their hands to quicken the process since they were focusing on the overall process and not on obtaining precise data. The team then vigorously shook the white container to separate the small particulates and animals from the sediment. The water was then poured into a 2 mm then a 1mm steel mesh sieves already immersed in sea water to sift out animals. Once the water turned clear, the team added more sediment to be elutriated and sifted. This process was done on the entire sample from the grab.



(a) *(b)*

Figure 2.7 ***(a)*** *The contents of the grab were released and washed into a plastic container.* ***(b)*** *Elutriated sediment was poured into two stacked sieves with 1 and 2 mm meshes.*

The team then pulled the sieves out of the water and observed the different shells, rocks, and animals in each. The rocks and shells varied greatly in size on the large mesh, ranging from about 1 mm to 15 mm. Some soft animals (such as worms) were able to squeeze their bodies through fine sieves, potentially allowing them to escape collection. The contents of both sieves were placed into a small container filled with sea water and placed under a microscope for a quick close look at the sample. Dr. Paavo would thoroughly examine each specimen for actual data collection.

(a) *(b)*

Figure 2.8 ***(a)*** *A close-up image of the objects caught on the 2 mm sieve. The size of the objects varies from about 1 mm to 2 mm.* ***(b)*** *Dr. Paavo examining the sample to identify organisms.*

2.4.2 Pier Learnings

Understanding what specific aspects of benthic sampling were the most difficult and time consuming were the two greatest takeaways from going to the pier. The team saw how the minimum of six minutes required to lower and raise the grab could quickly add up to large amounts of wasted time over the course of taking numerous samples for a location. This wasted time is further stymied when the grab misfires. Even though the grab did not fire too early while the team was at the pier, Dr. Paavo emphasized that misfires were not uncommon while taking samples on a boat. The team did not see how long it would take Dr. Paavo to sort through the collected samples.

Dr. Paavo further discussed the difficulties and potential dangers of using grabs on a rocking boat. The potential for the grab to misfire is increased due to the movement of the boat and ocean currents. Sampling deeper parts of the ocean also means that the time it takes to raise and lower the grab is increased as well. The rocking of the boat also causes the grab to be a potential danger. Weighing about 15 pounds, if arm and cable are not carefully moved, the grab can dangerously swing on a boat and injure someone. The grab itself also bears a cutting threat. Once fired, the sharp claws of the grab rapidly spring together, easily digging into an individual's arm. The grab cut into the black plastic container the team was using and Dr. Paavo told us that grabs often collect pieces of a fish that it cuts through.

Seeing these problems first hand shows how useful a benthic rover could be. This general method of sampling has remained largely unchanged since the late 1800s and can be improved upon with automated sampling.

2.5 Types of Rolling Mills

Rolling mills of various types were researched to evaluate how they could potentially fit in a prototype test bed.

2.5.1 Steel Mills

There are numerous types of rolling mills and equipment designs for many different processes. Much of the technical information about rolling mills available is about rolling metal. While rolling steel requires more force than this project will need, the mill orientation and setup provides valuable background information.

Classification of roller mills is based on the number of rolls and their arrangement. The most common and simple rolling mill is called a Two High Rolling Mill (Figure 2-6). The Two High Rolling Mill has a configuration of two rollers that feed material in a constant direction. The feed mechanism relies on friction between the fed material and the two rollers to continue drawing the work through. The Continuous Rolling Mill provides a solution to projects that need consecutive rollers when the initial and final states are too large to complete in one pass (Figure 2-7).

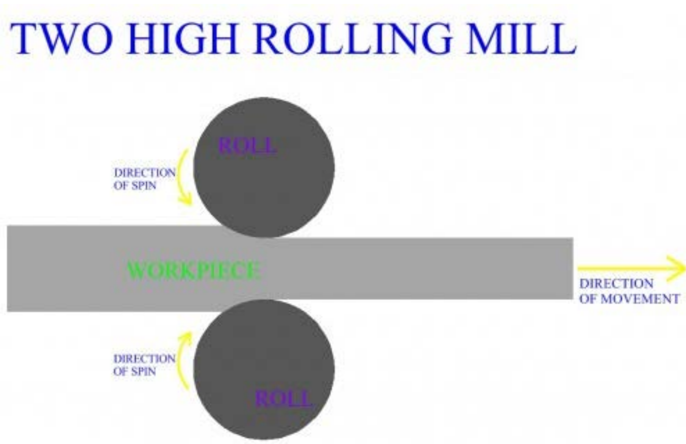


Figure 2.9 *Two High Rolling Mill. This schematic shows the most probable roller mill configuration for the marine test bed. [6]*

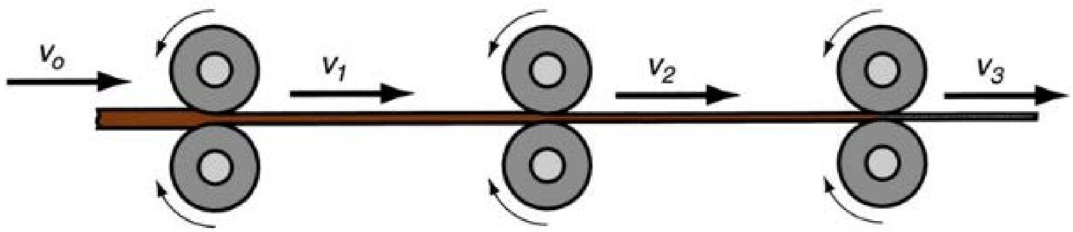


Figure 2.10 *Continuous Rolling Mill sequence to account for multiple pass requirements. [6]*

2.5.2 Clay Slab Roller

The clay slab roller is a device used in ceramics to flatten clay through a roller mechanism (Figure 2.11). The clay thickness is selected and controlled by making height adjustments to the free roller. One roller is fixed while the top roller can be moved in a vertical direction, thus opening or closing the gap between the two rollers. The drive system utilizes friction between the clay and the rollers and is human powered by a hand crank.

Figure 2.11 *Typical clay slab roller for ceramics. Black hand wheels on top allow for control over mill height. [7]*

The ability to adjust the free distance between the two rollers is of specific interest to this project. The marine test bed may be used with different sized benthic organisms which will require different "flattening" tolerances. The two black handed wheels rotate a ball-screw actuator mechanism, translating rotational motion into linear motion. The only problem with this type of system is that it can bind if the actuators are not aligned. A similar system can be created with a bolt and a stationary nut.

2.6 Similar Products

2.6.1 Continuous Plankton Recorder (CPR)

The Continuous Plankton Recorder (Figure 2-9) is an instrument used to survey plankton over large swathes of oceans. The CPR started taking samples in the 1930s and has undergone few changes since its conception. Utilizing a network of volunteer ships to tow the CPR, a quarter million samples over 6.5 million nautical miles have been taken. These samples have provided useful data for monitoring plankton levels across the world for use in research and policymaking. [8]

Figure 2.12 *The current model of the Continuous Plankton Recorder (CPR). The opening allows for a collection cassette to be easily inserted and removed. [8]*

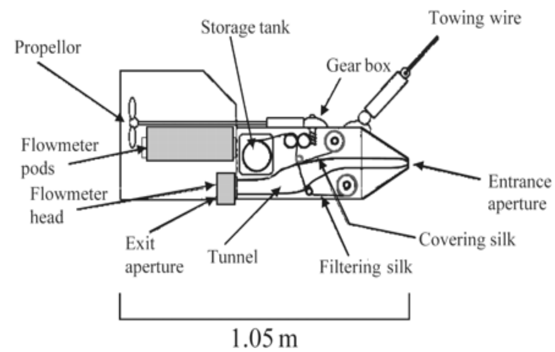


Figure 2.13 *A diagram showing the fundamental aspects of the CPR. Water flows through the aperture and the filtering silk to continuously capture plankton. [9]*

The CPR has a body length of about one meter and weighs about 85 kg (~190 lb). It is towed by boats at depths of 5 – 10 m below the surface by a 10 mm wire rope. Built from nickel-plated marine-grade 316 stainless steel, the CPR is sturdy enough to be towed at 25 knots (~29 mph) and in rough oceans. The CPR brings in water through an aperture with a 1:29 ratio to be filtered by a roll of silk. The water passes through the filtering silk leaving the plankton behind. An impeller on the back of the CPR provides power for the gearing system that moves the silk filter at a rate proportional to the speed of the ship. This proportion allows for biologists to estimate the length of the silk sample to a distance traveled by a ship. As the filtering silk rotates, it is covered by another layer of covering silk to keep the plankton in place. The silk then rotates into a storage tank that has a separate preservative formaldehyde bath to maintain the integrity of the plankton for long trips (Figure 2.10). [8, 9]

The Cassette

The cassette (Figure 2.11 and 2.13), is the most crucial part of the CPR because it serves as the filtration system for the plankton. The cassette has multiple components, including filtering material, covering silk, the gearbox, and the storage tank.

Silk with a leno weave and mesh size of 270 μm is the most commonly used material for filtration in the cassette. Nylon and WP2 netting (with a mesh size of 200 μm) are also utilized in similar machines, but to a lesser extent in the CPR. The silk comes to users pre-marked and numbered every 6 inches with India ink, allowing for easy post-processing cutting. The supply roll is long enough such that it only needs to be replaced every 36 hours. Accounts vary about the ratio of silk versus distance sampled. Ratios range from 4 inches of silk approximating 10 nautical miles of travel to 6 inches of silk representing 2.3 nautical miles of travel. [9,10]

The gear box, powered by the impeller, provides proportional motion for the silk filter compared to the movement of the ship. It functions similarly to how a video cassette tape pulls from tape from supply reel to a take-up reel using an intermediary rotating head. A fusee mechanism with a tightened wire is used to adjust the tension of silk as the diameter of the storage roll increases (Figure 2.12). [11]

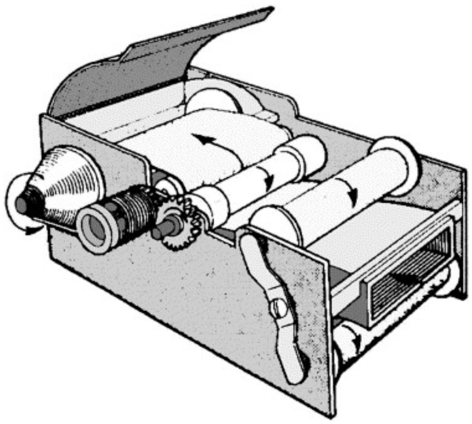


Figure 2.14 *Diagram of the CPR cassette. The inlet of the cassette can be seen on the right while the conical fusee mechanism is on the left. [9]*

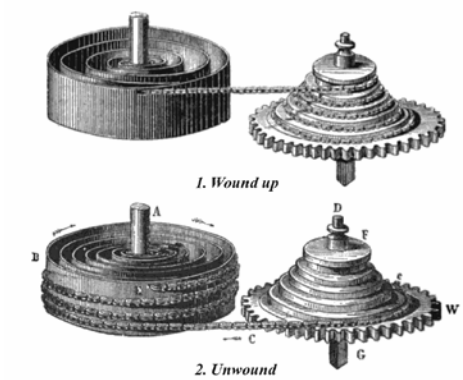


Figure 2.15 *A fusee mechanism in its wound and unwound positions. As the spring weakens as it is unwound, the radius it wraps around increases, maintaining constant torque. [11]*

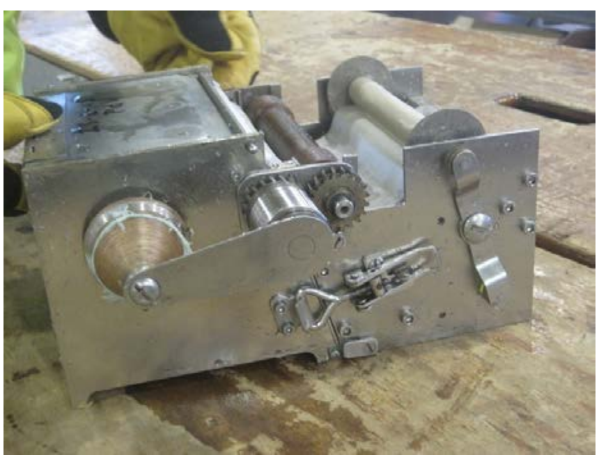


Figure 2.16 *Photo of the CPR cassette. The storage tank is located on the left behind the fusee mechanism. [10]*

Figure 2.17 *A completed roll sample is wrapped up for storage. [10]*

The storage tank is located in the back of the cassette. It is filled with preservatives to keep the plankton intact until they can be brought to the lab. The collection spool can be removed from the cassette so that a new roll can be added. This allows for plankton collection to continue even on long voyages and for completed samples to be easily transported.

CPR Problems and Attachments

The main issue surrounding the CPR today is the reliability and accuracy of the data it produces. A study comparing the CPR to its cousin, the Longhurst-Hardy Plankton Recorder (LHPR), showed that for similar samples taken over the same time period yielded different results. [12] These differences ranged from a factor of 5 up to a factor 40. The study listed a variety of reasons for the different results. It suggested that the silk background from the CPR made it difficult for researchers to identify the different types of plankton, specifically small and clear species. For larger and opaque species, the study proposed that certain zooplankton actively avoided the CPR. It attributed four factors to the avoidance of specific plankton species. The first is the speed of the collection device. The study hypothesized that the faster the device is moving, the more likely it will be to capture the plankton since the plankton will have less time to escape. The speed capabilities of the plankton are therefore the second factor; the faster they are able to move and react the less likely they will be caught. Mouth area of the CPR was listed as the third factor. A larger mouth head gives a larger area to catch the plankton. Finally, the flow dynamics of the CPR could create a forward “bow wave” that plankton could sense and know to avoid. Since the flow dynamics of the CPR have not been tested, this is a viable option.

Another problem the CPR faces is regulating the flow into the filter. A study conducted in 2006 looked at the volume filtered by the CPR compared to the amount of volume it should cover during a trip. The study recorded up to a 30% reduction in volume filtered due to the speed of the ship towing the CPR and up to 60% reductions in volume filtered due to plankton clogging the filter. A combination of ship speed and clogging resulted in a maximum of 78% reduction of the filtered volume. The overall study indicated that there was a need for an improved flow meter to improve the resolution of the CPR data. [13]

New technology has been added to the CPR to increase its accuracy and to obtain additional information. The “Aquapack” and “Minipack” electronic sampling packages measure temperature, conductivity, depth, chlorophyll levels, pitch, roll, and vibrations in the CPR. Its built in clock also helps double check captains’ handwritten time logs for when and where samples were taken. [13]

2.6.2 MBARI Benthic Rover

The Monterey Bay Aquarium Research Institute (MBARI) has developed a benthic rover that moves across the seafloor, taking photographs and measurements of the animals and sediment it passes by. Project engineer Alana Sherman and marine biologist Ken Smith worked with a team of engineers to create such a rover and began testing in 2006, shown in Figure 2.15.

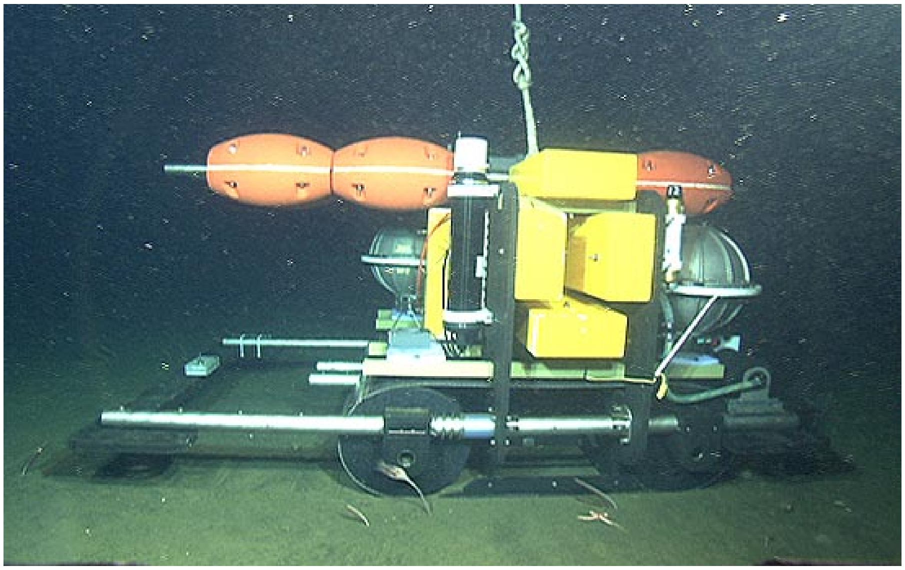


Figure 2.18 *The MBARI Benthic Rover in operation during a test 890 meters below the surface in 2006 [14].*

The MBARI benthic rover operates in the dark depths of the bathyal zone and has a maximum depth of 6,000 m. The seafloor is filled with dead organic matter that benthic creatures thrive on. The rover acts as a mobile physiology lab and is designed to gain information on the supply and demand for carbon to better map out the carbon cycle on the ocean floor.

To do this, it measures the oxygen levels on the benthos by lowering 30 cm wide chambers into the sediment and inserting oxygen probes. These chambers isolate the sediment samples for up to three days and agitates it to collect accurate readings. The consumption of oxygen allows scientists to calculate the demand for carbon on the benthos. It uses fluorescent scanners to measure the supply of carbon by detecting "still-active chlorophyll" in plant cells. When plant cells this deep have still-active chlorophyll it indicates that they were recently in a sunlit region. Acoustic scanners search for worms and other organisms using ultrasound 4-MHz pulses [14].

Each test that the MBARI performs takes up to three days in the same location. It then measures the direction of the current using onboard current meters, and moves 5m in that direction. It stays in operation underwater for up to one year and is built entirely from titanium and plastic. In addition to carbon cycle measurements, the MBARI also collects high-resolution images for animal identification.

As a deep water rover, the MBARI helps scientists understand carbon cycling in the ocean. This cycle is fundamental to understanding how benthic animals survive at such dark depths on the seafloor.

2.7 Technical Challenges

2.7.1 Sea Water Submersion

The project presents several design challenges because the system will be submerged in seawater. This limits materials and components the system can use, specifically regarding bearings or bushings and metals.

Bearing selection can be a design challenge in a saltwater environment. Plain bearings as single parts were examined for their use in low speed, light to moderate load applications. Graphite plain bearings are commonly used; however, their wear resistance over time is not as reliable as heavy-duty polymer materials [15]. Nylon and Acetal bushings work well for light loaded applications; however, they wear out quickly when gritty particles are introduced. In addition, nylon absorbs water and swells in size. Polymeric alloys such as Polyphenylene Sulfide and PTFE (Teflon) have increased wear resistance and a longer lifespan than Nylon and Acetal. Some PTFE formulations also include small inclusions of lubricants suitable for marine environments so that wear and lubricating surface exposed help in the metal-polymeter contact zone.

Ball bearings are generally not often used in seawater applications since they corrode easily or leak lubricant. However, there are plastic ball bearing assemblies that can work very well when immersed in seawater. These ball bearings have bearing ring and cage made from Acetal Polymer with stainless steel balls inside. Since they are made out of plastic and stainless steel they are resistant to corrosion and do not require lubricants to operate. [16].

Typical metals such as carbon-steel and aluminum are unusable in this system due to corrosion. As such, other materials or metals will have to be found. The CPR is built from marine-grade 316 stainless steel that is nickel-plated to further prevent corrosion and wear. The MBARI was constructed entirely out of plastics and titanium to combat corrosion during its long voyages. Both systems utilize expensive materials to combat the challenge of corrosion. 304 stainless steel is less expensive than 316 and may be a suitable alternative for test bed purposes.

2.7.2 Belt Material Selection

One of the essential design requirements for the test bed is to find an appropriate type of material for the belt system. A bottom belt should be transparent for inspection through a microscope and camera while the top belt can be translucent or opaque (with suitable adjustments for the imaging system). The top belt should remain porous enough to allow water to pass through and rough enough to "catch" the neutrally buoyant hydrophobic animals. Both belts must be able to withstand submersion in seawater and a 5% ethanol solution. Top belt material candidates are as follows.

Egyptian cotton bedsheet material is a possibility due to its woven fabric and high-thread count. The type of weave can provide a surface with enough texture for benthic animals to attach to. In comparison with other fabrics, Egyptian cotton will not stretch under tension which is preferable.

A continuous roll towel is an appealing option because it is a durable cloth towel that comes pre-rolled up to 40 meters (Figures 2.16 and 2.17). This product is normally sold as an alternative to the common paper towel dispenser. It is manufactured from 70% cotton and 30% polyester, which will require testing to obtain tensile strength and stretch values. Nature’s Linen currently has a patent pending on their continuous roll towel and has accepted the team’s request for a sample of their product. This type of linen is high quality that is reinforced with “scrim”, which is a very light textile that is commonly used as a reinforcement in glass or carbon fiber composites [17].

Figure 2.19 *Continuous cloth roll towel in pre-rolled package. [17]*

Figure 2.20 *Continuous Roll Towel Dispenser. [17]*

Medical woven rayon acetate tape is another possibility due to its woven construction and pre-rolled product. The tape could perform well at "catching" the benthic animals in the capture area due to its adhesive quality. It is strong and does not stretch. In addition, it comes in an opaque-white color which is a perfect backing for viewing the collected animals. Although these types of tapes are considered "breathable", testing would be needed to analyze their permeability to water [18].

Another possibility is filtering silk. This type of material was used in the CPR and previously discussed. The key factor is that it is permeable and does not stretch. The silk comes pre-marked and numbered every 6 inches. In addition, silk has a very high tensile strength of 1000 MPa, which is highly desirable.

Lastly, Hydroknit cloth is a very durable, highly absorbent material that is made by bonding soft pulp fibers into a strong polypropylene base. The key properties include wet strength, cloth-like appearance, tear-resistance, and absorption. There are several Hydroknit products that have detailed data sheets that include tensile strength and water capacity values. However, this material is too soft and "squishy" and benthic animals might get lost in the material [19].

2.7.3 Rock and Shell Inclusions

Since some small rocks and shells may pass through the crushing system, they have the potential to cause damage. A rock or shell could get caught in the crushing mechanism, potentially either causing the mechanism to jam or blocking the entrance to the mechanism. Materials and material handling systems must be chosen which minimize sample damage when inclusions are present.

2.7.4 Supply Reel Tension System

One concern in regarding the supply reels is the possibility of them unwinding on their own. Several scenarios describing this situation are as follows. If the collection system is stationary (i.e. not being driven) and the belts are connected from both supply spools to the collection spool, there is a chance that the spools can unwind accidentally. This could happen due to buoyancy effects of the belt material floating upwards, or an upwards force of liquid and macrofauna being inputted to the system via bilge pump. Another situation of accidental unwinding could be when the driven collection spool stops and the supply spool's rotational inertia cause them to keep spinning, and thus unwind.

To avoid accidental unwinding, the team looked into the mechanical components that allow for drag in a fishing reel. The drag acts as a slip-clutch system and operates by the friction induced by two discs pressed against each other. One disk is attached to the end of the spool while the other disk is adjustable. The tighter the two disks are pressed together, the higher the friction and thus higher resistance to rotation (Figure 2.18). When the load exceeds the set torque, the friction discs will experience a controlled slip and allow for unspooling only when desired.

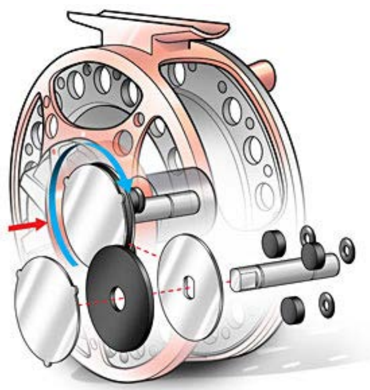


Figure 2.21 *Fishing reel slip-clutch drag system.*

These friction discs are often made from Rulon which is part of the PTFE plastics family. This type of material would perform well in a seawater environment acting as a drag washer. If implemented, this drag system would be placed into the removable spool.

Another method of inducing frictional drag is to apply a controlled pressure onto the spool axle with a material such as rubber or cork. A solid piece of rubber or cork can be pressed against the axle to increase its resistance to rotation (Figure 2.19). If a setscrew is used, the pressure can be adjusted until a desired resistance is reached.

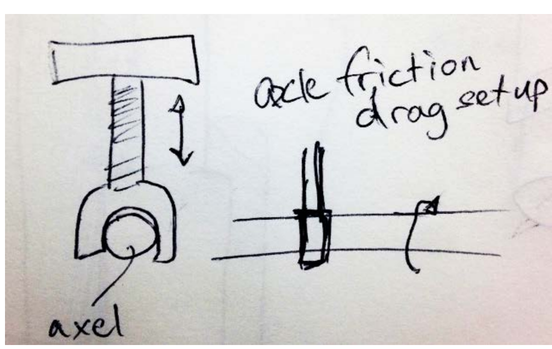


Figure 2.22 *Drag can be introduced into the supply spool by applying pressure directly to the axle with a material such as rubber or cork.*

The prony belt works similarly (Figure 2.20). Instead of using a solid material that presses directly onto the axle, a prony belt uses a tensioned belt which also induces friction and thus resistance to rotation. The tension of the belt can be adjusted at its mounting surface to apply a desired amount of friction. A prony belt would be easier to implement into the frame of the test bed than mounting the direct friction drag. However, the belt may wander on the axle and experience higher wear; this would require more frequent maintenance and replacements than the direct friction drag.

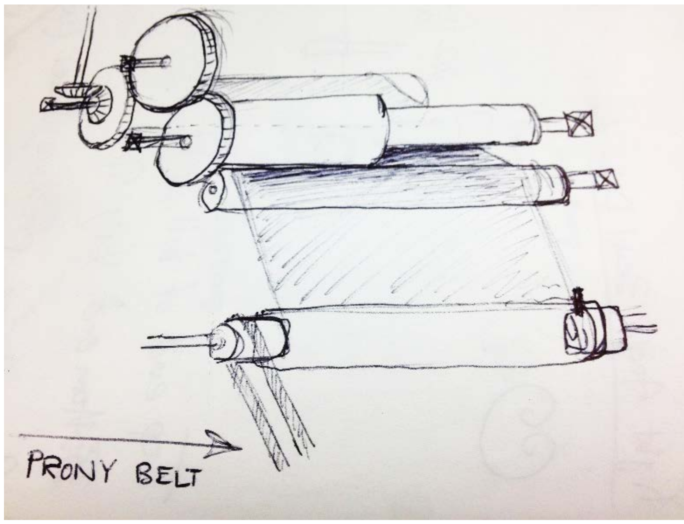


Figure 2.23 *A prony belt can induce friction on the axle and give tension to the supply spool.*

3. Objectives

3.1 Problem Statement

Coastal environments are evaluated by benthic studies of small organisms living in the sediment. Current methods for this research require timely manual labor and provide limited discrete data. A "coastal benthic rover" could automate this process and provide more continuous data about the macrofauna. Such a rover would require a system that could capture the organisms and prepare them for further analysis.

3.2 Scope

The team have been presented with a time intensive project and need to propose a scope that is manageable for two members. This scope was created by assessing customer requirements from Brian Paavo and thorough background research.

The team will build a "proof of concept" test bed to prove that such a system can be designed and built. The team's scope is limited to a prototype of the system that could be implemented into a future "benthic rover." The prototype will be human-powered and tested, submerged in a tank that can hold at least 150 liters. Uniformly ground or diced shrimp particles will be used as an analogue for marine macrofauna for testing the collection mechanism. The prototype will be evaluated based on its ability to collect and flatten the shrimp bit analogues. If the prototype is successful, rocks and shells may be introduced to test how the system interacts with these disturbances. If time permits, the team will also determine at what speeds the prototype operates efficiently for varying volumetric flowrates of shrimp bits.

The team determined that aspects beyond the collection and crushing mechanism are beyond the scope of the project. Instead, they will focus on the mechanical system described above. As such, applying a motor to the system is out of scope, but could be easily implemented if the human powered system works. Likewise, implementing a system that measures the area of the crushed bits is out of scope since it is not a critical requirement. The proposed identification mechanism including a camera positioned at the output of the mill requires more time than the team has available. A timing element is also out of scope since it can be implemented in multiple ways without having to integrate the collection system. By focusing on the collection system, the team hopes to develop a reliable baseline for future upgrades to later be added. A summary of the project scope can be found in Table 3.1.

Table 3.1 *Summary of Benthic Rover scope and goals.*

In Scope	*Reach Goal*/Out of Scope
Capture & crush macrofauna analogue floated into a belt path by air and/or water	*Operate with rocks and shells*
Continuous operation	Motor driven system
Collect on removable spool	Dye injection
Uncrushed animals identifiable	Time stamp

3.3 Engineering Specifications

Based on background research, customer requirements, and the project scope, the team has set engineering specifications that the final system will be evaluated against. A summary of the specifications can be found in Table 3.2.

The team determined that the system should collect at least 90% of the analogue that enter. The team believes this to be a reasonable target for the prototype since they will be able to manually change the speed of the belt and the flow rate entering the system. Capturing 100% of the bits is unlikely, so a standard of 90% collection rate will help evaluate what speeds the system needs to run at for different flowrates. Based on the CPR cassette, finding the correct speed for the appropriate flowrate holds high inherent risk. If the collection mechanism is unable to capture a significant number of shrimp bits, the entire system will consequently fail.

The system also must separate the bits into two separate treatments. Half of the "animals" should be crushed to within 0.25 mm (0.01 in). Since system will encounter animals with diameters of 0.25 – 2 mm, the system must be able to flatten the larger animals to create a roughly uniform "squished" thickness of 0.25 mm. The necessary tolerance of the resulting thickness will have to be determined at a later time in conjunction with an automated camera system that will measure the crushed area. From a statistics standpoint, the team will aim for an average tolerance of ± 10%. The pressure needed to crush the "animals" will also have to be determined during testing. If the crushing mechanism will be developed to crush rocks and shells, a new minimum pressure will be needed. The tight tolerances and potentially high pressures needed to pulverize rocks and shells make the crushing mechanism a high-risk parameter. This risk is further complicated by belt characteristics such as thickness variability.

The other treatment must allow for the animals to remain recognizable after collection and storage so that specialists can categorize them. For the prototype, this means that the shrimp bits should come out of the collection system unscathed without large tears, gouges or in multiple pieces as an evaluation tool. This should not prove difficult as this half of animals should simply be collected and stored immediately.

The lifespan of the belt material should be 1 year or more in a preservative bath. This allows for the collected organisms to be analyzed at a later time. The team anticipates that the belt materials will easily be able to meet this parameter. The team also anticipates low tension in the collection mechanism will keep the risk of the belt tearing low.

The lifespan of the drive train should last 5 years. How much use the "benthic rover" will see on a yearly basis is unknown as of now. Depending on how heavily the "Benthic Rover" is used and how well it is maintained, the team finds that the lifespan of the drivetrain is a medium risk.

The entire system should fit into a 150-liter (~0.1 m^3) tank. The exact dimensions of the geometric constraints will be determined in the marine biology lab. The final system should easily fit into the tank, but difficulties may arise with moving the system in and out of the tank. Likewise, the drive system must protrude from the tank so that a person can easily power it. The advantage of this constraint is that it will provide a smaller package to place in the final "Benthic Rover." These are both medium risks that can be worked around with an adequate design.

Replaceable spools are crucial since it allows for rolls to be removed for research and new rolls to be added for additional data collection. The spool should intuitively fit in the system. The team would like for a trained user to be able to remove and replace the spools in about five minutes. Depending on the locking mechanism and how the spools connect to the drive train, this mechanism can prove to be a challenge. Adequate design should reduce risk, but potentially fragile or worn components make the replaceable spools a medium risk.

Since the system will be human-powered, the torque required to run the system must not be greater than what an average person can output without straining himself or herself. A NASA study of human performance characteristics found that a typical person can output a maximum of 17 Nm of torque. [20] The team does not want users of the device to reach their maximum output since smooth continuous motion is desired. The team also wants users to be able to move the system at different speeds for different entrance flowrates. As such, the team is specifying the maximum torque input to be 5 Nm. The team believes this to be a low risk since the forces required for the system should be low.

The maximum production cost of the system will be determined by the amount of funding received. The team has access to $1,000 from the project sponsor and is looking for additional sources of funding. Regardless of how much funding there is available, the team will work to find cost-effective solutions to the problem that will meet the requirements above.

Table 3.2 *Design specifications; italicized requirements classify reach goals.*

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk*	Compliance**
1	Collect Shrimp Bits	90% @ TBD Flowrate	Min	H	T
2	Separate Collection	2 Groups	-	L	I
3	Crushed Half Thickness	0.25mm	± 10%	M	T
4	Crushing Pressure	TBD	TBD	H	A, T
5	Belt Lifespan	1 Year	Min	L	A
6	Drive System Lifespan	5 years	Min	M	A
7	Drive System Torque	5 Nm	Max	L	A, I
8	Replaceable Spools	5 minutes	Max	H	T
9	Production Cost	$1,000	Max	L	A
10	System Volume	0.1 m^3	Max	M	I
11	Belt Tensile Strength	TBD: Cannot stretch or tear under loading	Min	L	A, I, T
12	Undamaged Specimen	Identifiable under microscope	-	L	T
13	*Rock and Shell Failure*	<10mm D	-	H	T

* High (H), Medium (M), Low (L)
** Inspection (I), Analysis (A), Test (T), Similarity to Existing Designs (S)

The team developed a House of Quality (QFD - see Appendix A) to ensure that the specifications appropriately meet Dr. Paavo's requirements. The QFD revealed that the specifications are relatively evenly distributed in weight. No single specification stood out as drastically more important or critical than the rest. Since most of the specifications heavily correspond with each other, it is difficult to increase the importance of one without increasing the others as well.

A comparison of potential competitors revealed that current products do not meet all of the project sponsor's needs. The Continuous Plankton Recorder is a good model to base the team's system off of. Able to collect plankton across the globe for over 80 years, the CPR is a robust and reliable continuous collection instrument. However, it suffers from accuracy issues from reduced flowrates and plankton avoidance due to how it is towed. The CPR does not have a crushing mechanism nor has to handle distinct amounts of rocks and shells either as only soft-particulates remain suspended in the waters sampled. The MBARI Benthic Rover proves to be a system that can collect measurements of the benthos, but its capabilities and research goals do not match this project's requirements. The MBARI rover's main purpose is to gather data on benthic animal's oxygen usage in order to map the deep ocean carbon cycle. However, it is a durable and robust machine that can handle full submersion in seawater at least one year and can navigate unknown benthic environments. The rover provides valuable information on material selection, machine design, and autonomous pathing.

4. Design Development

The next step in the design process was ideation. The team practiced a brainstorming technique called "Brainsketching." This process involved silently writing and drawing ideas for five minutes then sharing them with each other. Ideas were primarily conceptual and built upon each other. Judgement on ideas was postponed and there was an emphasis on producing as many ideas as possible. The team conducted several brainstorming sessions since there were multiple subsystems to design. Rough prototypes of ideas were built to better visualize and explain ideas.

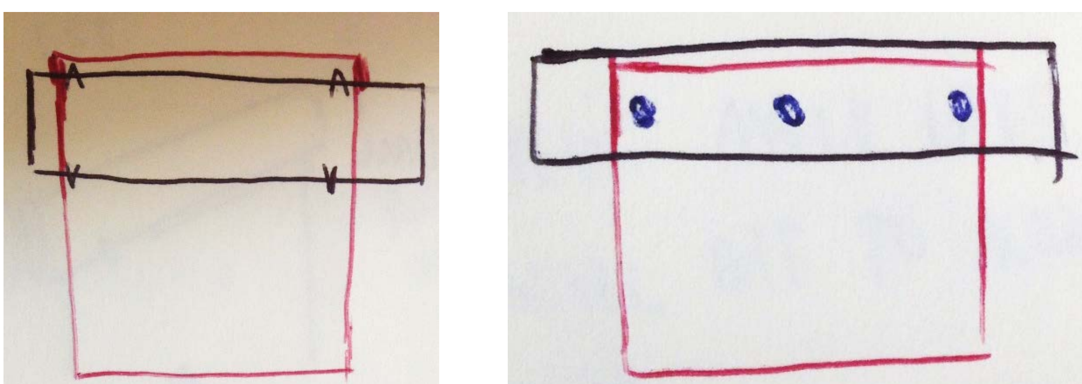
4.1 Replaceable Collection and Supply Spools

Both the collection and supply spools must be easily replaceable to allow for the collection system to run multiple times. The collection spool specifically presents a challenge since it must be well-attached to the drive system during operation. The team focused on two elements for the spools: how the belt will be attached and removed from the spools and how the spools will connect to the drive system.

4.1.1 Belt-Spool Attachment

The spools can have disposable and reusable configurations for attaching the belt to the spool. Reusable spools would directly attach to the drive system while disposable spools would rest on a permanent core that connects to the drive system. Disposable spools would be removed and stored with the belts.

Disposable spools are more versatile in attaching to the system. Since the belts are removed with the spool, both permanent and nonpermanent methods of attachment can be used. Adhesives or miniature spikes can be used to directly attach the belts to the spools (Figure 4.1). A key advantage of these methods is that the belt can be easily wound and stored on the spool for post-processing. Spikes on the spools would firmly attach the belts to the spool. However, this might cause uneven bumps to develop throughout the roll. The spikes also present a safety hazard to users depending on how sharp they are.



(a) ***(b)***

Figure 4.1 ***(a)*** *A simple sketch showing how the spikes can be oriented to attach the belt to the spool.* ***(b)*** *The blue dots indicated spots of adhesive to apply the belt to the spool.*

Reusable spools require that the collected belt material slides off of it so they can be reused. This constrains configuration to nonpermanent methods of attachment to the core. One nonpermanent method is to use open seam round tubing for the spool (Figure 4.2). The user can insert the belt into the seam which will be secured by friction on subsequent layers after the first initial wrap. Once the collection is complete, the belts can slide off the spool. For this to be possible, the belts must not be wrapped too tight on the spool that they cannot slide off.

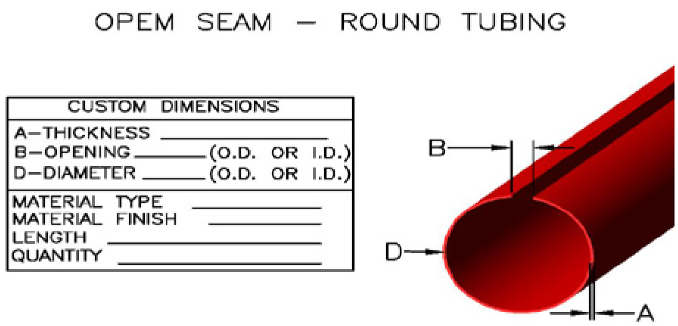


Figure 4.2 *CAD drawing of open seam round tubing. The belts can be slid into the opening and wrapped around the tube to attach them to the spool.*

Another way to attach the belt material to the spools on both the collection and supply side would be to include a metal band bent in the shape of a wide, upside down *u* (Figure 4.3). This band would clasp down on the belt and hold it in place. The user could pre-roll the supply spools and use this band to start the process. Once placed in the test bed, the supply spools could be manually unrolled, pulled through the mill, and clasped under the collection spool's band. Once this is set-up the test bed would be ready to collect animals. A downside to this design is that the belt would not be able to slide off the spool for post processing. It will need to be unwound and unclasped in order to be fully removed. This makes this design non-reusable for the collection spool but a great candidate for the supply spools if the open seam extrusion does not work properly.

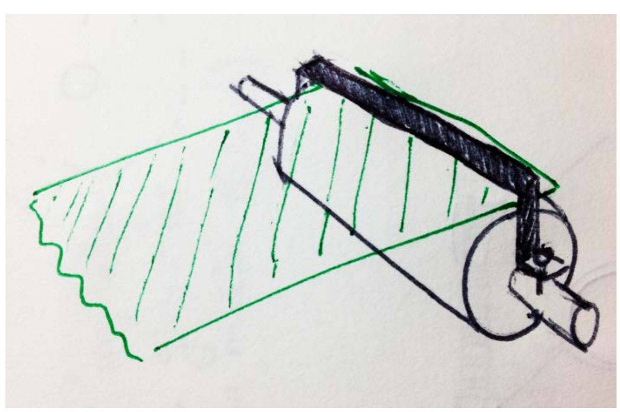


Figure 4.3 *Retention Clip for attaching material to spool.*

4.1.2 Spool-Core Attachment

The spools require attachment to the drive by means of an inner, permanent core. Several ideas of how to attach and remove the collection spool to the core and drive are shown in Figure 4.3. These ideas focus on various ways of connecting the collection spool in a way that is both secure and easily replaceable.

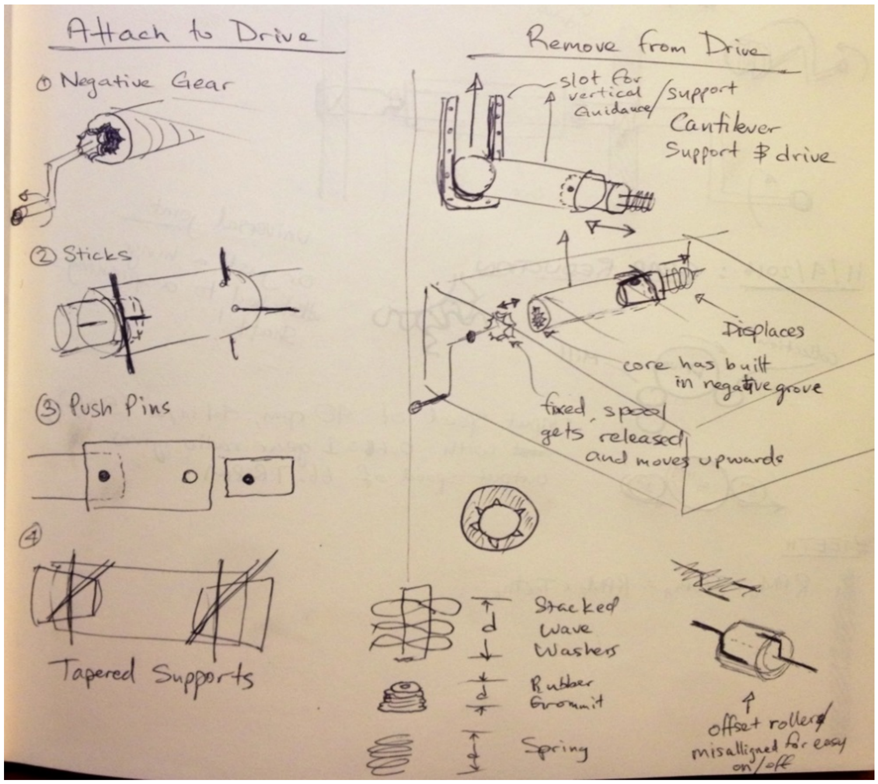
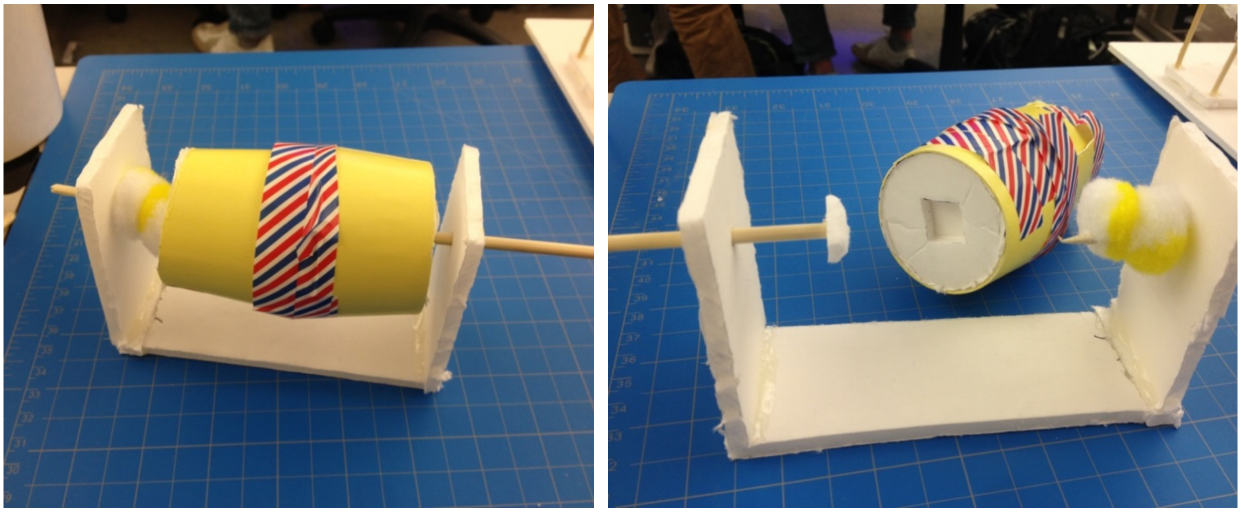


Figure 4.4 *Ideation sketches detailing ways to attach and remove the collection spool to the drive mechanism. Also included are methods of securing the spool to the permanent core.*

The first sketch on the top left details a "negative gear," or an internal key (Figure 4.3). The spool has a negative recess of a key shape which connects to the positive key of the drive. A spring-loaded support could be placed on the opposite side of the key to keep the spool balanced. If a force is applied to the spring-loaded support, the spool could be pulled off of the key and out of the system. The shape of the key shown in the prototype (Figure 4.4) can be analyzed for efficiency, manufacturability, and ease of connection if selected.



(a) **(b)**

Figure 4.5 ***(a)*** *Negative gear design for connecting the drive system to the collection spool.* ***(b)*** *A close-up of the negative gear design. Shape of gear is arbitrary and is a generic concept.*

The spools can also attach to the core with snap locking tube pins as shown in the third sketch in Figure 4.3. These types of tube pins are used on kayak or stand-up paddle board paddles and allow for quick length adjustments for telescoping tubes. Their main function is to lock movement when activated and unlock when released. Another "stick" idea utilizes clevis pins or cotter pins, to allow for quick installation and removal (Figure 4.5). However, there are several problems that arise when using cotter pins. The pins can be easily lost or misplaced during operation. Also, lining up the holes of the core and the spool may add unnecessary work and time to replacing the spools. Lastly, the holes may wear over time depending on spool and core material chosen.

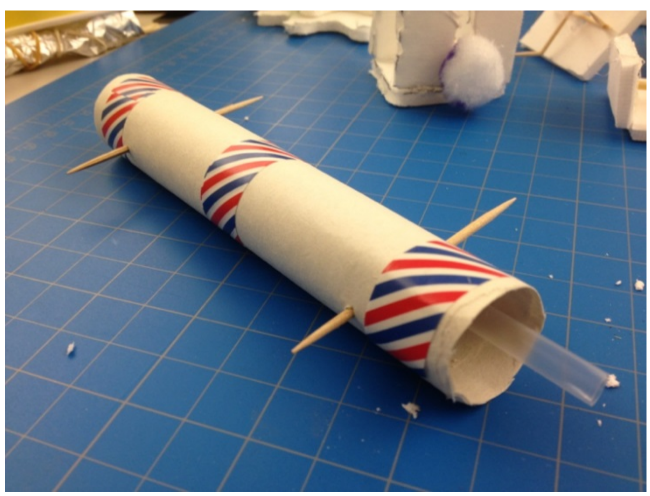


Figure 4.6 *Holes can be drilled and aligned with the core and disposable spools to accommodate cotter pins to lock for rotation.*

The fourth sketch in Figure 4.3 portrays tapered supports for a split core. This configuration would utilize the friction between the permanent core and the disposable spool to rotate together. The two sides of the core need to be supported by a displaceable structure (e.g. wave washers, springs, or rubber grommets) in order to allow for removing the spool after use (Figure 4.6). While this design would be simple, cheap, and safe to use, it unfortunately would experience slipping and would be unreliable.

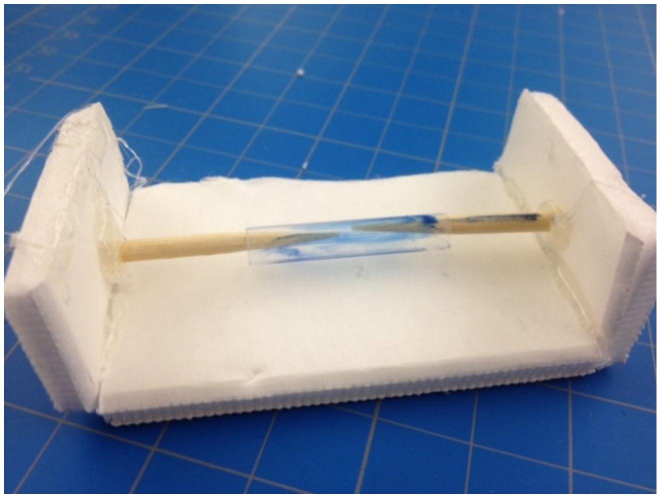


Figure 4.7 *Physical model of tapered supports (springs not shown).*

A design sketch of a pivoting spool is shown in Figure 4.7. By maintaining a fixed drive system and core, the possibility of components breaking or ceasing to work should be reduced. This added level of stability is a strength to the design. The core itself will rotate 90° by means of a universal joint or a simple hinge connected to a shaft. As seen in the top right of Figure 4.7, the spool will be able to slide off the core and be easily replaced. When the core is set back down, it reconnects to the drive system by a keyway or notch. The spool can be secured to the core by one of the ideas previously discussed (e.g. clevis pin or tube pin).

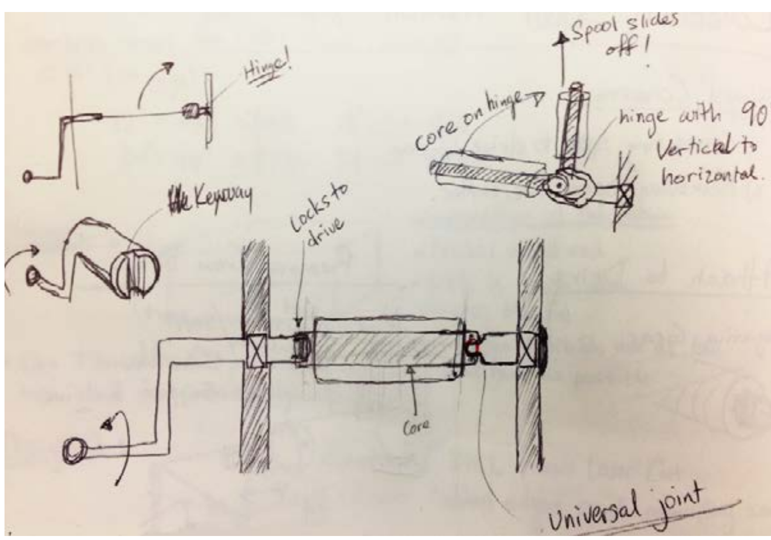


Figure 4.8 *Fixed drive system and permanent core give stability to the system. Permanent core rotates 90° and allows for easy removal and replacement of collection spool.*

Both spring-loaded core and key/slot connection ideas can be combined to create a very functional design (Figure 4.8). This method maintains permanent cores that the spool can easily be connected to and locked for rotation. It is both easy to use and takes away the possibility of losing cotter pins. The locking mechanism was deemed reliable and thought to simplify the number of components needed. This idea was implemented into the preliminary test bed design (Section 6.3).

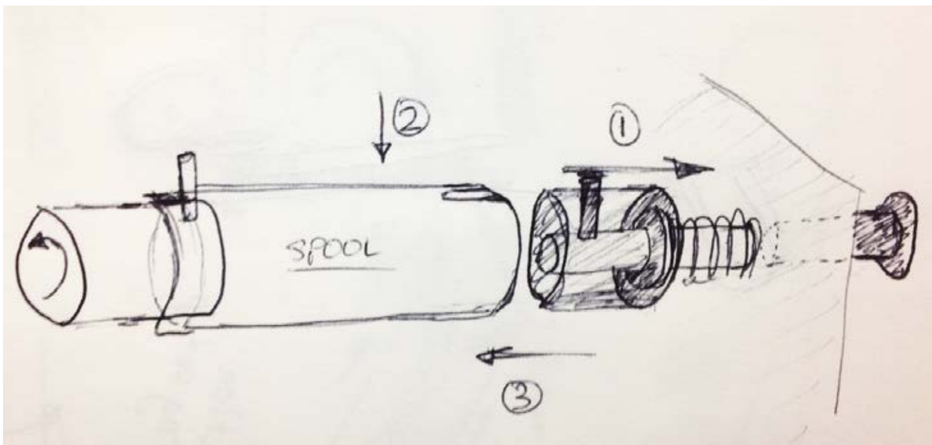


Figure 4.9 *Spring loaded core with key and slot to attach to the spool.*

The team later realized that the design shown in Figure 4-8 had a major fault in that stainless steel springs do not perform well in sea water for long periods of time. The team therefore looked at other spring-like components, but found that the deformation needed to attach and release the spools would too large to fit in the specified volume. The team therefore proposed a flexible clamping mechanism that allows for both the rotation of the spool and induced friction for a tensioning system (Figure 4-8). The supports shown would be flexible by design to "pop" the spool into place, and then lock it with the shown bolt to allow for easier replacement of the spools. The bolt would allow for the belts to be tensioned by squeezing and applying friction to the shaft of the spools. This idea was further developed for the Mark I test bed.

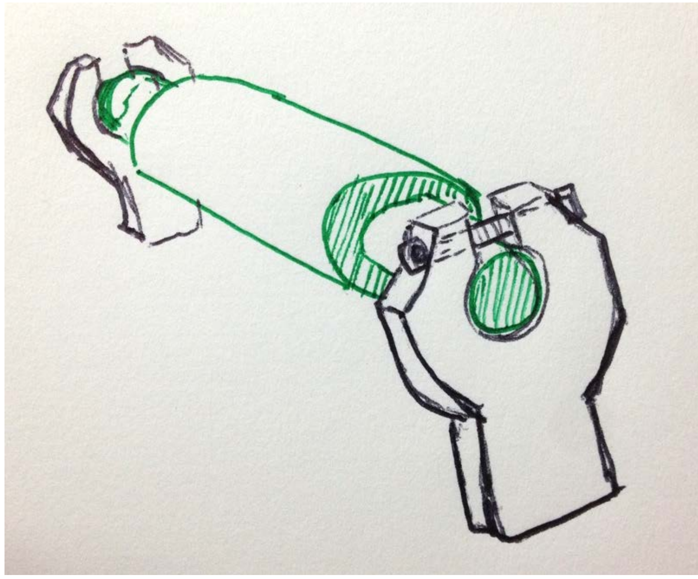


Figure 4.10 *An alternative design to the permanent core is shown. A quick-release mechanism with adjustable torque. The two supports are mounted into the frame (not shown).*

4.2 Crushing Function

4.2.1 Preliminary Ideation

Sketches of the first crushing mechanism ideas can be found in this section. These ideas range from general mill and stamping processes that would be directly implemented in the test bed to simple post-processing methods that would be quickly done after the sampling.

Parallel rolling mills (Figure 4.9) have the advantage of easily fitting in to the continuity of the test bed. They constantly roll and continuously crush objects as the belt moves through them. The mills can output a precise, consistent thickness of most animals that pass through. An inclusion of a spring on one of the parallel rolling mills could allow for rocks and shells to pass through to prevent jamming. However, for those brief moments that the mill is raised to allow the rock inclusions through, the animals next to them would not be crushed.

Fixed mill plates (Figure 4-9) could also provide continuous crushing by squeezing the animals into a small gap. However, the team was unable to find a way to prevent rock inclusions from jamming this sort of mechanism. Plates do have the advantage of easy assembly since no bearings or bushings are required.

The angled rolling mill (Figure 4.10(a) and Figure 4.11) has similar advantages of continuous crushing but takes a different approach for compensating for rock inclusions. Using multiple rollers on the bottom belt with an angled upper mill can push unwanted inclusions off of the belt. Small grooves, similar to those on a drill bit, could catch or push inclusions off as well. However, the grooves would leave gaps of uncrushed organism. A second, uniform roller behind the drill bit roller would ensure that a uniform layer of crushed organisms is left behind. The angled rolling mill requires more fabrication and design due to the complications of mounting an angled roller and having more than two rollers.

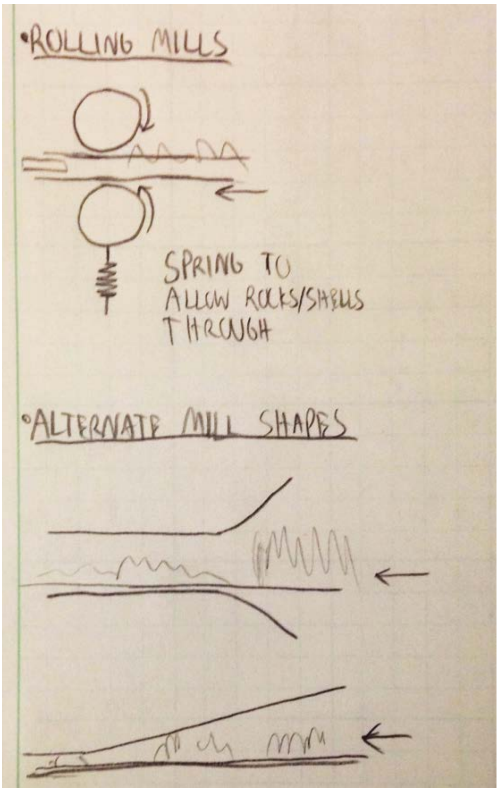
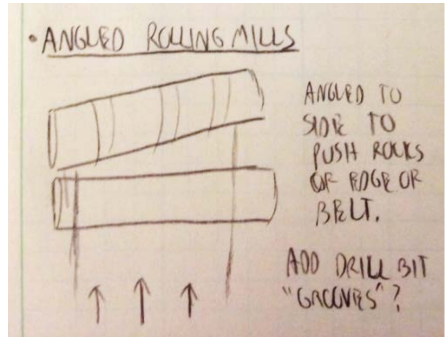
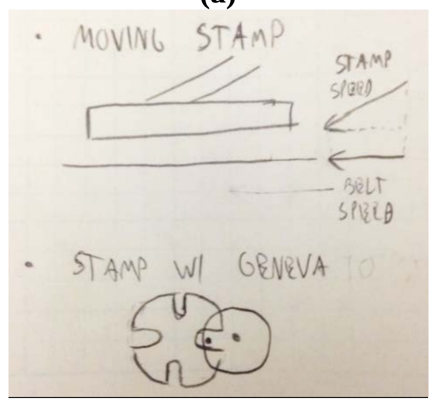


Figure 4.11 *Sketches of two kinds of mills. The top is a rolling mill resting on a spring, the bottom is two fixed plates at different angles.*



(a)



(b)

Figure 4.12 ***(a)*** *The front half of the angled rolling mill. This half separates rocks and shells before the animals are crushed.* ***(b)*** *Models of both stamps. The moving stamp has the same horizontal velocity as the belt when it moves down.*

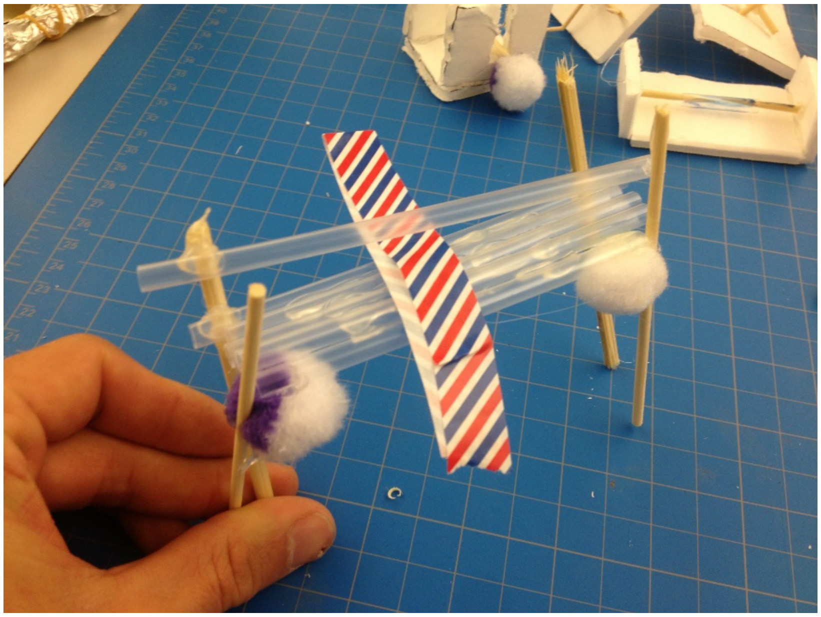
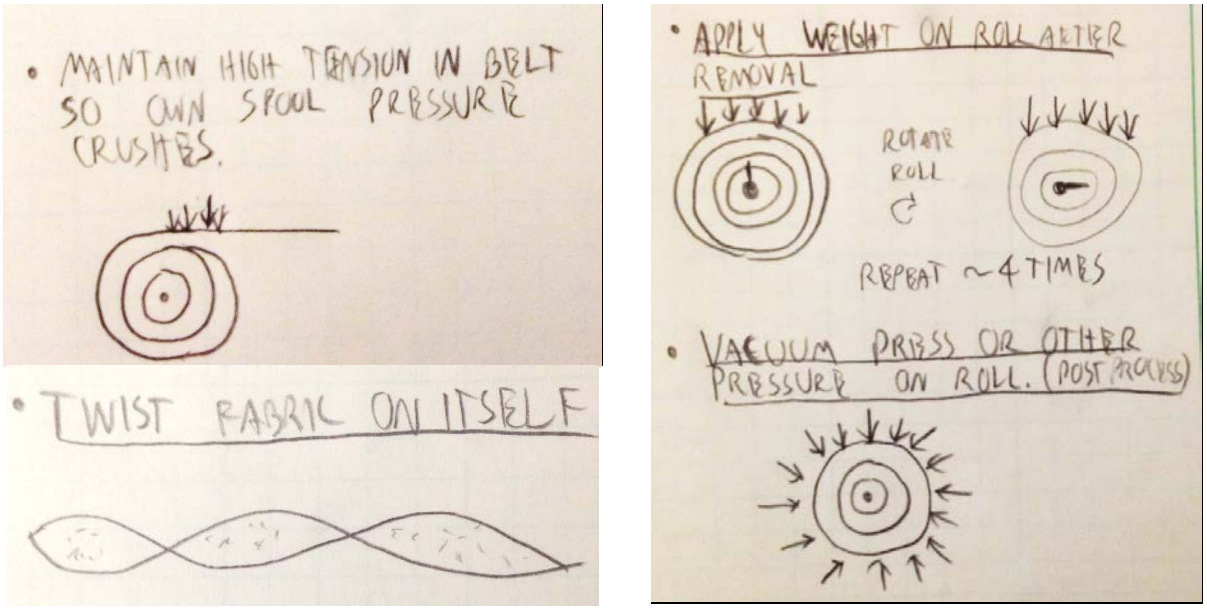


Figure 4.13 *Physical model of the first half of the angled rolling mill.*

A stamping method was discussed in two iterations. The first iteration requires a timing mechanism (such as a Geneva mechanism, Figure 4.10(b)) to stop the belt and bring in a stamp to crush the animals. However, stopping the belt is highly problematic since it would require the inlet flow to stop as well to maintain the accuracy of the sampling. The second iteration for the stamp solves this issue by moving the stamp horizontally at the same speed of the belt as it moves down to crush the organisms (Figure 4.10(b)). This removes the limitation of having to stop the belt and allows for the test bed to run continuously. Although it is out of scope, a timing mechanism such as a needle or dye droplet could be implemented into this stamp variation. The stamp would require a large enough base so that it would not miss any organisms as it rotates. It also must have a soft surface to account for rock inclusions.

Depending on the toughness of the macrofauna, the team speculated that it could be possible to crush the animals using the tension in the belt. One method is to twist the belt on itself in a tight enough manner that the animals are squished (Figure 4.12(a)). The difficulty with this method is implementing it with the final continuous collection. The belt would have to be tightly twisted and then unwound for collection in a small space to accomplish this. Another method is to pull on the belts with enough tension that the animals are crushed in the collection spool. The necessary tension to crush the animals throughout the spool is unknown at this time, the uniformity of the pressure will vary and need to be tested for this to be a viable concept.



(a) **(b)**

Figure 4.14 ***(a)*** *Sketch of how the animals could be crushed using tension in the belts.* ***(b)*** *Post-processing methods such as applying weights onto the belts or pulling a vacuum on them could crush the animals.*

The team also considered crushing the animals in the collection spools after the collection process is completed. Depending on the width of the collection spool, a fitted weight could be placed on the collection spool (removed from the test bed) to apply pressure on the roll. By rotating the collection spool and placing the weight on it a few times, a uniform pressure could be applied on the roll to crush the animals (Figure 4.12(b)). A quicker and more uniform method of applying pressure would be using vacuum compression. This method could provide up to atmospheric pressure (14.7 psi or 101kPa) around the spool under ideal circumstances. A bladder mold could provide higher pressures if necessary but is a costlier and more time-consuming solution. These post-process designs are limited by the thickness of the belt material and how many layers of material are on the collection spool. The thicker the material and the more layers the spool has, the more pressure that will be required to crush the organisms. The organisms might not be uniformly crushed as well if there are pressure gradients throughout the spool. Basic testing of the post-processing will have to be done to see if these methods are viable.

4.2.2 "Soft" Mills

An idea with potential, the team looked to expand on the "spring" rolling mills idea. The previous idea made use of a spring to let unbreakable objects pass through the mills without jamming them. However, using springs (steel or plastic) on the mills did not seem to be a sufficient solution to the problem. Attaching springs to the mills seemed unrefined considering that when the mill raises to let a rock through, it no longer crushes any animal adjacent to the rock (See Figure 4.15). The following "soft" mill ideas looked to address these problems.

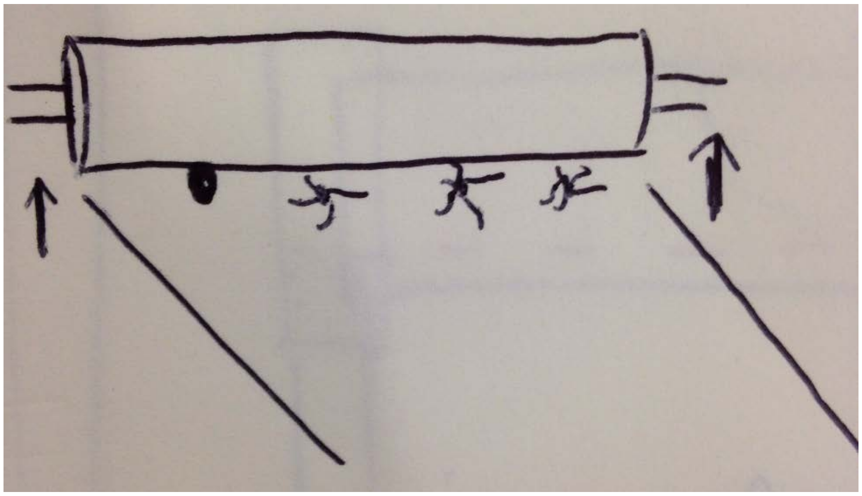


Figure 4.15 *A major flaw with "single spring" mills. A single circular rock on the fair left raises the mill, causing the three squiggly animals on the right to not get crushed.*

The basic premise behind "soft" mills is using a material property of the rolling mills to "test" objects passing through the mills. The materials in the mills would be in a "goldilocks" state, strong and hard enough to crush macrofauna but flexible enough to yield if an unbreakable object enters the mills. After yielding, the mill would return to its original position so it could continue crushing the softer macrofauna. Since the mills would be intrinsicly flexible, it opens the possibility for them to be segmented, something that would be difficult to accomplish with springs. Figure 4.16 depicts what a segmented mill might look like and how each segment of the mill would interact with various objects. The image on the left shows how the mill keeps its original shape and squishes the squiggly macrofauna but raises to let unbreakable rocks through. The image on the right shows a cross-section of what the individul mill segments might look like. The outer shaded ring would be a material hard enough to consistently crush the macrofauna while the inner shaded circle is the shaft that it would rest on. The hatched part in between the shaft and the ring would be some sort of foam or rubber that is stiff enough to not deflect under pressure from the animals,

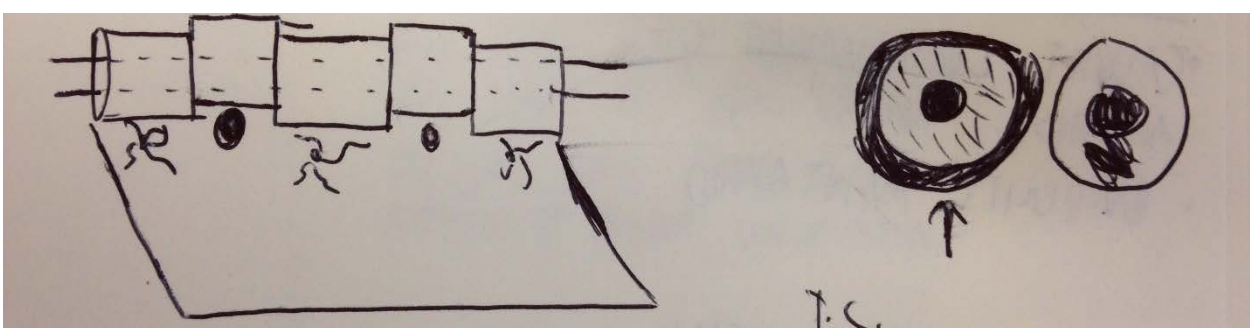


Figure 4.16 *Segmented mills allow rocks to pass through without causing parallel animals to pass through uncrushed. The mill segments combine the flexibility of a foam interior with the hardness of a metal or hard plastic outer ring.*

but soft enough to allow rocks through.

Figure 4.17 shows various ideas for 3D printed segmented mills. Instead of using a foam or rubber interior, a 3D printed part could be designed to obtain a desired stiffness. Different shapes and different plastic extrudes could allow for these soft mills to be designed for specific environments. Marine areas known to have harder animals could use a stiffer print while locations with softer animals could use less stiff prints.

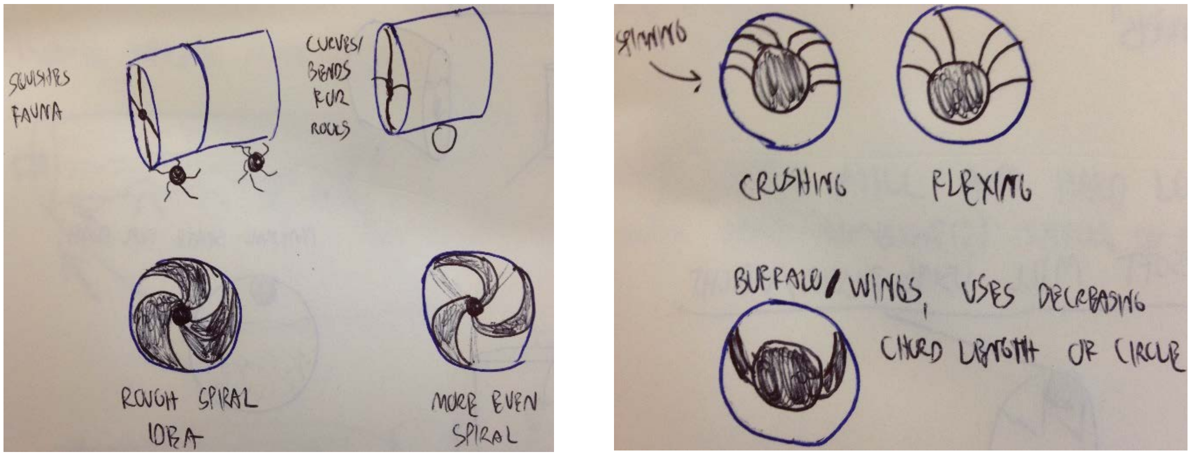


Figure 4.17 *Ideas for 3D printed segmented mill shapes. Different shapes and different plastics could allow for the mills to have a variety of stiffnesses depending on the location that they are being used.*

Figure 4.18 depicts soft mills that use materials more dense than water loosely held around a central shaft by a hard shell. These dense materials, liquids or small solids, would cause the hard shell to rest on on the top of the shaft as seen on the right. As animals pass through, the weight of the dense materials would keep the mill in place. But unbreakable objects would apply enough force to lift the weight and pass through the mill. These “filler” mills can be easily have their “stiffness” modified by changing the amount of material in each segment, allowing for quick prototyping and testing.

Figure 4.19 shows the idea of a “soft” and segmented mill taken to the extreme. Instead of encasing a “soft” material in a hard shell, the team speculated that it could be possible to simply use the soft materials on their own in a single mill. This continuous surface offers the advantage of never missing crushing an animal next to an unbreakable object since the fully “soft” mills would be infinitely segmented. Ideas for materials varied from foams and rubbers to encasing a liquid into a malleable plasitic similar to a “water weenie” or “wiggler” toy. Animals and rocks would not get stuck in the foams or rubbers since they are encased by the two belts as they enter the mills. A potential failure mode for this design includes the soft exterior of the mills being unable to crush the thin shells of captured animals.

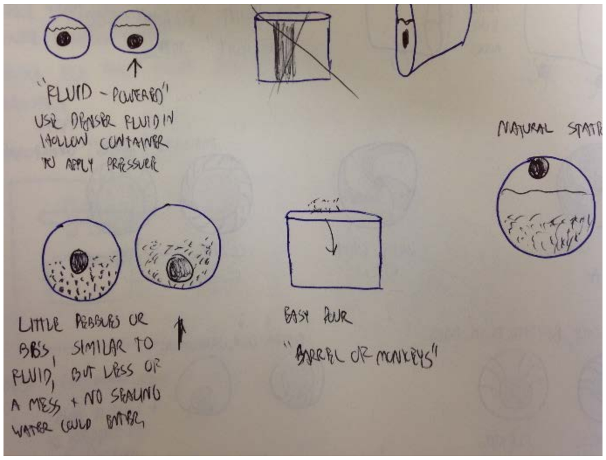


Figure 4.18 *"Filler" mills are hollow containers filled with substances that are more dense than water. The weight of the mills crush soft animals but are lifted by unbreakable rocks.*

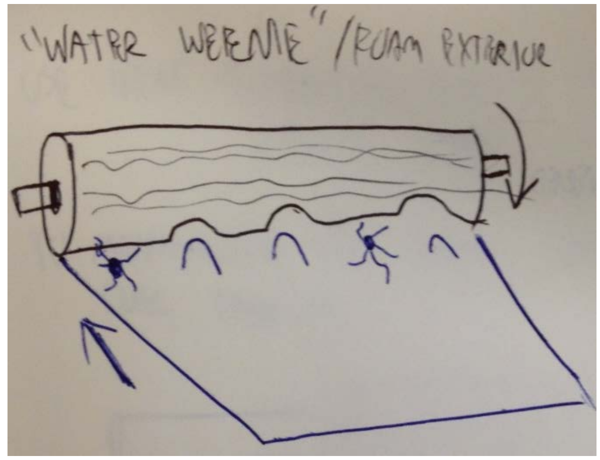


Figure 4.19 *A "soft" mill without a hard shell ensures that animals are always crushed. These mills can be made from foam or plastic filled with liquid.*

These segmented mills still face the problem of missing animals if a rock is directly adjacent to one underneath a mill segment. However, the segments prevent an entire row of animals from being missed from a single rock. The mill segments must be tightly packed together as well since any gaps in between them could cause them to miss crushing parts of animals. Using multiple mills with offset segments could help consistently crush the animals (Figure 4.20) Minimizing the width of the mill segments and the gaps in between them is therefore critical to its success. Many of these mills also can not be driven, meaning that the opposing mill must be driven. This could be could be important in determining the layout of the test bed.

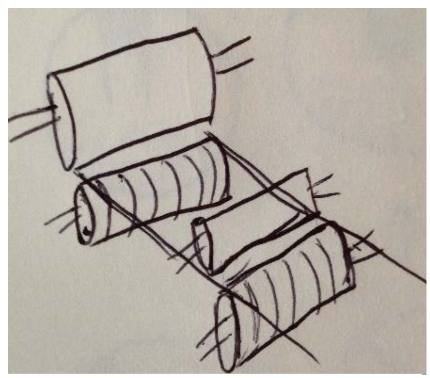
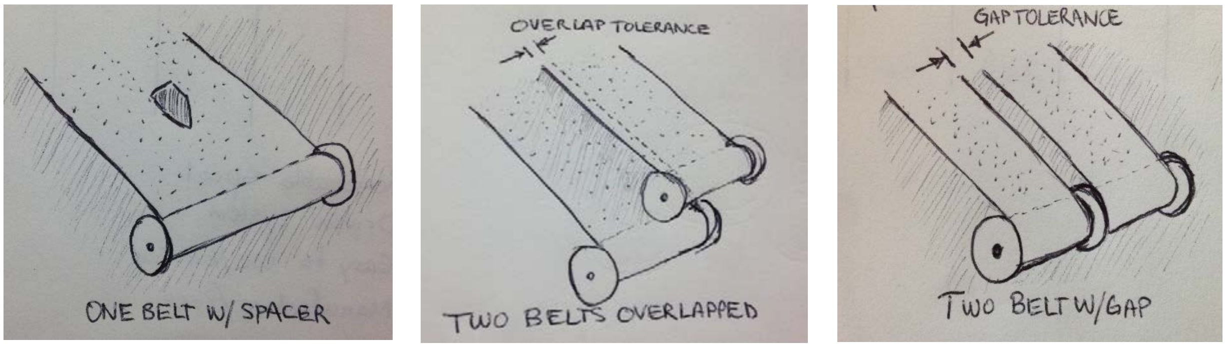


Figure 4.20 *Placing two sets of segmented mills in series could help reduce the number of missed animals compared to a single*

"Soft" mills were not integrated into either the preliminary or Mark I design as they address a reach goal. However, they may be further developed if the team is able to get to their reach goals.

4.3 Collection Layout

The team developed three different belt layout ideas which can be incorporated into two different system configurations. These three belt designs are discussed below.



(a) *(b)* *(c)*

Figure 4.21 *Three different belt configurations.* ***(a)*** *Two belts are pre-cut and rest on the same core but have a gap between the two and may miss some animals.* ***(b)*** *Two pre-cut belts are overlapped by layering the spools and cores to "close the gap" and collect more animals.* ***(c)*** *A single belt on a core can be used with a spacer on the belt to distribute the animals into two distinct supply lines.*

The first belt design (Figure 4.13(a)) uses a single belt on a single core. This is the simplest layout as only one core is required, reducing the complexity of the system and reducing manufacturing and operation time. Half of the belt would pass under any crushing system directly implemented into the system (e.g. mills, stamps) while the other half would remain untouched. The final collection spool would be removed as a single spool with both crushed and intact treatments. As a single spool, the two treatments would not be mixed up or lost with other spools in storage. Specialists would have to be careful in handling the spool to not interfere with both sides as they work. If a large gap separates the two treatments, the final spool could be cut into two separate spools. The separate spools would allow for post-processing treatments such as vacuum pressing to be applied to one side only. This can only be implemented in the stepped-down mill system layout (Figure 4.13).

The second belt design uses the two parallel belts on a single core (Figure 4.13(c)). The belts are precut in this layout, allowing for the two treatments to occur along different paths. The crushing treatment can occur in a different space than the simple collection treatment. This separation ensures that no overlapping of treatments occur. Animals meant to remain intact will not accidentally get half-crushed in the crushing mechanism. The spools also return as two separate treatments and can go directly to wherever they need to be analyzed. The crushed side can immediately go to any post-processing that it requires and the intact side can immediately be identified by specialists. However, one problem with the parallel belt system is that it could potentially allow animals to slip through the small opening between the belts. The rising water and air could push this gap further open at larger flowrates. Rudimentary testing will have to be done to determine if significant amounts of animals escape through this middle gap. This belt can be used in both the stepped-down mill system layout as well as the mill avoidance layout.

A solution to the problem presented by the gap would be to raise and overlap the two belts (Figure 4.13(b)). Any animals that the bottom belt misses would be caught by an overlapping upper belt, minimizing the number of animals missed. However, this layout adds complexity to both fabrication and operation of the system. This set-up can be used in both mill configuration layouts as well.

The team developed two main collection layouts for the system which can use different belt designs previously discussed (Figure 4-14 and Figure 4-15) One collection layout uses a stepped-down diameter mill, and the other avoids the mill entirely.

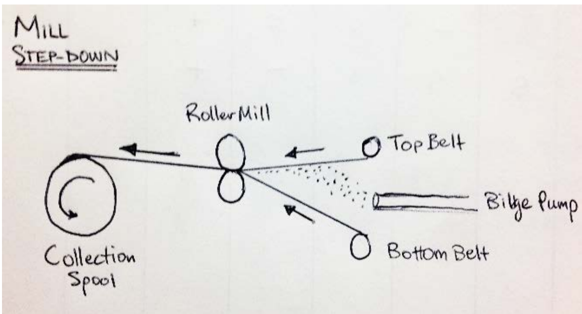


Figure 4.22 *The step-down roller mill configuration feeds the top and bottom belt into a mill and is collected on the other side.*

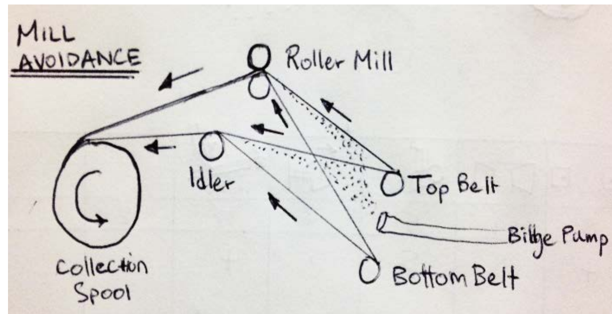


Figure 4.23 *The mill avoidance configuration allows for a second top and bottom belt to avoid the mill entirely.*

A roller mill with a stepped-down diameter is a simpler design and will be easier to fabricate (Figure 4.14). This is because it does not require an idler for a separate belt. It can use both a single belt or two separate belts. The identification side of the belt can pass through the clearance section of the mill and leave the macrofauna untouched. There is concern that some macrofauna reserved for identification will be caught in the middle and get flattened unintentionally.

The mill avoidance configuration (Figure 4.15) allows for the identification belt to completely avoid the mill and remove any unintentional flattening. The identification belt would require a separate idler to bring the top and bottom belts together. However, this configuration adds additional components as well as the need to analyze tension due to multiple belt path angles.

4.4 Gear Train and Reduction Design

The team examined several drive systems in order to meet the continuous collection engineering requirement. Pulleys and belts were ruled out due to their poor performance submerged in seawater, as well as a chain and sprocket. A gear train was determined to be the most efficient to run underwater by using urethane gear cogs with high backlash. The high backlash allows for organisms and rocks that may get stuck in the gear teeth to fall out. Although backlash is generally not sought after, the test bed system will only be driven in one-direction. This ensures constant gear teeth meshing and continuous rotation.

The driven gear may be directly attached to the mill and collection spool gears (Figure 4.16). The mill and collection spool gears will be identical to ensure the belt is fed through the mill and collected on the spool at the same linear speed and direction. The team wants to achieve a maximum linear belt speed of 250 mm/s. Faster speeds may introduce problems that arise with consistency in flattening and collecting the macrofauna.

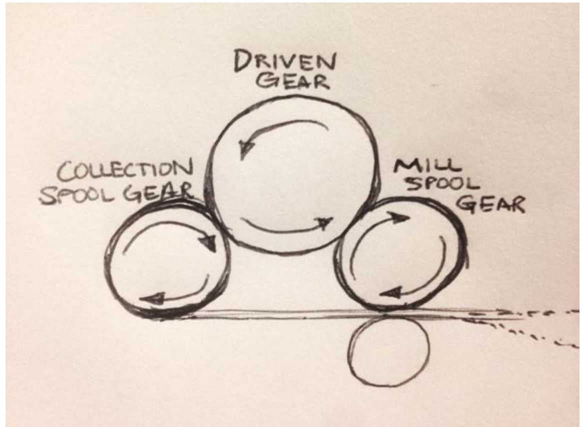


Figure 4.24. *Gear train configuration. Driven gear is directly connected to the collection spool and mill gears.*

In order to choose a gear reduction configuration, the team calculated a range of values of linear belt speeds from input and output gear speeds with a gear ratio of 0.75:1. The linear velocity at the edge of a spinning disc can be found by $v = (w)(r)$, where r is the radius of the disk (mm) and w is the rotational velocity (rad/s). However, as the collection spool winds up the belt, the radius grows with each layer of belt material and the linear velocity increases. To account for this, the team used an average spool radius based on an empty and full spool.

The input torque was set at a value of 5 Nm to ensure continuous human output without straining the user. It is also set to overcome the preloaded tension in the system. As shown in Table 4-1, an input speed of 40 RPM results in a linear belt speed of 262 mm/s and meets the maximum belt speed requirement. From there, the user can slow down the system to very low speeds as needed.

Table 4.1 *Linear belt speed values achieved with a gear ratio of 0.75:1 and a set input torque of 5 Nm.*

Gear Ratio [0.75:1]					
Input Torque [Nm]	Input Speed [RPM]	Output Speed [RPM]	Output Speed [rad/s]	Average Spool Radius [mm]	Linear Belt Speed [mm/s]
5	5	6.67	0.70	50	35
5	10	13.33	1.40	50	70
5	15	20.00	2.09	50	105
5	20	26.67	2.79	50	140
5	25	33.33	3.49	50	175
5	30	40.00	4.19	50	209
5	35	46.67	4.89	50	244
5	40	50.00	5.24	50	262

A technical challenge arose when speculating about flowrates of animals and continuous collection. Because the system is not fully automated (e.g. powered by a human rather than a motor), the drive system is subject to inconsistent rotation from the user due to human error. This is not a huge problem due to this project being a proof-of-concept. However, the team looked into transmission possibilities to include pre-set collection rates. These known collection rates would have a set input flowrate and corresponding gear ratio in order to meet that collection rate. Unfortunately, a transmission would introduce more moving parts into the system which is not ideal in a seawater environment. While not within the scope of the project, implementing a transmission is a reach goal.

4.5 Belt Material Testing

The team conducted a simple test on three different belt materials (blue disposable micro towel, white reinforced paper towels, and roll cloth) to see how they interacted with the analogues. The goal of the test was to determine if any of the three materials could be used in the final product. The team used blood worms and dried shrimp shells as analogues and filled a shallow Pyrex dish with sink water for the test. The analogues were poured into the dish and both floated to the water's surface. Each of the belt materials were then pulled along the top of the Pyrex dish so that the belt was barely submerged in the water, as shown in Figure 4-17.

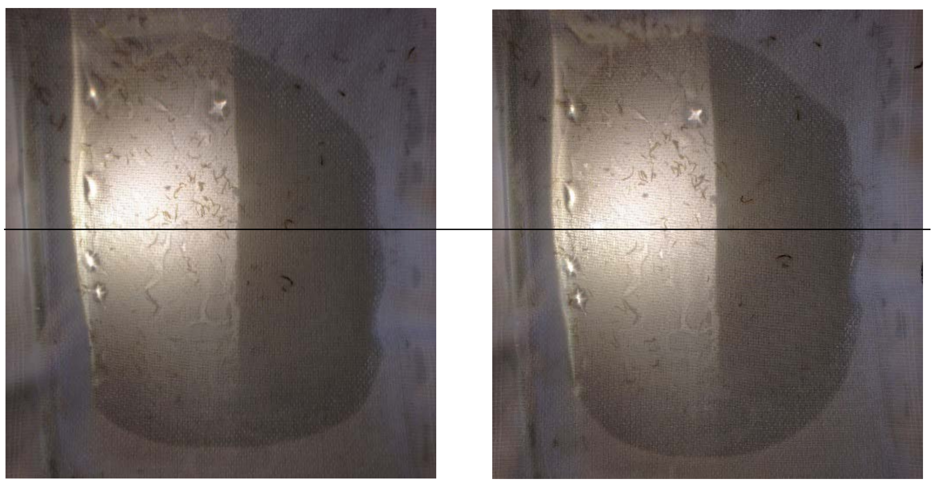
(a) ***(b)*** ***(c)***

Figure 4.25 *Three belt materials were tested on their "stickiness" and how well they could catch the analogues as the belt was pulled along the test-dish. A blue disposable micro towel* ***(a)****, white reinforced paper towel* ***(b)*** *and a roll cloth towel* ***(c)*** *were used in this initial test.*

After testing each belt, the team compared their behavior against each other. The team found that the blue disposable micro towel caught the most analogues as the team lifted it out of the water. The "fuzzier" nature of the micro towel was likely the reason why more of the analogues stuck to it. However, its integrity was questionable since the team was able to tear it with their hands easily. Also, the team realized that the blue color may complicate future image processing if the caught animals need to be stained or dyed. The white reinforced paper towels caught fewer analogues once it was pulled out of the water. It too was significantly weakened from being soaked in the water. The team therefore believes that both the blue micro towel and reinforced paper towel will not be usable for the final system as they will likely dissolve over time in water since they are paper products.

The roll cloth caught the least amount of animals once it was pulled out of the water. However, it maintained most of its strength and remained difficult to tear apart. Since it was the only material that will not break in a finalized system, the team decided to use the roll cloth in the first prototypes. Even though the roll cloth caught the least amount of analogues once pulled out of the water, Dr. Paavo found the fact that some of the analogues stuck to it in the air to be promising. More of the analogues were likely caught on the roll cloth when it was submerged underwater and fell off once exposed to the air due to the hydrophobic nature of the animals/analogues.

The team looked further to see if the analogues were actually moving with the roll cloth. A preliminary test showed that the majority of the analogues moved with the roll cloth. The two images in Figure 4.26 show a before and after photo when the belt was moving upwards. The analogue clump in Figure 4.26(b) clearly moved upward when compared to the same analogue clump a few moments before in Figure 4.26(a). This movement could have been the result of the analogues sticking to the belt material or the analogues being caught in a small current introduced by a boundary layer from the moving cloth. Either of these reasons would be acceptable so long as the analogues can be collected when the two belts are sandwiched as they enter the mill.



(a) ***(b)***

Figure 4.26 ***(a)*** *A clump of analogues caught in the center of the belt.* ***(b)*** *The same clump of analogues were stuck to the belt but shifted upwards which demonstrates the successful "sticky" nature of the belt to catch the animals as it is pulled along in the test.*

4.6 Initial Air Pump Testing

The team did some initial testing to see how the analogues and belts would interact with an air pump. Tubing with a ½-inch radius air stone attached was placed in a large Tupperware container with some analogues (Figure 4.27). The team noticed that as the analogues were placed into the container, the pump immediately pushed the analogues away in a turbulent and random fashion. This turbulence made it difficult to determine how the analogues were moving before they reached the surface and were pushed to the sides. The team also found that the roll cloth was not permeable enough to rest above the air pump, as air pockets formed underneath it. These air pockets could prove problematic in the system since they would prevent the analogues from attaching to the belt. Due to the random behavior of the analogues and the formation of air pockets, the team was discouraged from using the air pump. More testing with a full system prototype may remove the air pump from the final design. A possible alternative to the air pump could be a water pump, since it would propel the analogues in a less turbulent fashion.

(a) (b)

Figure 4.27 ***(a)*** *Side view of air pump in operation.* ***(b)*** *Top view of air pump. Note the minimal dispersion of bubbles as they rise to the surface. However, at the surface they quickly disperse.*

5. Preliminary Design Selection

The concepts previously mentioned were then evaluated against each other in design matrices shown in Appendix B. By comparing how well each concept fulfilled the overall requirements of the project, the team was able to develop a lead preliminary design described in the following section.

6 Preliminary Design

6.1 Collection Layout

A simple CAD model of thepreliminary is shown in Figure 6.1. The proposed system uses a single belt on a single belt with a spacer (not shown) to separate the animals into two groups. The team reasoned that this design was the simplest and most efficient method of collection. With no gaps in the belt for animals to slip through, the team anticipates that they will be able to increase the percentage of animals that they catch. The single belt also keeps the belt system manageable since parallel branches will not have to be made. A spacer will be implemented to separate the animals into two treatments. The width of the spacer will be determined based on how the belt is cut to apply the treatments. If the belt is cut as it runs through the system, then the spacer can be slim since it only needs to keep the animals off of the cutting line. If the belt is cut after being removed from the spool, then a larger gap may be needed since the belt may not be precisely cut. The length of the spacer will be determined by how far the animals are propelled by the bilge pump.

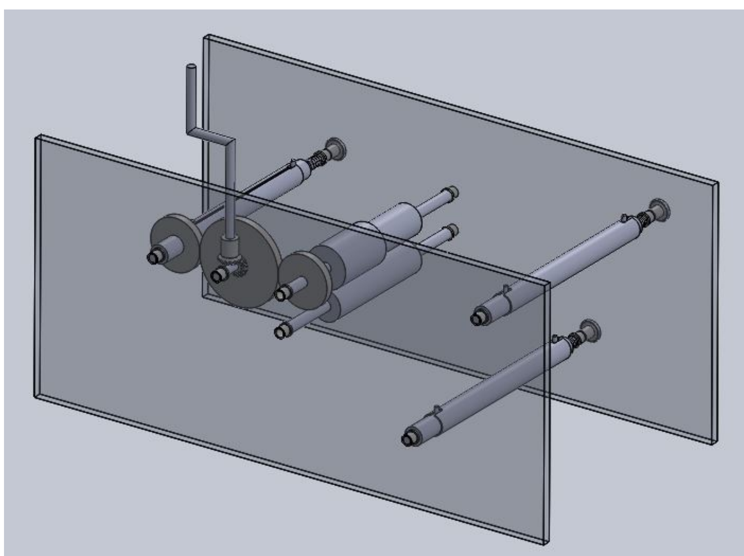


Figure 6.1 *CAD model of overall system configuration.*

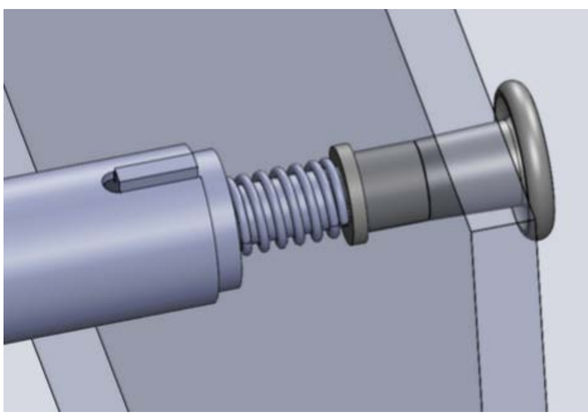
Overall, reusable spools best fit the requirements for this project. While disposable spools would simplify storage of the samples, they also unnecessarily complicate the belt replacement process. Multiple spools would need to be fabricated for multiple tests, hindering the "ease-of-use" of the system. This hindrance does not compensate for the small benefit of better organization. Sliding the belts on and off permanent spools therefore makes the most sense for this system.

6.2 Belt-Spool Attachment

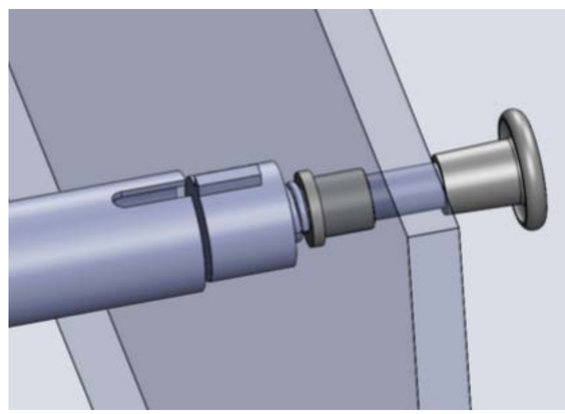
Open seam extrusions were determined to be the optimal method of attaching the belt to the spool. These extrusions come in a variety of sizes and materials. The outer and inner diameters can be easily specified along with an appropriate opening for the belt to fit into. Spatial constraints and tensioning methods will help specify the outer diameter of the spools. How the belts fit into the opening and how the belts slide on and off of the spools will determine the size of the opening and the inner diameter. The extrusions must be made from a material that can withstand a seawater environment. The team also will have to consider how to initially wrap the supply spools as manually wrapping them will be time-intensive and prone to human mistakes.

6.3 Spool-Core Attachment

The team decided to use springs and a slotted keyway to mount the spools and lock their rotation (Figure 6.2). The spring provides a horizontal force to keep the cores in the spool and can be pulled out to remove the spools. The slotted keyway allows for the spool to be driven by the drive system. A potential challenge with this design configuration is balancing the size of the key with the spatial constraints needed so that the belts can be removed. A small, thin key would allow for the belt to be easily removed but could potentially shear and break. A larger, thicker key may not break as easily but limits the ease of belt removal. Likewise, identifying a spring that can withstand a seawater environment and manually pulled will be critical for this design.



(a)



(b)

Figure 6.2 *A spring-loaded permanent core with a key will be used to connect to the spool by a slot and lock rotation. The spool is loaded in case* ***(a)*** *and removed in case* ***(b).***

6.4 Crushing Mechanism

The team decided to use two rolling mills for the preliminary design. The two rolling mills allow for the belts to pass easily through them without getting caught. The team decided to fix both mills to the frame of the test bed to give them greater rigidity. Attaching springs to the mills seemed clunky and did not effectively meet the reach goal of handling grit since animals would still not get consistently crushed. The team instead planned on increasing the torque in the driven mill so that the mills can potentially crush any grit that may enter the test bed.

6.5 Drive Mechanism

The drive will attach to both the collection spool and the top mill (Figure 6-4). The mill and the spool should rotate at about the same speed to prevent the belt from jamming. The simplest method of ensuring that they run at the same speed is to attach both of them to the drive gear with gears of the same size. The team will draw varying SolidWorks models to determine if a more complex train is required to meet spatial or tensioning needs.

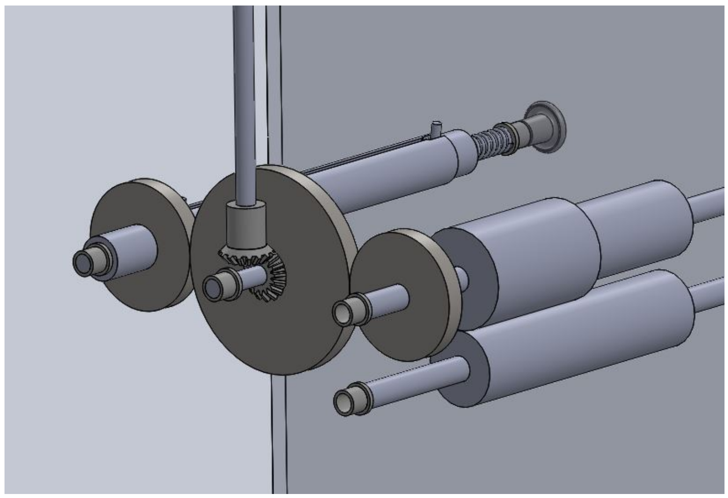


Figure 6.3 *Drive system with simplified spur gears to connect the collection spool to the top mill. These components will be driven by a hand crank that is orientated vertically to come out of the water and be powered from above. It connects to the spur gears by a bevel gear.*

7. Prototype Test Bed

7.1 Overview

This section discusses the design and manufacture of the first prototype as well as learning outcomes from observations of the first experimental wet run of the device. The prototype was created to be a rudimentary test bed and proof of concept behind the basic ideas for a preliminary design. The team looked to find potential problems with the collection layout and mills that may not have been foreseen during the initial design phase. As such, the prototype was designed to be promptly manufactured and reconfigurable on-the-fly. After completing its fabrication, the team submerged the prototype in a fish tank and experimented with different component layout configurations to optimize analog capture and with various mill gap spacings to observe the variation and consistency in flattened analog thickness.

To summarize the learning outcomes from experimenting with the prototype, several critical design flaws were discovered. The following problems negatively impact the functionality of the device:

- The clearance fit for the mills in their positioning holes is too loose, causing slop
- The fabric and film layers separate between the mills and collection spool, causing some captured analogs to release as well as misalignment between the layers
- Some analogs drift away from the collection zone and float to the water surface outside of the device
- Water currents can cause the release analogs already captured on the spool before they enter the mill
- The spool system does not currently maintain tension, leading to drift
- Air bubbles become trapped in the film spool when submerging

These flaws have been addressed in the design of the second-iteration prototype, Mark 1 (Mk I). The particular resolutions to each issue is discussed in detail in Section 8.

7.2 Designing the Prototype

7.2.1 Reconfigurable Layout

A critical aspect of the design to verify for functionality was the positioning of all of the components relative to one another. To investigate, the team developed four methods for modifying the system layout quickly and easily. The first method consisted of cutting holes in the sidewalls at different locations to accommodate possible desired layouts (Figure 7.1(a)). The second method utilized slots with small surrounding pin holes to locate the shafts in smaller distance intervals (Figure 7.1(b)). The third method used slots with screws to locate the shafts with near-infinite variability (Figure 7.1(c)). The fourth method consists of a slotted baseplate with 3D printed components and similarly uses holes and pins for positioning as seen in Figure 7.2.

The first method was the simplest to manufacture but offered the least amount of modifications. Since the holes would be directly cut into the frame, additional tools would not need to be built to locate shafts. The location of the shafts would also always be precisely known. However, this set up limits the range of shaft locations to be tested since the holes must be spaced apart from each other. The minimum distance between the shafts must be greater than the shaft diameters.

The second method offers smaller variations in positioning at the cost of a more complex design and more manufactured parts. Since the surrounding holes have smaller diameters, it allows for the shafts to be moved smaller distances than from method one. This would allow the team to obtain more fine-tuned data on the collection layout. This method also makes it so that the Mark I does not have to be pulled apart each time the shafts are moved since they can be slid throughout the frame.

The third method gave the largest range of shaft movement but was the most complex and requires the most manufacturing. This method theoretically offers infinite adjustment since there are no discrete points to locate the shafts. Infinite adjustment could be useful for small shaft movements, but make it more difficult to determine the precise location of each shaft. Additional time would have to be used to design and manufacture the screw sets.

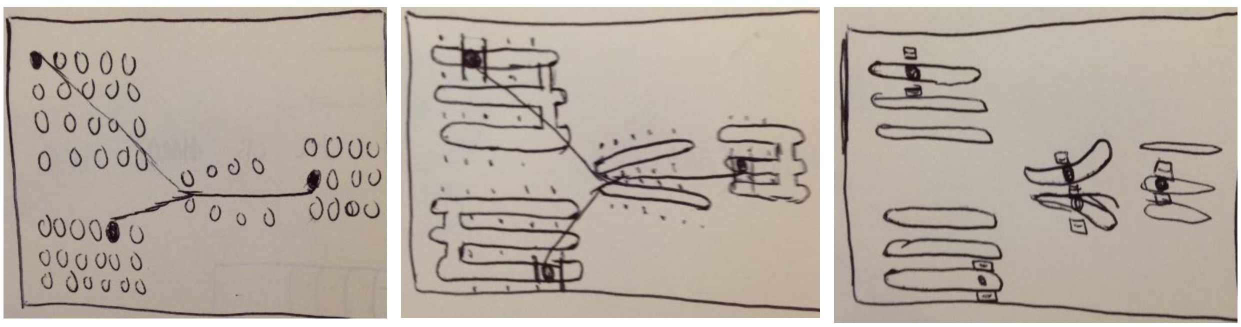


Figure 7.1 ***(a)*** *Sidewall with discrete positioning holes.* ***(b)*** *Slots with discrete positions.* ***(c)*** *Open slots.*

The fourth possible design utilized 3D-printing methods to create the support structure and securing pins of the prototype. A general drawing of the idea, shown below in Figure 7.2, shows how 3D-printed supports could ride in a slotted baseplate machined out of plastic. Holes and pins would allow the pieces to move along the slot and telescope vertically, allowing for a many layout combinations. The idea behind 3D-printing the components was to reduce the time spent fabricating parts since they could be made while the team members dedicated time to other tasks.

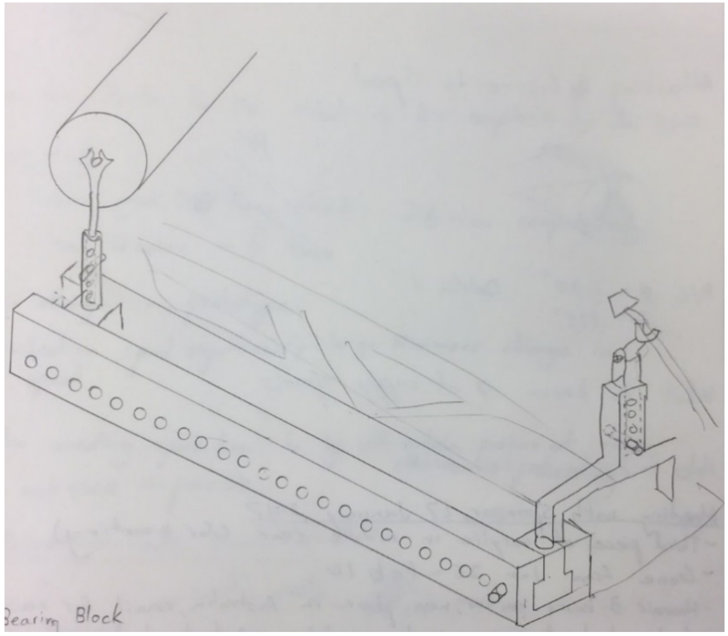


Figure 7.2 Sketch of a 3D-printable prototype design.

The team decided to use the first method for the prototype largely due to its ease of manufacturing. The team wanted to quickly prototype and test generic layouts and did not think that the precision offered by the other two methods was necessary considering the scale of the shafts. The lack of discrete positions made the third method unattractive since the team could not easily measure every shaft location. The slots from the other methods would have allowed the shafts to be moved without disassembling the frame. Instead the team looked to find an easy way to disassemble the frame to move both shafts and mills. A side view of the layout can be found in Appendix C.

7.2.2 Frame Considerations

The team decided to use two sheets of 18” X 24 X 0.220” thick acrylic for the frame sidewalls with the intention of seeing if it is an appropriate material for the final unit. The acrylic was easy work with using a laser cutter to align holes precisely. Holes were cut in the four corners of the frame to run supports across them for stability. The supports were made from polycarbonate shafts and were tapped on the outside to secure them in place.

7.2.3 Spool, Belt, and Drive System Considerations

The spools in the prototype were made out of PCV with a small slit milled across them to allow the belts to initially be wrapped around them. The team used the roll cloth for the top belt and the stage plastic for the bottom belt.

Before the device was ready for operation, the spool materials must be cut to proper width and length, then wound sufficiently tight before being fitted into the system. While the team had initially discussed having the fabric span six inches wide, the waste of the remaining stock material was deemed excessive since approximately 4 inches of material would remain. By compromising to a width of approximately 5.5 inches, the team able to cut the roll directly in half perpendicular to its longitudinal axis and double the usable material per roll purchased. Until determined otherwise, the team will wind 10 meters of material onto the supply spools.

7.2.4 Crushing Considerations

The mills used in the prototype were made out of polycarbonate. Polycarbonate was selected as a first mill material since it is easy to machine and was easily accessible to the team. It is hard enough to crush the analogues used in the prototype, but likely is not hard enough to crush shells and other gritty material. The team accepted this as a limitation to the prototype and instead focused on how consistently the plastic mills crush the analogues. The team plans to use harder materials such as marine grade stainless steel in future iterations for improved performance and to potentially crush excess grit.

7.2.5 Analogue Release Mechanism

The team developed two simple methods to simulate macrofauna entering the system. Both release mechanisms relied on the natural buoyancy of the macrofauna and of the analogues to float them into the collection belt. The first method used an inverted funnel to slowly release large amounts of analogue at a consistent rate. Funnels with different end diameters could be used to model different macrofauna flowrates. If clogging were to become an issue for the smaller funnels, the team plans to use either an air pump or a water pump inserted into the funnel to gently push them out. Based on the initial air pump material tests (Section 4.6), the team believes the water pump to be the better pump. The second method used a turkey baster filled with analogue to squirt set amounts of analogue towards the collection belt (Figure 7.3). Despite not having a consistent flow of analogue, the team thought that the turkey baster would allow for greater control of the release of the analogues. The turkey baster can be moved around the tank more easily than an inverted funnel and can shoot the analogues at sharper angles more easily.

Figure 7.3 *Using the turkey baster to release analogues towards the top belt. The baster had a relatively narrow dispersal area, useful for squirting bloodworms.*

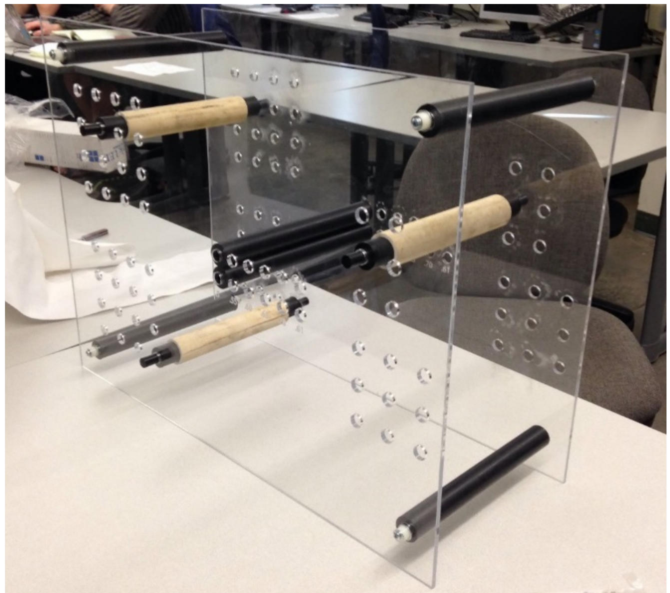


Figure 7.4 *Assembled prototype showing variable layout configuration positioning holes.*

7.4 Testing and Learning Outcomes

7.4.1 Testing Preparation

A 40-gallon glass tank was filled with water from a hose to prepare for testing. The supply spools were wrapped by hand and loaded into the frame of the prototype. The two belts were then pulled through the mills and wrapped around the collection spool. The total assembly was then placed into the tank. The analogues were then loaded into the bulb of the baster so testing could begin. Separate tests were done using dried bloodworms and dried shrimp shells.

The team found that it was easy to wrap the roll cloth around the PVC by hand, but that the stage lighting was more difficult to wrap tightly. Since the stage lighting had little stretch, wrapping it by hand without additional tension created significant gaps in the plastic spool. The team later found that by pulling on the plastic at an angle that the plastic could be wrapped tightly around the spool. The team also found that both belts had a tendency to wander from the center of the spools as they were being wrapped. This caused the belts to be misaligned as they moved across the system and entered the collection spool.

When the prototype was placed into the tank, the team immediately noticed air bubbles rising from different sections of the prototype. Air bubbles escaped from the spool slots and in between belt layers on the spools. The bubbles were especially prominent on the plastic belt where the belt gaps were larger and the bubbles stuck to the surface of the plastic. While the team does not know if these air bubbles would have any negative impact on the success of the prototype, they removed most of them from the system by tilting the prototype and tapping each of the bubble locations.

7.4.2 Collection Observations

The analogues were released about three inches below the top belt by gently applying pressure to the turkey baster bulb. The bloodworms floated upwards and stuck to the cloth well. They moved with the upper belt through the system and to the collection spool without issue. The shrimp shells also moved with the belt, but did not stick to the cloth fibers as well and came off of the belt more easily the bloodworms. Although the analogues both successfully stayed with the belt moving at low speeds, disturbances in the water column pushed them off the belt. This disturbance was a result of injecting a second set of analogues towards the belt with the turkey baster. While water jet propulsion ideas to direct the flow of analogues are possible, they need to be analyzed and tested to not disturb the already "caught" mechanisms.

Slight belt angle adjustments of from 0° to 15° did not seem to make a significant difference in the capture rate of the analogues. Steep angles were avoided since the analogues would likely not stick to the belt at angles greater than 45°.

The set-up was slightly tricky when the belt materials were wet. Feeding the wet fabric into the slot on the collection spool after being pulled through the mills was not very easy. Frayed fabric edges and bunching of material obstructed the slot opening. Initial solutions to this problem included widening the slot holding the belts or using an alternate belt attachment mechanism.

The bloodworms and shrimp exited the turkey baster in clumps. This is a problem for gathering and imitating dispersed, continuous collection data. Some analogues even exited the baster accidentally when tilted upwards. One possible way to avoid this is to reduce the exit hole diameter in the turkey baster to only allow a few analogues to pass through at a time.

After the analogues were ejected from the turkey baster, the majority of them floated upwards and were caught between the two belts. However, some of them floated out from the sides of the belt and were not captured.

After obtaining hands-on experience moving the spools and floating analogs, the team determined that the initial proposed belt speed of 250 mm/s was significantly too high. This speed was lowered to decrease fabric use, increase the concentration of samples on the collection spool, and increase system operation time, settling on a conveyor speed of 50 mm/s (~2 in/s). To determine the proper collection spool rpm operating point, a Matlab script was created. This program uses various parameters such as fabric thickness and length, along with spool radii to determine the required driving rpm that achieves an average linear speed of 50 mm/s on the spool. The master script is published in Appendix D.

7.4.3 Tension Observations

As the belts were pulled through the system, the team noticed the need for tensioning in the spools. The belts on the supply side sagged under their own weight. They would also flap up and down as the spools unrolled and if the water from the analogue dispersal was released too quickly. These are major issues since the flapping makes it more difficult for the analogues to stick to the belts as well as causing the belts to unroll at an uneven rate. On the collection side a lack of tension caused the two belts to be slightly separated as they entered the collection spool. The two belts had a gap of about half an inch, large enough to allow some of the analogues and future animals to escape.

The team applied some tension to the spools by fixing the polycarbonate so that the PVC would spin on it. The PVC-polycarbonate surface had a greater coefficient than the polycarbonate-acrylic surface. The greater coefficient provided more tension in the belts since it required more torque to move the belts. Tensioned in this manner, the belts did not sag under their weight and had a smaller gap on the collection side. The belts would slightly flap half an inch or so under moderate pressure from a person’s finger. The team found that the additional tension came at the cost of increased difficulty spinning the spools. Increasing the tension in the belts more may make it uncomfortable for users to operate the system.

7.4.4 Mill Observations

It was difficult to determine visually if either of the analogues were crushed. The bloodworms passed through the mills without any increased resistance indicating that they might not have been crushed. As the shrimp shells passed through the mills, the team noticed that it became more difficult to spin the spools, indicating that the shells were being compressed by the mills. However, a visual inspection of the shells did not give any indication that they were crushed. An imaging program or some other method would have to be used to determine the extent to which the shrimp shells were crushed.

8. Final Design Description

8.1 Overview

The Mark I (Mk I) is the team's final design for the marine animal test bed (Figure 8.1). It was derived from the preliminary design with updates and modifications that resulted from observations during prototype testing. Improvements from the preliminary design include the addition of a containment area, a slotted adjustable mill, and redesigned spool supports.

The Mark I consists of two vertical acrylic plates held together by nylon braces in each of its corners. It has an upper cloth supply spool that holds a roll of cloth and a lower plastic supply spool that holds a roll of stage lighting plastic. Both belt materials are fed through the mills in the center of the Mark I into the final collection spool. The spools are held in place by acetal supports that clamp onto the spool shafts. By clamping onto the spool shafts, these supports provide both easy access to the spools and allow for the belts to be tensioned.

In the future rover, the animals would be released into the containment area where most will become caught on the top cloth belt. Those that do not immediately reach the cloth will have no other place to go due to the walls from the containment area surrounding them. From the containment area, half of them will pass through the adjustable mills. The mills are able to be adjusted by small, finite increments to ensure that the animals are properly crushed. The animals would then pass around a tensioning beam before being wrapped around the collection spool. Users would then be able to remove the top mill and the spools to observe and analyze the captured animals.

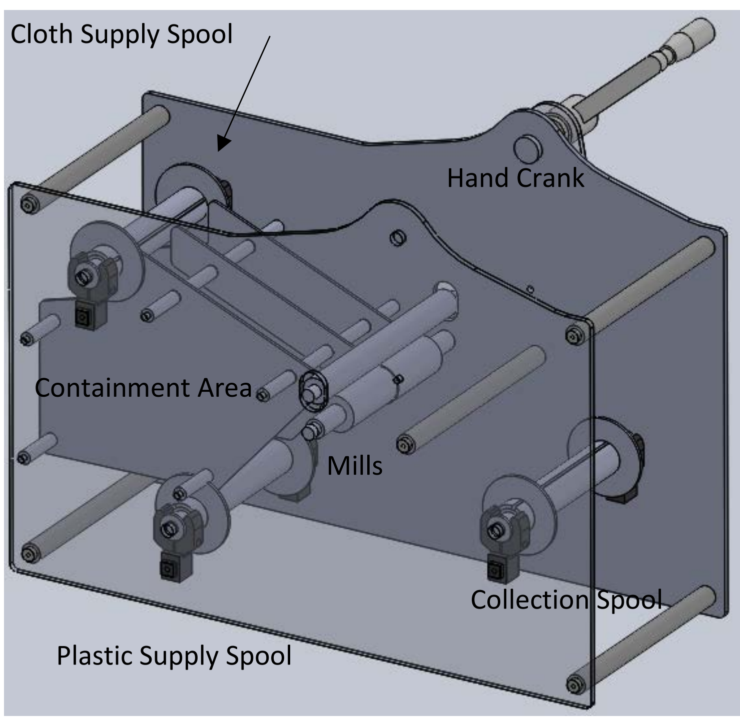


Figure 8.1 *Mark I test bed final CAD design and assembly.*

8.2 Detailed Descriptions

8.2.1 Frame Design

The design of the frame utilizes the accuracy and freedom of the laser cutter to include slots and holes in many locations for mounting. Two 0.220” thick parallel frames are supported in each of the four corners by standoffs. Square holes are cut to fit the spool holders, which restrict rotation in the spool holder and ensure proper location and orientation. The slot allows for the top mill, which is not driven, to be pulled out of the frame and removed for ease of belt attachments. As there are many features shown on the frame, the drawing of the part is can be found in Appendix E.

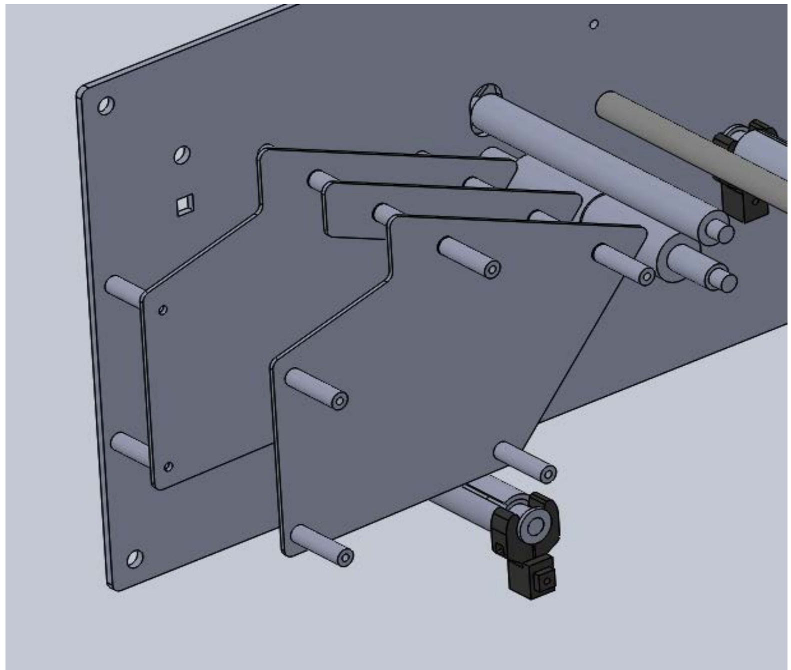


Figure 8.2 *Containment area and treatment divider shown as cutouts from acrylic sheet.*

A “containment” area was designed so injected could not be lost in the surrounding tank and could only get move towards the mills once in this area. This was achieved by adding guide walls which the belt materials run along (Figure 8.2). The cloth belt runs along the top of the two guide walls, preventing animals from floating around the belt. A thin separating barrier in between the two guide walls was added to ensure no animals get caught halfway between the crushing and clearance sections on the mill, ensuring separated treatments.

8.2.2 Drive System

The vertical bevel gear and direct gear train were replaced by a chain and sprockets design in order to simplify the drive system. In order to use only spur gears, the driving gear had to be raised so its center was above the top of the tank. This increased the distance among the mills, drive shaft, and collection spool, requiring gears of six to seven inches in diameter to directly connect them. A gear train made of smaller gears could have also worked, but would have created a more complicated assembly design and required more components. Therefore, plastic chains and sprockets commonly used in robotics were selected to meet marine environment requirements as well as span the distances between the driven shafts (Figure 8.4).

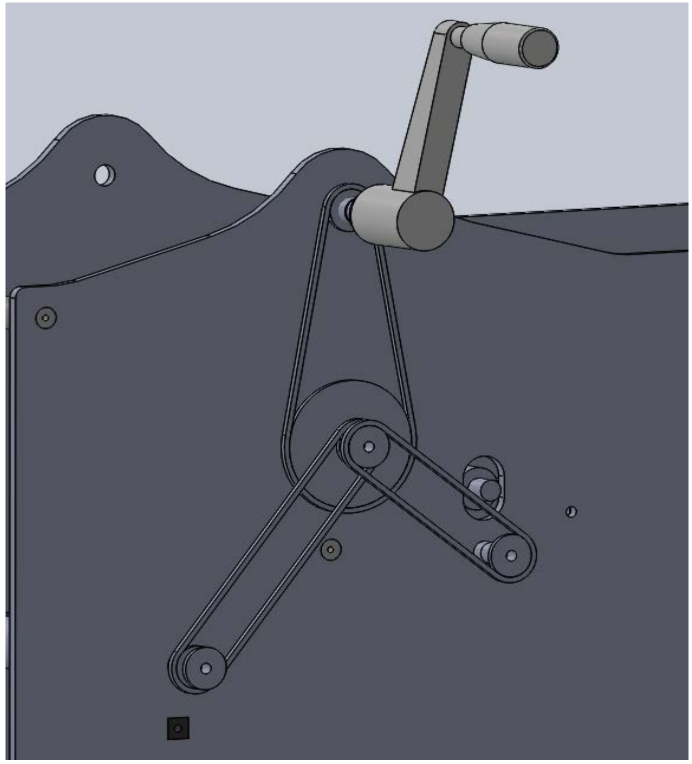


Figure 8.3 *Chain and sprocket configuration. Drive crank with gear ratio to achieve 60 rpms at the crank and 4 rpms at the spool and mills.*

To solve the previously-discussed issues related to having a gear train form of power transmission, the use of sprockets and chain was implemented. These parts will be made of acetal for its corrosion-resistant properties in a saltwater environment and relatively cheap cost. Acetal is also stronger than typical plastics, so the sprockets and chain should have a longer life before needing replacement from possible tooth wear. The chain, according to a manufacturer of a similar product, can carry 'moderate loads' in small-scale robotic applications [21]. It is more than strong enough to bear the small loads expected for this application, a claim also supported from knowledge gained during personal experience using the chain.

To achieve the desired 50 mm/s average linear speed of the belt through the mills, the collection spool as designed must have an angular velocity of 4 RPM. This spool must be driven by a hand-crank positioned outside of the water, and a 1:1 gear ratio would result in the operator driving the crank at the same 4 RPM, a difficult task to accomplish. To make it easier for the operator to maintain a consistent speed, a gear reduction of 5:1 was chosen between the driven hand-crank and the collection spool and similarly with the mill, as shown in Figure 8.3. Since the load on the chain is not a concern, the team chose to use the smallest gears possible to reduce cost. As such, a 60-tooth sprocket was chosen to be on the collection shaft while a 12-tooth would mount on the hand-crank shaft. Therefore, the operator will be able to drive the crank at a more reasonable 20 RPM, or one revolution every three seconds, causing the belt speed to average around 50 mm/s.

To connect the sprockets to the collection spools and mill, a small shaft will be made to go through the sidewall and into the collection spool and sprocket. The collection spool will require drilling a hole into its side facing the transmission along its longitudinal axis and a second tapped hole through its surface to intersect the previous hole for a set screw. The small shaft will be attached to the collection spool with a set screw, pass through the sidewall, where the sprocket will also be attached via a set screw. The drivetrain is easily disengaged for collection spool removal by loosening the set screws and sliding the shaft out far enough to exit the collection spool hole, allowing release.

8.2.3 Spool Holder

The spool holder is the most complicated single part of the system (Figure 8.3), however; it provides two very important necessities for continuous, successful operation. First, the geometry of the part reduces set-up time. It allows for the spool to be secured in place by pressing the spool cores through the interference opening of the holder and popping it into place. The spool holder diameter of 0.75 inches is a clearance fit with a bilateral tolerance of +0.02 and -0.00 inches (reference Appendix E). This allows for the spools to spin freely. Second, as the bolt below the spool is tightened, the spool holder diameter slowly closes and "squeezes" the spool core to create friction. This friction on the shaft creates the tension in the system needed to keep the spools from

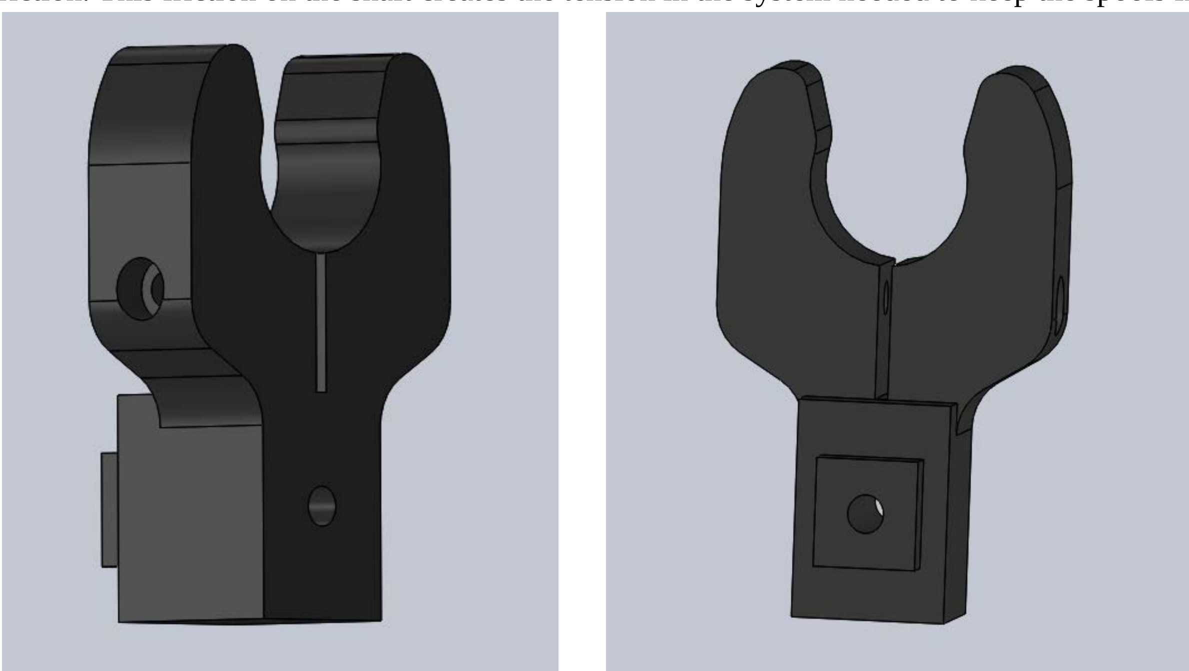


Figure 8.4 *Spool holder and friction mechanism. This part's unique geometry makes it useful in both attaching and removing the spool as well as creating the necessary tension in the system.*

unwinding on their own.

This part will first be made from acetal plastic and manufactured on a CNC machine. It is supported in the frame by a square extrusion to eliminate rotation and will be bolted in place. This part is unique in the way that it creates an easy way attach and remove the spools as well as induce tension in the system. It allows the spool to snap in through an interference fit at the opening. Below the shaft is a groove that allows the acetal to flex. A bolt through this groove is tightened to close the gap and apply pressure on the shaft. This pressure is uniformly distributed around the shaft and creates the necessary tension in the system.

8.2.4 Crushing Mechanism

The team decided to use stainless steel 316 tubes epoxied onto plastic cores mounted securely to the frame as rolling mills. This design obtains the hardness needed to crush animals as well as reducing cost since it avoids purchasing solid marine grade steel shafts. To include adjustability and have a precise, measurable gap between the two milling surfaces, pin holes are cut in the frame that are 0.25mm apart vertically. These are predetermined vertical distances so the user will know the maximum thickness of animals caught on the collection spool.

8.3 Cost Analysis

The bill of materials (reference Appendix F) details the number and quantity of parts along with their description, material selection, vendor, part status, and total cost. This detailed spreadsheet tracks the progress of each component and helps keep the part list organized and up to date.

Because much of the frame, containment area, and spool guides will be made from acrylic, many sheets will need to be purchased to fit all the required geometries. This results in nearly $140 of material cost. The manufacturing time will be quick, however; this is because these acrylic components will be cut on a laser and only will require set-up time.

The spool support will be one of the more time intensive parts of this assembly. These six components will be fabricated on the CNC and made from a block of acetal. The total material cost of all six parts will be close to $35.00, which excludes manufacturing time. The team sees this part as the most time-consuming part to manufacture because it has many features that will require multiple machining processes. However, purely viewing the assembly on a material cost basis, $35 is not very expensive.

The drive system will be relatively inexpensive because it is using plastic sprockets and chains to meet material requirements for marine environments. Seven sprockets and four chains including mounting components comes out close to $60. Other components include fasteners and a hand crank from McMaster-Carr with a total cost of $54.

The total cost for the system is $410, which excludes belt materials and any unforeseen expenses that may result in part failures or re-designs. If a motor is introduced later in the design to eliminate the need for a human to power it by hand, that will need to be purchased.

8.4 Materials, Geometry, and Component Selection

The main reason why the cost for this design is much lower than the total budget is that building a device for a marine environment narrows the material selection. This leaves plastics and highly corrosion resistant metals. Because this project's goal is to build a prototype which will test the possibility of the continuous collection of benthic macrofauna, plastics were chosen over these metals. The team chose to use plastics for much of the build, to also help ease the fabrication process and reduce cost. This way the team was able to build a prototype and a final design in order to test the functionality of the design without spending too much money.

The frames, containment area, spool guides, and treatment divider are all made from acrylic. Nylon chains and sprockets are used in the drive system, which replaced gears in the previous design. Spool cores are made from a polycarbonate plastic readily available. The spool holders are manufactured from a block of acetal. Other materials include PVC pipe, SS 316 tubing, and stainless steel fasteners.

8.5 Maintenance and Repair Considerations

Maintaining the proper functionality of the device over long periods of time poses an interesting challenge given the expected operating conditions. Saltwater can be highly corrosive and small floating particulate could potentially get embedded in undesirable locations in the system. As such, the team plans to investigate maintenance practices that will improve the longevity of the device and its components by minimizing additive wear. Possible cleaning methods the team wishes to look into include removing the unit entirely from saltwater and spraying it down with water, potentially mixed with a cleaning agent to help remove built-up grime. Small fits where certain parts meet, such as shafts in holes, will be identified as problem areas for embedded particulate that causes pitting and may require further disassembly for proper cleaning. While the unit and its components may be regularly cleaned, it is believed that some parts will slowly become tarnished to the point of lost function effectiveness due to the corrosive environment, eventually requiring replacement.

8.6 Safety Considerations

The final design must account for the safety of the customer and of the end users of the system. A preliminary checklist of potential hazards (Appendix G) was run through to determine general hazards that the system might create.

The team does not anticipate there to be many hazards associated with this project. The main hazards include the mills pinching users incorrectly using the system, drive system that is not ergonomically safe for users and water spills. The team will minimize the risk of users being pinched by the mills by clearly marking them as pinch points and physically making it difficult for users to get their hands caught in the mills. The team will develop more specifications on the drive system to ensure that users can comfortably operate and test the prototype.

Water spills are a significant hazard if the tank is near other electric equipment. Spills could damage the equipment and potentially shock users. This shock hazard is further amplified since the tank will contain salt water, making shocks more likely due to the more conductive water. Spills could also cause people to slip and fall depending on the floor surface. The team plans to prevent spills by placing a maximum water level indicator on the tank to keep any splashes contained inside the tank. The team will also have a kit to clean small and large spills in case of minor splashes or if the tank falls over. The tank will not be lifted while filled with water and will be slowly pushed on a cart if it needs to be moved while full.

The water in the tank must also be disposed of into a proper drain. Since the team will be filling the tank with treated water from a hose, the water cannot be poured into a storm drain. Instead the water must be disposed of into a drain that runs into the sewer system. These sewer drains can be found in toilets, sinks, and showers. The team will bucket out the water from the tank into a sewer drain to follow correct environmental procedures.

9. Product Realization

The overall CAD design (Figure 9.1) was finalized and components were fabricated and assembled. The following section details the process and highlights what went well what went wrong.

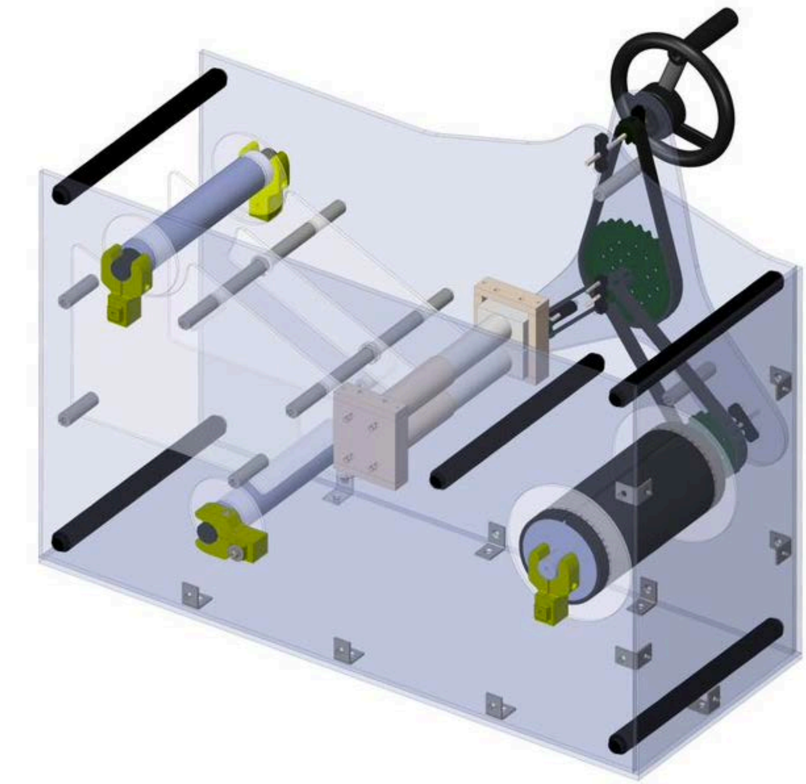


Figure 9.1. *Final CAD design*

The most critical component was the mill subassembly due to its gap tolerance. The distance between mill surfaces was specified to range from 1-4mm based on configuration of the design. The tolerances on these components were designed to consider errors in machining due to bad cutting tools provided by the shop as well as unwanted deformation from machining plastic parts. The parts were machined within tolerance and assembled to make up the mill subassembly (Figure 12.2) which was mounted to the walls of the test bed.

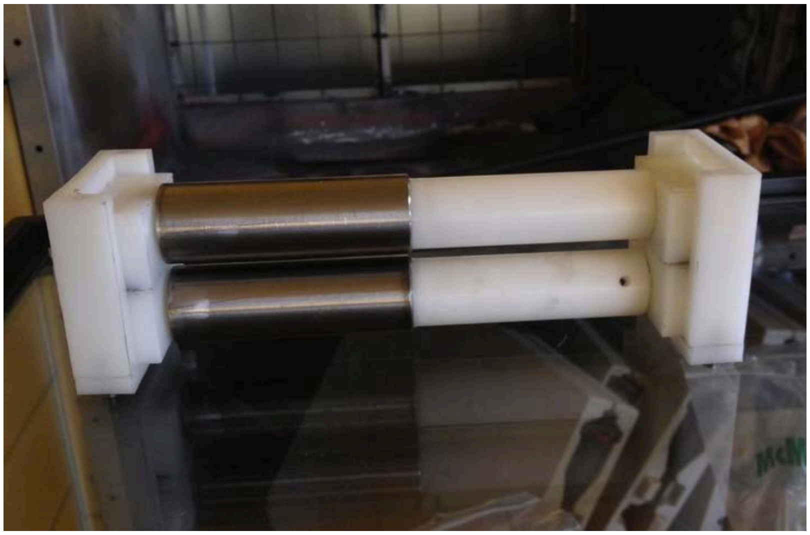


Figure 9.2. Mill subassembly complete and ready to test.

The team was successful in meeting the specification of the mill tolerance and achieved two main mill gap configurations: 1.6mm and 2.1mm. These values were measured using an optical comparator in the Mustang 60' machine shop on campus (Figure 12.3).

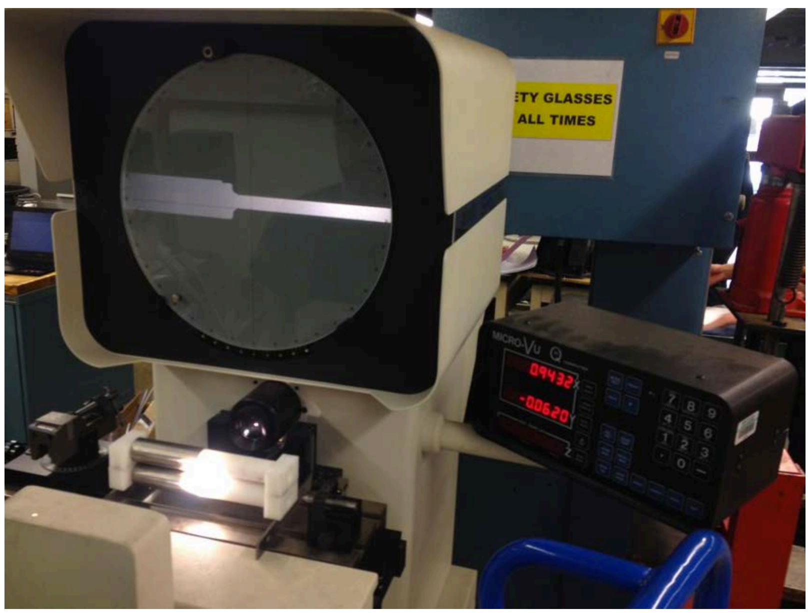


Figure 9.3. *An optical comparator was used to precisely measure the mill gap for biomass calculations.*

These values were measured to three decimals giving a relatively low resolution uncertainty and allowed the team to proceed with accurate biomass calculations. To reiterate, the biomass was calculated by multiplying the overall surface area of each crushed worm by the thickness of the worm. The thickness was assumed to be equal to the mill gap tolerance.

The drive system was assembled and mounted to the outer frame (Figure 12.4), with drive shafts protruding through and connecting to the bottom mill and the collection spool via set screws.

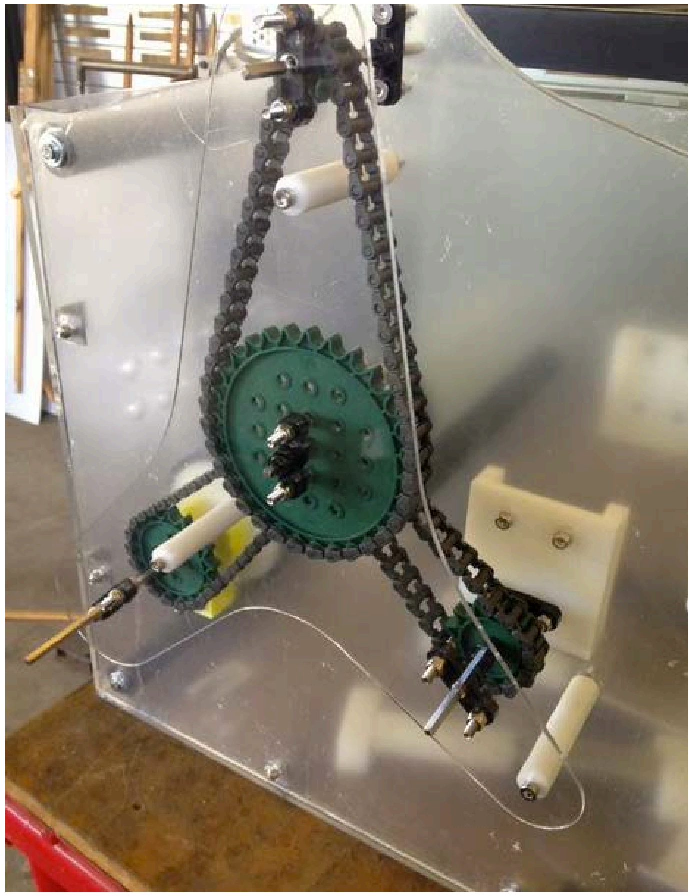


Figure 9.4. *Drive system assembled and mounted to the frame of the test bed with acrylic housing cover.*

Overall, manufacturing methods used include the use of a 3-axis mill, lathe, 3D printer, laser cutter, and general shop equipment such as a drill press, taps/dyes, and various power tools all available through Cal Poly machine shops in Mustang '60 and the Hangar. Additionally, the final completed system has no differences whatsoever from our planned design and was fabricated as specified in the previous sections.

9.1 Frame Superstructure and Containment Area

The system's sidewalls and containment area were made of acrylic sheets laser cut to size and with appropriate holes for component mounting. To make each piece, the solid models from SolidWorks were converted to vector files that can be used by the laser cutter Adobe Illustrator software. Once imported to this software, parameters such as laser intensity were adjusted given the thickness of the acrylic sheet used. Once the origin of the machine was set to the corner of an inserted sheet, the program was run and the machine automatically cut the sheets to specification. Support structure rods were simply made on a lathe with mounting screw holes drilled and tapped accordingly.

9.2 Mill Subassembly

The mill subassembly was created primarily using a 3-axis mill and lathe. The slider blocks, caps, and rails were machined by hand on a mill. These parts were fabricated as meticulously and precisely as possible to ensure the resulting parts were made within tolerance due to their sensitivity on the system's overall performance. Similarly, the mill rods were machined to size as accurately as possible on a lathe since they had a great effect on the gap between the mills.

9.3 Drive Subassembly

The drive subassembly required minimal custom fabrication. The vast majority of the parts used were off-the-shelf components. Only two of the purchased parts required post-processing, the handle and square drive shafts. The drive shafts needed only to be cut to length and filed for smoothness. The handle simply required a hole drilled into its cylindrical face that was then tapped for a set-screw to affix it to one of the drive shafts. All of the remaining components for the subsystem were used as-is and pieced together to form the functioning subassembly.

9.4 Recommendations for Future Manufacturing

Given the small tolerances required for the system, particularly in the mill subassembly but overall success of the system, we have only one main recommendations for manufacturing considerations of future components. Our recommendation is to reduce the tolerances on the mill components and use high-quality precision machining equipment with digital read-outs for measurements. While this will increase manufacturing time somewhat to ensure part compliance, this would improve the tolerance in the mill gap and reduce tolerance stacking such that the realized gap size more closely matches the precise designed specification. In terms of future design considerations, we would recommend spending more time focusing on the user-interaction element of the device. For example, we realized during assembly that some components were difficult to access. This could have been improved with further investment in design foresight in this regard and through user feedback in the future.

10. Design Verification

10.1 Overview

The following section describes the tests that the team used to verify that their design met the desired engineering specifications. Initial testing was done on the Mark I test bed using dried shrimp shells as animal analogues. The sections below describe the tests that were done on the prototype test bed. A detailed table summarizing the tests below and the necessary equipment can be found in Appendix H

10.2 Collection Test

The team found that the Mark I was able to collect 96% of the analogues that entered its system by doing a series of tests. Instead of using a turkey baster to inject analogues into the system as done in the prototype tests, the team used inverted cap as a dispersion method. By manually tilting the cap and letting the analogues float up individually, the team was able to estimate how quickly the analogues were entering the system. By changing the angle that the cap was held at, the team was able to see how well the system handled different analogue flowrates.

The team evaluated how well the Mark I collected the analogues by comparing the number of analogues that the system captured to the total number of analogues that entered the system. The team will floated four groups of 25 analogues into the system. Once all of the analogues were released, the team counted the number of analogues that were *not* collected. These analogues were compared against the analogues that were released. The results can be found in Table 10.1.

Table 10.1 *Collection Results*

Analogues Released	Analogues Missed	Percentage Caught
25	1	96%
25	2	94%
25	0	100%
25	1	96%

The majority of the analogues missed slipped in between the containment walls and the top belt. They tended to move towards the edge of the belt and would slip through if the belt slightly wavered. Collection could therefore be improved by increasing the width of the top belt, increasing tension in the top belt, and reorienting the containment walls to better mesh with the top belt. The team also noticed that if the analogues were released too far in the rear that they would get caught on the underside of the top supply spool. Since the top supply spool spins outwards, the analogues caught on it would roll outside of the containment area. The team therefore recommends that the future releasing mechanism releases the animals closer to the mills to prevent this roll-out from happening. With these improvements, the team believes that the collection success rate can be increased to 99%.

10.3 Biomass Test

10.3.1 Overview

The team tested how well the mills crushed the analogues by using an imaging processing system similar to one that would be implemented into the final rover. The team developed a program (described in detail in section 9.3.2) that can take images of the crushed analogues and find their area from a top-down perspective.

The team first weighed a set amount of each analogue on a scale with 0.001g precision. The scale was calibrated using weights from the thermal systems lab. The weighed analogues were then slowly released into the belts to ensure that each analogue was captured. The analogues were then passed through the mills. A Canon LIDE 120 scanner was used to capture the image of the crushed analogues in the belts. These images were entered into the image-processing program to evaluate how the mills increased the area of the analogues and find a correlation between the measured area and the analogues' mass.

The team carried out multiple crushed tests to determine a correlation between the area found by the image processing program and the dry mass of the analogues. The team found that under optimal conditions (no dirt, grime, or other marks on the belt), the image processing could correlate the area of the analogues to their mass to within ±10%. However, under suboptimal conditions, the correlation became less clear at around ±30%. The results of the testing can be found in Table 10.2

Table 10.2 *Biomass Testing Results*

Mass w/ Tray[g]	Biomass [g]	Area (.7 Filter)	Area (.75 Filter)	Area (.8 Filter)
2.7	0.13	62294	135160	216527
2.879	0.309	116323	213923	336770
2.705	0.135	76225	142745	189319
2.751	0.181	82238	130948	202785

10.3.2 Image Processing

A MATLAB program was created to evaluate the effectiveness of the mills. The program (code found in Appendix I) was designed to take images of a predetermined area and find the area of the crushed analogues. The program loads a color image of the belt and the analogues on it and converts it into a black and white image. Since the top belt is white, the program should identify all object on the belt as black and leave the rest of the belt as white. It then sums the total number of pixels and number of white pixels in the image. The number of black pixels can be found by subtracting the white pixels from the total number of pixels. Multiplying the number of black pixels by the ppi (defined by the height the photo was taken at) gives the area of the objects on the belt in the image.

This iteration of image processing worked well for initial testing since the only objects on the belt are the analogues. However, once grit and other objects are included on the belt this program will not work accurately since it will measure the area of both the analogues and the extra objects. The program would have to be updated to ignore the grit and only measure the area of the analogues. One method would be to stain or dye the analogues and have the program filter for a range of colors similar to the stain. There are different stains that can color animal tissue, but the team is not able to make a recommendation for one yet as many of the stains are carcinogens.

The program could also be improved with more refined filters and shape recognition. More refined filters than a simple darkness filter could allow for greater accuracy when measuring the area. Pixels significantly smaller than expected analogue sizes could be filtered out as an example.

Lighting from the behind the belts may improve the program’s accuracy. Shadows of the objects were currently added to the area measured by the program since they were dark on the white belt. By adding back lighting, the team hopes to be able to reduce size the shadows the objects cast.

10.5 Spool Replacement Timing and Ease of Use

Through consistent use of the Mark I, the team tested how easily the spools were replaced. They found the easiest method of spool installation and removal was to have the grabbers pre-tightened and press the spools in.

In order to verify that the spools and overall system is intuitive and easy to use for new users, the team planned on asking four people to set up the spools and mills. The team would have the individuals attempt to replace a set of depleted spools with full spools. The individuals would be required to complete this task with only set of instructions to determine how intuitive the assembly is. The team would time the individuals and will ask where they had trouble refreshing the system.

After having discussed any troubles with the individuals, the team would have them repeat the process and replace the spools again. This second replacement run would be timed as to determine if the instructions need to be clarified or if a minor redesign is necessary to make the system easier to use. However, the team did not have the time to complete this test.

The team wanted the spools to be replaced in under five minutes by individuals who are familiar with the system. This requirement was met as the team quickly and efficiently reloaded spools during the collection and biomass testing. The team does recommend finding a better method for wrapping spools to prevent the belts from wandering.

10.6 Undamaged Specimen

The team observed the analogues on the uncrushed side of the belts for each test. They looked for signs of the analogues being crushed, pulled, or otherwise damaged. They found that the intermediary bar after the mills squished all of the analogues from tension in the belt. After removing the intermediary bar, the analogues passed through undamaged.

10.7 Grit Failure

The team did not do any grit failure testing. If time permitted, the team would work to meet its reach goal of understanding how the system handles grit and other small hard particles. The team would sift through different sizes of particles and deliberately place them into the system. The team would look for any problems that may occur as the grit passes through the mills and into the collection spools. A new imaging system would have to be developed as described to fully analyze the impact of the grit on the crushed size of the analogues. The team would therefore mainly look to see what size of grit the mills can handle before they jam or have other mechanical issues. A prototype soft mill could be introduced determine if a soft mill is a viable solution to prevent jamming.

11. Conclusions and Recommendations

The Marine Benthic Rover Test Bed Team has designed and plans to manufacture a device that captures benthic macrofauna in a fabric spool, flattens them to a consistent thickness, and then allows for the spools to be easily removed for scientific analysis. Special environmental considerations must be taken into account during design, such as the effects of the saltwater environment on component maintenance and longevity and the inclusion of hard sediment particles into the system. As a system overview, the proposed design consists of a frame (sidewalls and supports), supply spools for the fabric and film, a containment area to trap organisms, mills to flatten them, and a collection spool around which the captured organisms are wound.

As a proof-of-concept study, a prototype was constructed, as seen in section 7, and was used to evaluate the functionality of the initial design concept and reveal potential design flaws. From the observations made during these test trials, modifications were implemented into the next design iteration to be made, resulting in the team's proposed final design dubbed Mk II. These changes include the addition of a hand-cranked sprocket and chain drivetrain to power the collection spool and bottom mill, a variable-resistance quick release for removable shafts, steel mills, tension rollers between the mills and collection spool, and guideways on all spools,

Once the final design prototype was complete, it was tested in accordance with our design verification plan. The Marine Biomass Analyzer successfully demonstrated that benthic organisms can be captured and flattened to a consistent thickness for image processing. We recommend that future iterations use precision manufacturing for the mill assembly to reduce tolerance stacking and improve the accuracy of the biomass calculations. We also suggest researching "soft" mills to alleviate potential problems with the mills interacting with hard rocks and shells. A more compact design may also be required to fit the device on a rover as well. With these recommendations in mind, we believe that a "coastal benthic rover" can be built from this concept.

Moving forward, the team recommends investigating the performance of soft versus hard mills, the necessity of bushings on the spool shafts, the use of commercial-grade cleaning agents for system maintenance, and the utilization of precision manufacturing equipment and technicians to improve tolerances. In this regard, the team hopes that this report can be used to continuously refine the product design to improve its functionality and ease-of-use wherever possible.

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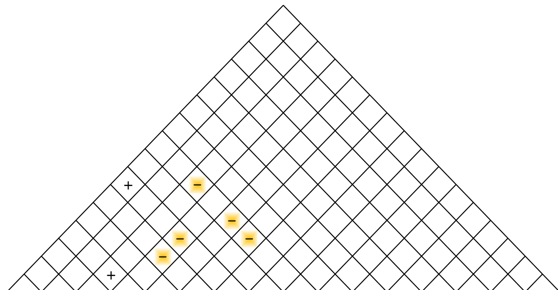
APPENDIX A: QFD: House of Quality
Project: Benthic Rover
Revision: 0
Date: 10/25/2016

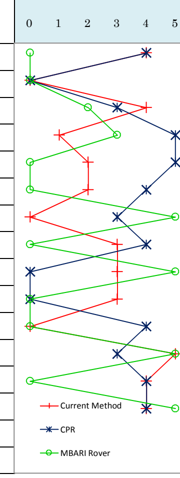
Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

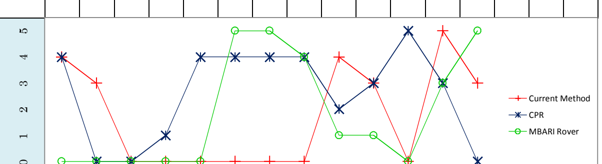


Row #	Weight Chart	Relative Weight	Marine Biologists	Volunteer Users			Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	Collect Shrimp Bits	Separate Collection	Crushed Half Thickness	Crushing Pressure	Belt Lifespan	Drive System Lifespan	Drive System Torque	Replaceable Spool	Production Cost	System Volume	Belt Tensile Strength	Undamaged Specimen	Rocks and Shell Failure				Current Benthic Sampling Method	*Continuous Plankton Recorder*	*MBARI Benthic Rover*			Row #
		WHO: Customers						Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	NOW: Current Product Assesment - Customer Requirements					
								Direction of Improvement	▲	◇	▼	▲	▲	▲	▼	◇	▼	▼	▼	◇	◇									
1		10%	9	5			9	Capture and Store Animals	●	●	▽	○	▽	▽	○	○	▽	▽	○	○	○				4	4	0			1
2		7%	8	2			9	Half of Animals Flattened	○	●	●	●	▽	○	●	▽	○	▽	▽	▽	●				0	0	0			2
3		8%	9	2			9	Half of Animals Identifiable	○	●	▽	▽	▽	▽	▽	▽	▽	▽	▽	●	▽				4	3	2			3
4		10%	9	5			9	Continuous Collection	●	●	▽	▽	▽	○	●	●	○	▽	○	▽	●				1	5	3			4
5		9%	7	5			9	Removable Spool	○	●	▽	▽	▽	▽	▽	●	○	▽	▽	▽	▽				2	5	0			5
6		8%	3	7			9	Device Fits in 150L Tank	▽	▽	▽	▽	▽	▽	○	○	▽	●	▽	▽	▽				2	4	0			6
7		5%	3	3			9	Drive System	●	○	▽	●	▽	●	●	○	●	●	●	○	○				0	3	5			7
8		11%	5	9			9	Easy to Run System and Re-Set Up	○	▽	▽	●	▽	▽	●	●	▽	○	▽	▽	○				3	4	0			8
9		7%	3	6			9	Handle Rocks and Shells	○	▽	●	●	○	●	○	▽	▽	▽	○	▽	●				3	0	5			9
10		3%	3	1			9	Split Collection in Half	○	●	▽	▽	○	▽	▽	○	▽	○	▽	○	▽				3	0	0			10
11		3%	4	1			9	Hairy, Strong, Permeable Top Belt	●	●	●	●	○	▽	▽	▽	●	▽	●	▽	▽				0	4	0			11
12		3%	4	1			9	Time Stamp Collection	●	●	▽	▽	○	▽	○	○	○	○	○	▽	▽				5	3	5			12
13		3%	5	0			9	Dye Injection for Biomass	○	▽	●	▽	▽	▽	▽	▽	●	○	▽	▽	▽				4	4	0			13
14		11%	5	9			9	Durable System	▽	▽	▽	▽	●	●	○	▽	●	○	●	▽	●				4	4	5			14
15		0%																												15
16		0%																												16



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	90% @ TBD Flowrate	2 Groups	<0.25mm	TBD	3 Years	5 Years	<5 Nm	5 Minutes	TBD	0.1m^3	TBD	Identifiable under micrscope	<10mm			
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9			
Technical Importance Rating	454.38	541.72	268.18	390.1	224.51	320.29	446.75	403.73	340.75	266.88	318.02	196.59	439.45			
Relative Weight	10%	12%	6%	8%	5%	7%	10%	9%	7%	6%	7%	4%	10%			
Weight Chart																
Current Benthic Sampling Method	4	3	0	0	0	0	0	0	4	3	0	5	3			
Continuous Plankton Recorder (CPR)	4	0	0	1	4	4	4	4	2	3	5	3	0			
MBARI Benthic Rover	0	0	0	0	0	5	5	4	1	1	0	3	5			

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 B: Design Matrices

Concept	Weight	Crushing Consistency 25%	Rock Inclusions 20%	Ease of Fabrication 10%	Integration with System 25%	Cost 10%	Maintenance 10%	Total 100%
Rolling Mills	Rating	90	50	75	90	90	75	
	Weighted Rating	22.5	10	7.5	22.5	9	7.5	**79**
Alternate Mill	Rating	100	10	75	75	90	50	
	Weighted Rating	25	2	7.5	18.75	9	5	**67.25**
Stamp (Geneva)	Rating	90	50	50	10	50	50	
	Weighted Rating	22.5	10	5	2.5	5	5	**50**
Stamp (Moving)	Rating	90	50	50	90	75	50	
	Weighted Rating	22.5	10	5	22.5	7.5	5	**72.5**
Spool Tension	Rating	10	90	75	100	90	90	
	Weighted Rating	2.5	18	7.5	25	9	9	**71**
Weights	Rating	50	90	90	50	90	90	
	Weighted Rating	12.5	18	9	12.5	9	9	**70**
Vacuum/ Pressure	Rating	50	75	75	50	50	50	
	Weighted Rating	12.5	15	7.5	12.5	5	5	**57.5**

100 Complete satisfaction, objective satisfied in every respect
90 Extensive satisfaction, objective satisfied in all important aspects
75 Considerable satisfaction, objective satisfied in majority of aspects
50 Moderate satisfaction, a middle point between complete satisfaction and no satisfaction
25 Minor satisfaction, objective satisfied in some but less than half of the aspects
10 Minimal satisfaction, objective satisfied to a very small extent
0 No satisfaction, objective not satisfied in any aspect

Spool-Core Attachment							
		Ease of Operation	Ease of Fabrication	Integration with System	Cost	Maintenance	Total
	Weight	40%	15%	20%	10%	15%	**100%**
2 Keyed Cores + Spring	Rating	90	50	90	75	75	
	Weighted Rating	36	7.5	18	7.5	11.25	**80.25**
"Negative Gear" + Spring	Rating	75	25	75	50	25	
	Weighted Rating	30	3.75	15	5	3.75	**57.5**
2 Tapered Cores	Rating	90	90	10	90	90	
	Weighted Rating	36	13.5	2	9	13.5	**74**
2 Cotter Pin Cores	Rating	25	75	90	90	50	
	Weighted Rating	10	11.25	18	9	7.5	**55.75**
1 Hinged Core	Rating	90	10	75	75	75	
	Weighted Rating	36	1.5	15	7.5	11.25	**71.25**
	Rating						
	Weighted Rating	0	0	0	0	0	**0**
	Rating						
	Weighted Rating	0	0	0	0	0	**0**

100	Complete satisfaction, objective satisfied in every respect
90	Extensive satisfaction, objective satisfied in all important aspects
75	Considerable satisfaction, objective satisfied in majority of aspects
50	Moderate satisfaction, a middle point between complete satisfaction and no satisfaction
25	Minor satisfaction, objective satisfied in some but less than half of the aspects
10	Minimal satisfaction, objective satisfied to a very small extent
0	No satisfaction, objective not satisfied in any aspect

Belt-Spool

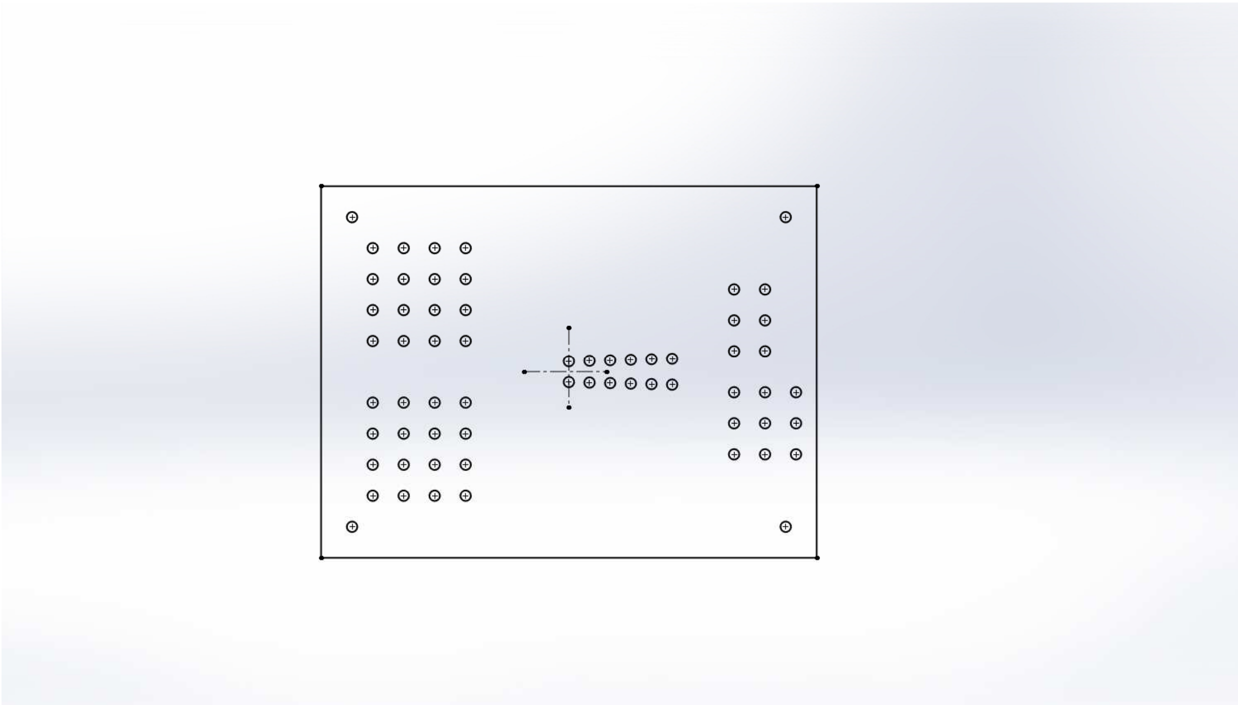
Concept	Weight	Ease of Operation	Ease of Fabrication	Cost	Total
		40%	40%	20%	100%
Open Seam Round Tubing	Rating	90	90	90	
	Weighted Rating	36	36	18	**90**
Adhesive: Belt-to-Belt	Rating	50	50	75	
	Weighted Rating	20	20	15	**55**
Adhesive: Belt-to-Spool	Rating	50	50	50	
	Weighted Rating	20	20	10	**50**
Spikes	Rating	25	10	10	
	Weighted Rating	10	4	2	**16**

100 Complete satisfaction, objective satisfied in every respect
90 Extensive satisfaction, objective satisfied in all important aspects
75 Considerable satisfaction, objective satisfied in majority of aspects
50 Moderate satisfaction, a middle point between complete satisfaction and no satisfaction
25 Minor satisfaction, objective satisfied in some but less than half of the aspects
10 Minimal satisfaction, objective satisfied to a very small extent
0 No satisfaction, objective not satisfied in any aspect

Belt Layout						
Concept	Weight	Collection Consistency 40%	Ease of Fabrication 20%	Integration with System 30%	Cost 10%	Total **100%**
Two Belts	Rating	50	75	90	75	
	Weighted Rating	20	15	27	7.5	**69.5**
Two Belts Overlapped	Rating	90	10	10	50	
	Weighted Rating	36	2	3	5	**46**
One Belt w/ Spacer	Rating	90	90	75	90	
	Weighted Rating	36	18	22.5	9	**85.5**

100	Complete satisfaction, objective satisfied in every respect
90	Extensive satisfaction, objective satisfied in all important aspects
75	Considerable satisfaction, objective satisfied in majority of aspects
50	Moderate satisfaction, a middle point between complete satisfaction and no satisfaction
25	Minor satisfaction, objective satisfied in some but less than half of the aspects
10	Minimal satisfaction, objective satisfied to a very small extent
0	No satisfaction, objective not satisfied in any aspect

Appendix C: Side View of Prototype Layout



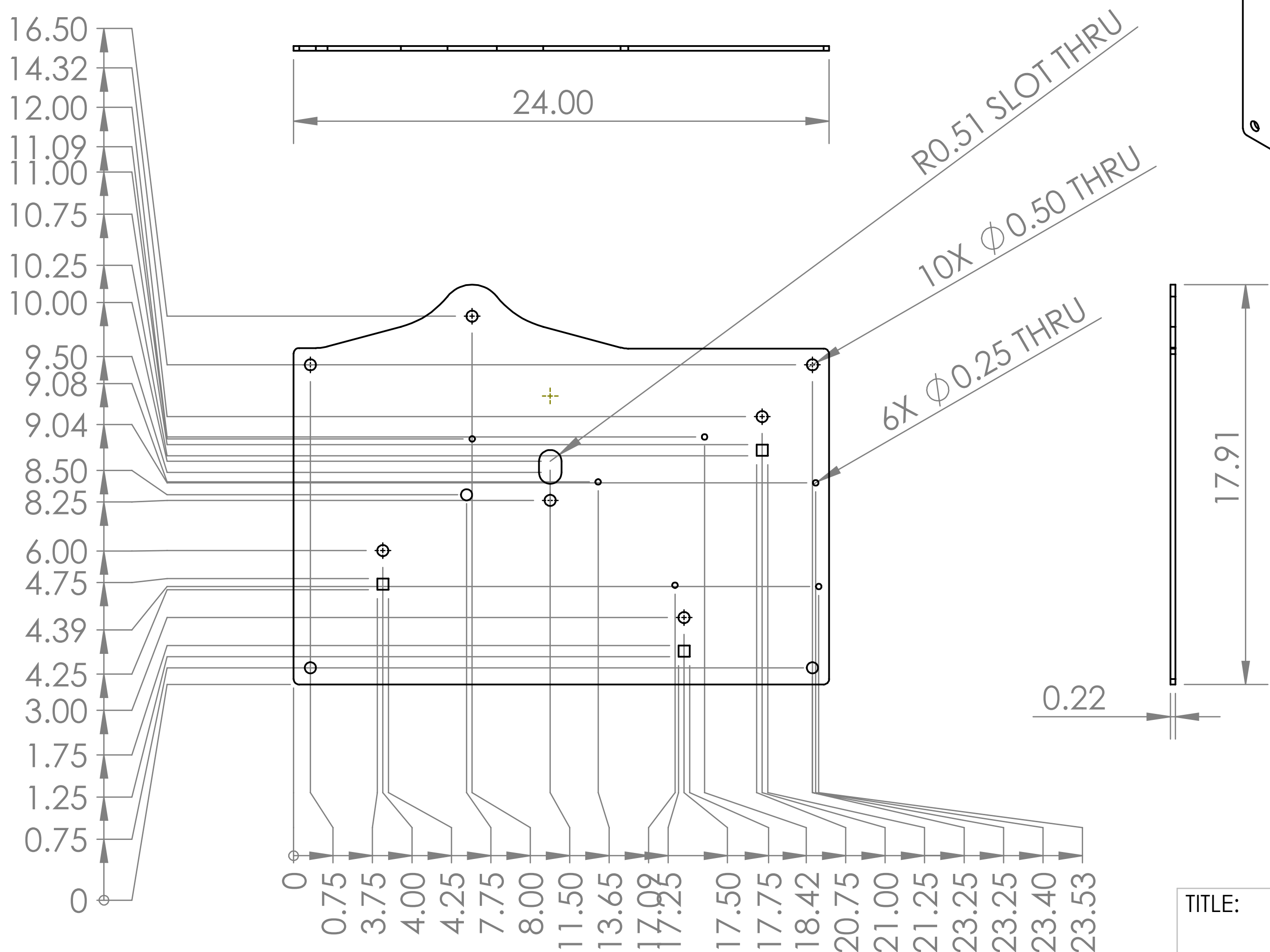
Appendix D - Belt Velocity MATLAB

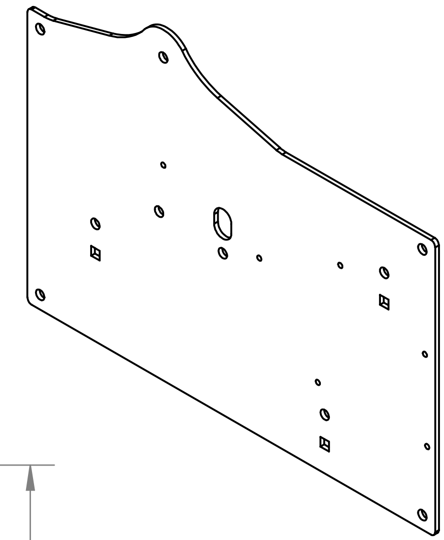
```
%% Drivetrain Analysis
% Written by Brian Paris
% 28 January 2017
% This script determines the rpm required from the collection spool
% that achieves a desired linear speed rate
% This aids us when considering that the collection spool and mills are
% driven directly together so we want to minimize variation in rpm.

%% Start from Scratch
close all
clear all
clc

%% System Parameters
fabricThickness = convlength(.026, 'in', 'm'); %[m], thickness of white
fabric, input [in]
clearThickness = convlength(.006, 'in', 'm'); %[m], thickness of clear
material, input [in]
totalThickness = fabricThickness + clearThickness; %[m], thickness of layers
going to collection
lengthOfWinding = 10; %[m], length of winding on supply spools, input [ft]
% desired linear speed
desiredLinearSpeed = convlength(1, 'in', 'm'); %[m/s], conveyor speed, input
[in/s]

% Nominal Spool Values
collectionSpoolRadiusEmpty = convlength(2, 'in', 'm'); %[m], radius of
collection empty spool
collectionSpoolRadiusFull = sqrt(lengthOfWinding * totalThickness/pi +
collectionSpoolRadiusEmpty^2); %[m], radius of full collection spool
collectionSpoolRadiusAverage = (collectionSpoolRadiusEmpty +
collectionSpoolRadiusFull)/2; %[m], average radius of spool

% RPM and Linear Speed
desiredSpoolRPM = desiredLinearSpeed*60/collectionSpoolRadiusAverage/(2*pi)
%[rpm], collection spool angular velocity
linearSpeedMin = desiredSpoolRPM/60*2*pi*collectionSpoolRadiusEmpty %[m/s],
conveyor speed when spool empty
linearSpeedMax = desiredSpoolRPM/60*2*pi*collectionSpoolRadiusFull %[m/s],
conveyor speed when spool full
```

Appendix E – Engineering Drawings

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005





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MATERIAL: ACRYLIC SHEET

FINISH:

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	1/30/17
CHECKED		
ENG APPR.		
MFG APPR.		

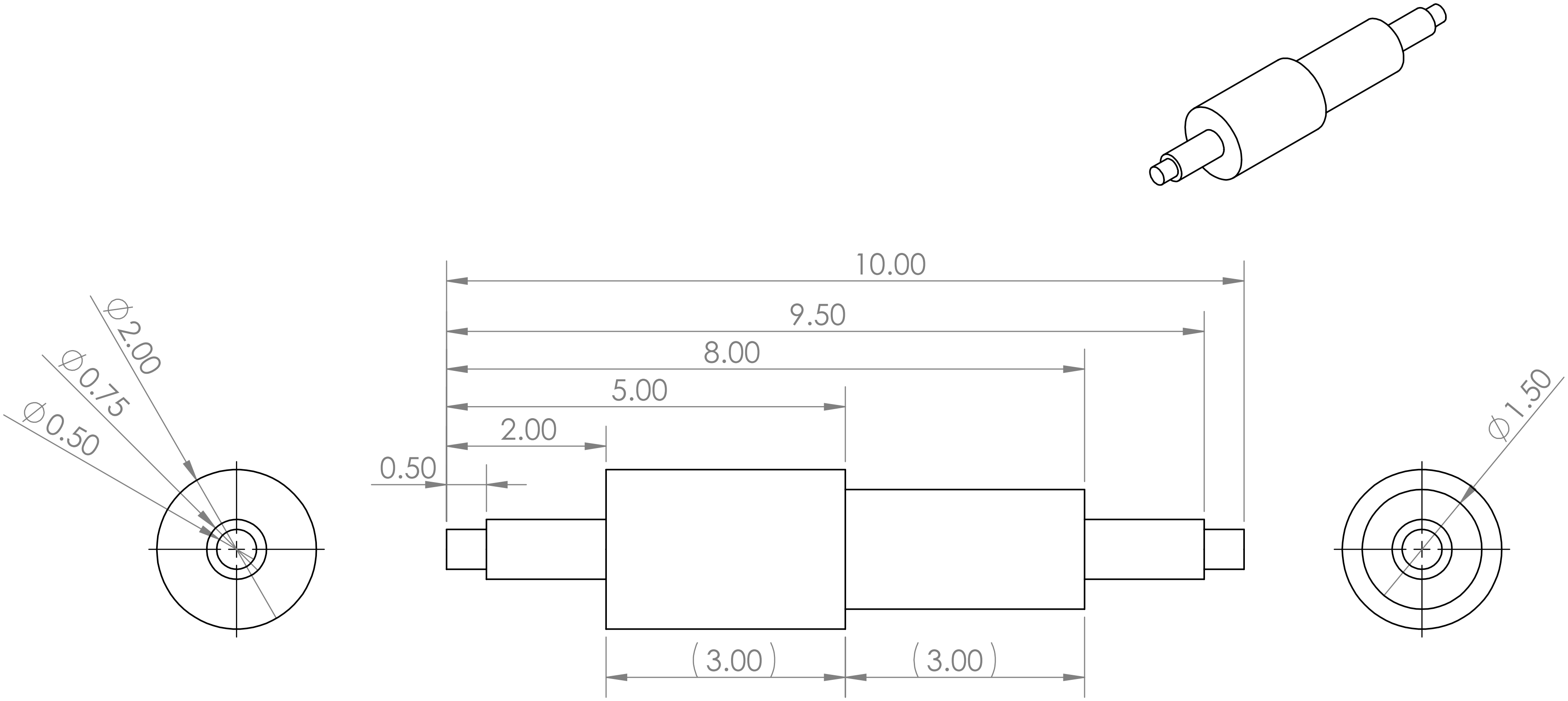
TITLE: FRAME

SIZE	DWG. NO.	REV
A	MB_001	0

SCALE: 1:8 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±



PROPRIETARY AND CONFIDENTIAL

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MATERIAL
SS 316

FINISH

DO NOT SCALE DRAWING

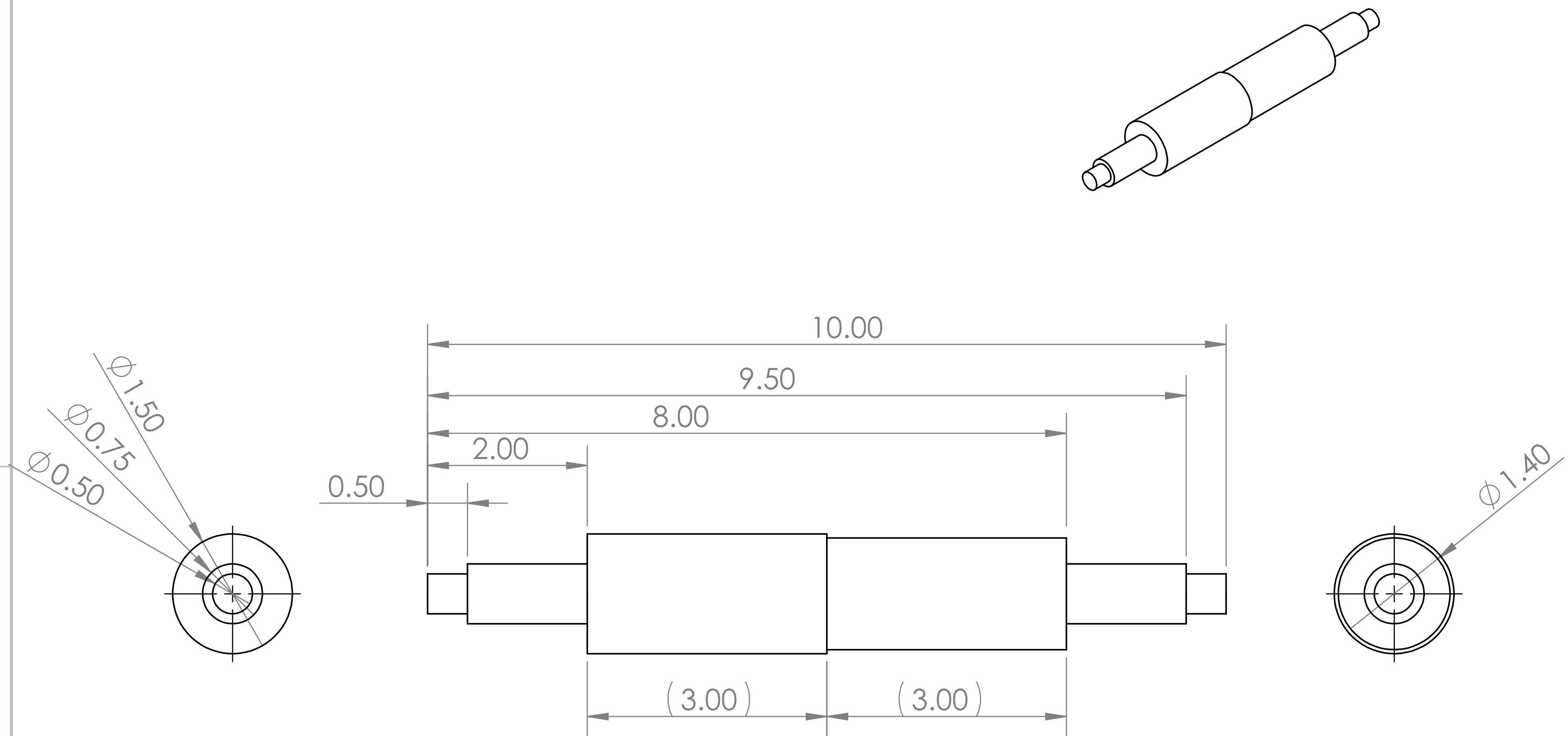
	NAME	DATE
DRAWN	KS	1/30/17
CHECKED		
ENG APPR.		
MFG APPR.		

TITLE:
CRUSHING MILL

SIZE	DWG. NO.	REV
A	MB_002	0
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



MATERIAL
SS 316

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	1/30/17
CHECKED		
ENG APPR.		
MFG APPR.		

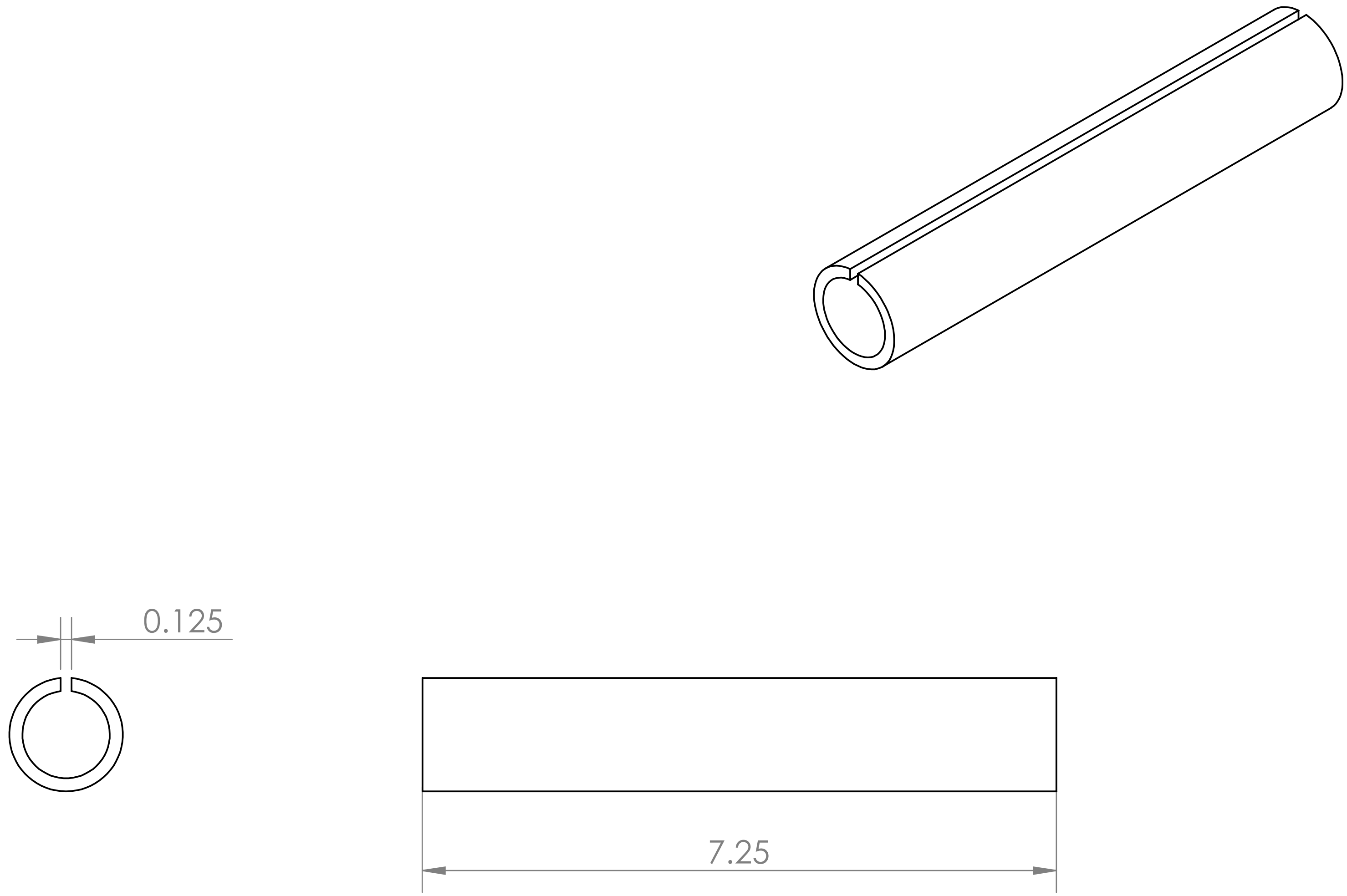
TITLE:
BOTTOM MILL

SIZE	DWG. NO.	REV
A	MB_003	0

SCALE: 1:8 | WEIGHT: | SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



TITLE:	BELT ATTACHMENT CORE	
SIZE A	DWG. NO. MB_004	REV 0
SCALE: 1:4	WEIGHT:	SHEET 1 OF 1

	NAME	DATE
DRAWN	KS	1/30/17
CHECKED		
ENG APPR.		
MFG APPR.		

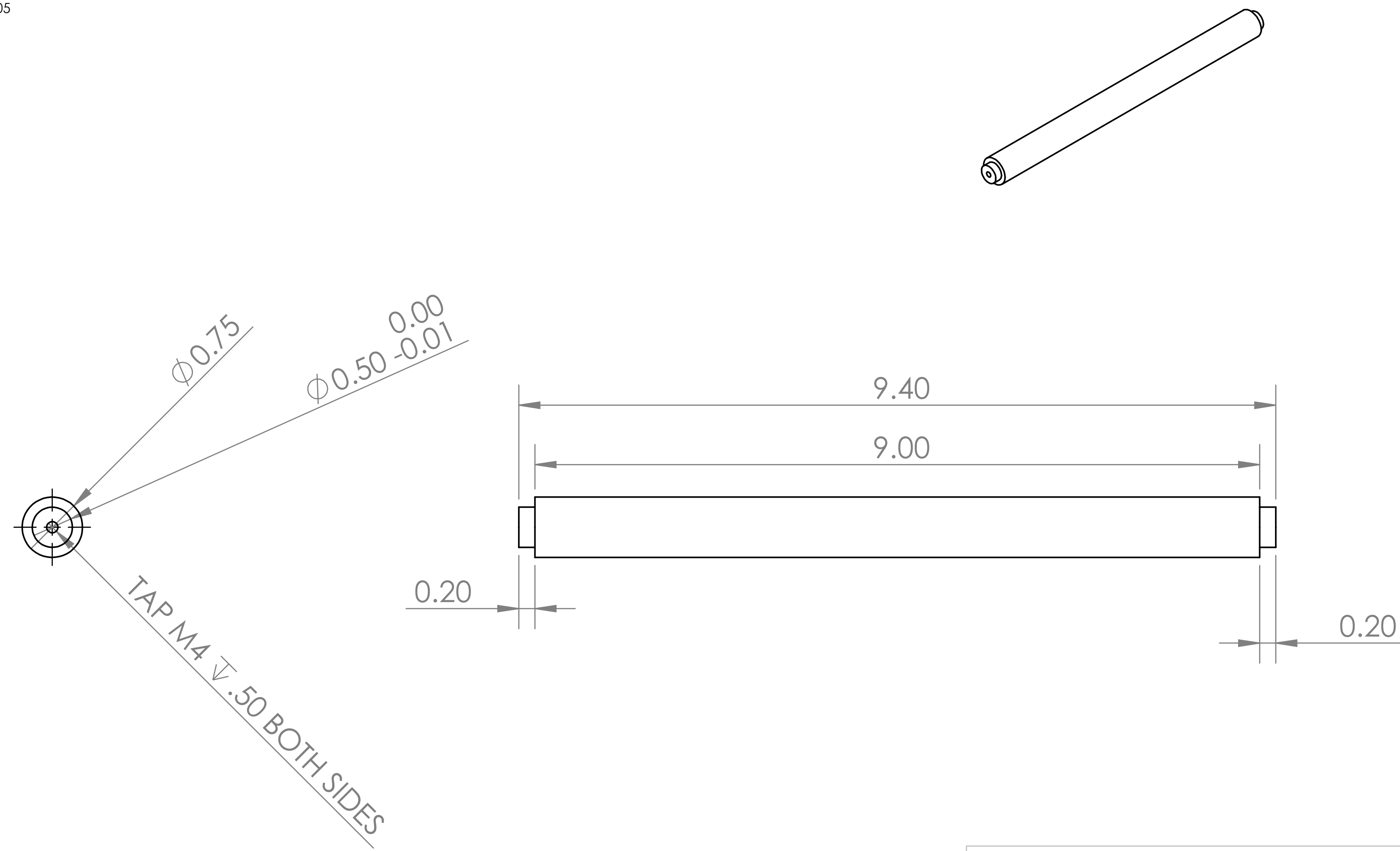
MATERIAL
PVC

FINISH

DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



TITLE:
FRAME STAND OFF SUPPORT

	NAME	DATE
DRAWN	KS	1/30/2017
CHECKED		
ENG APPR.		
MFG APPR.		

MATERIAL
POLYCARBONATE

FINISH

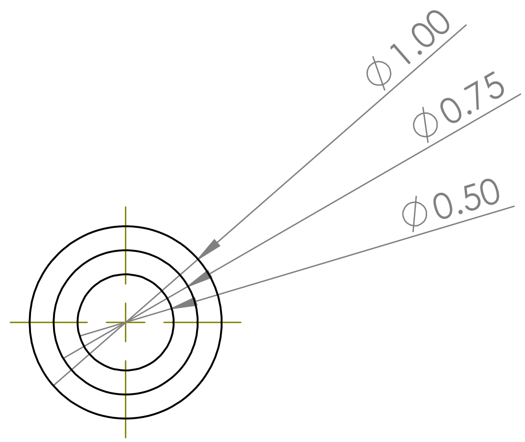
DO NOT SCALE DRAWING

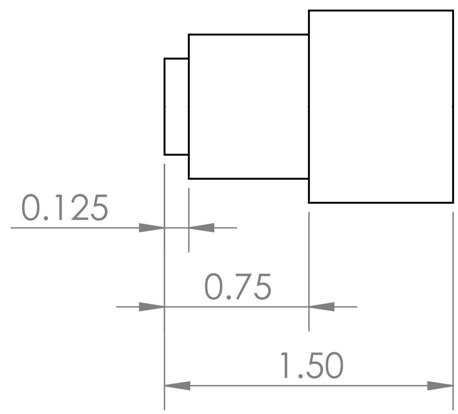
SIZE	DWG. NO.	REV
A	MB_018	0

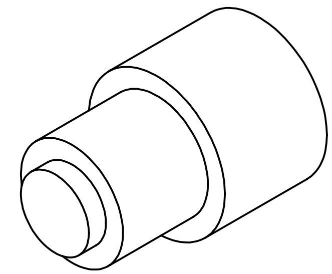
SCALE: 1:4 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005







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MATERIAL
POLYCARBONATE

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	1/30/17
CHECKED		
ENG APPR.		
MFG APPR.		

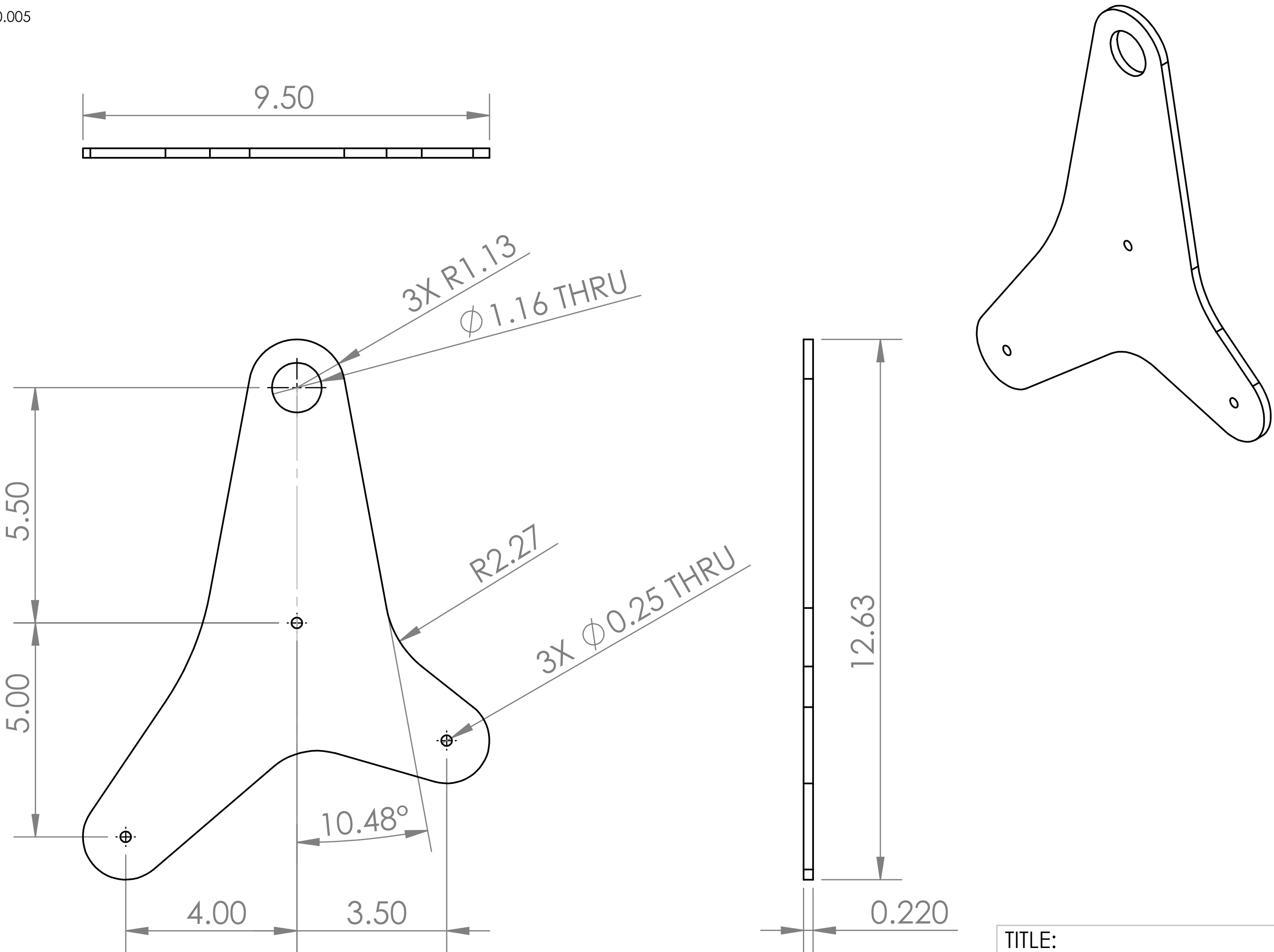
TITLE:
SPOOL CORE

SIZE	DWG. NO.	REV
A	MB_020	0

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ±N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



TITLE: SPROCKET HOUSING PLATE		
SIZE A	DWG. NO. MB_021	REV 0
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		

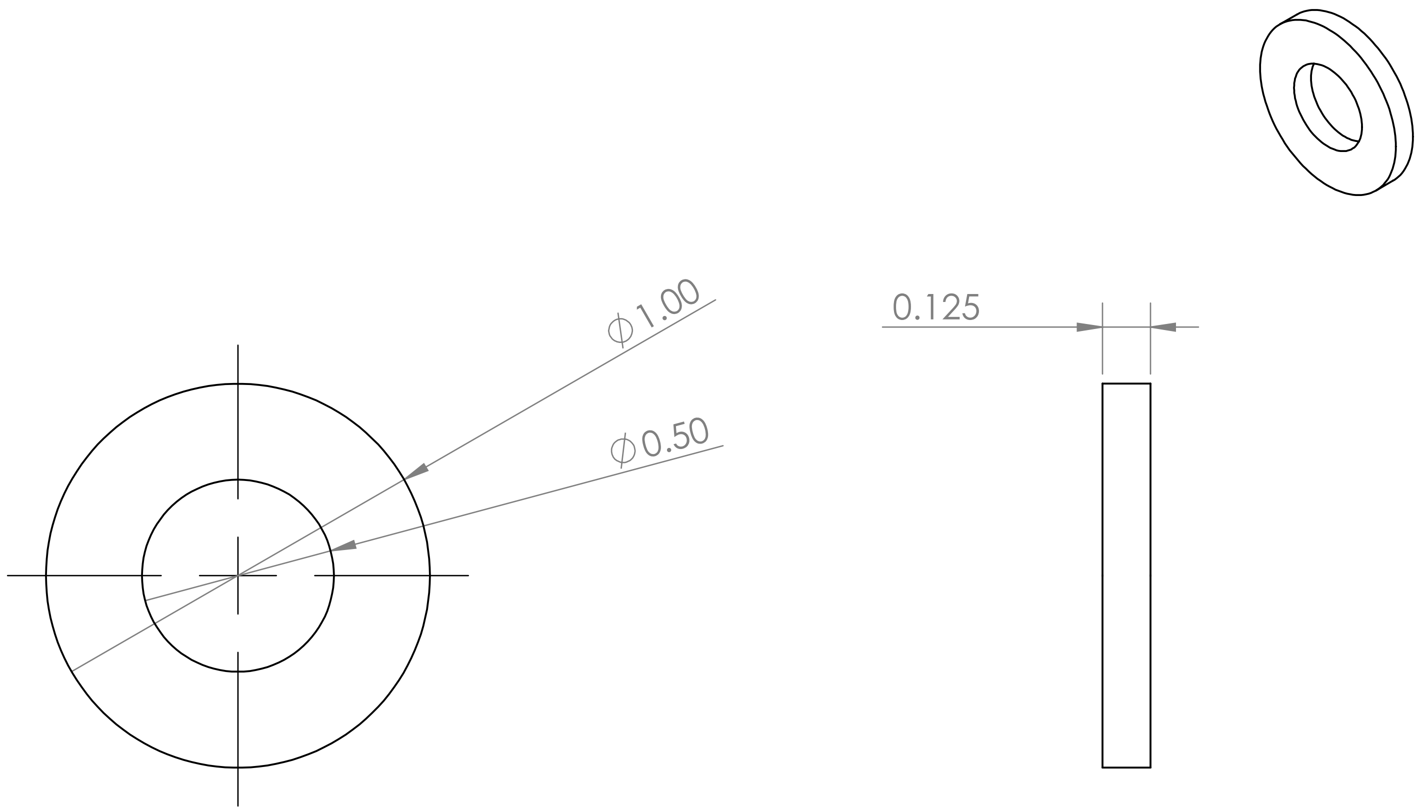
MATERIAL
ACRYLIC

FINISH

DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



PROPRIETARY AND CONFIDENTIAL

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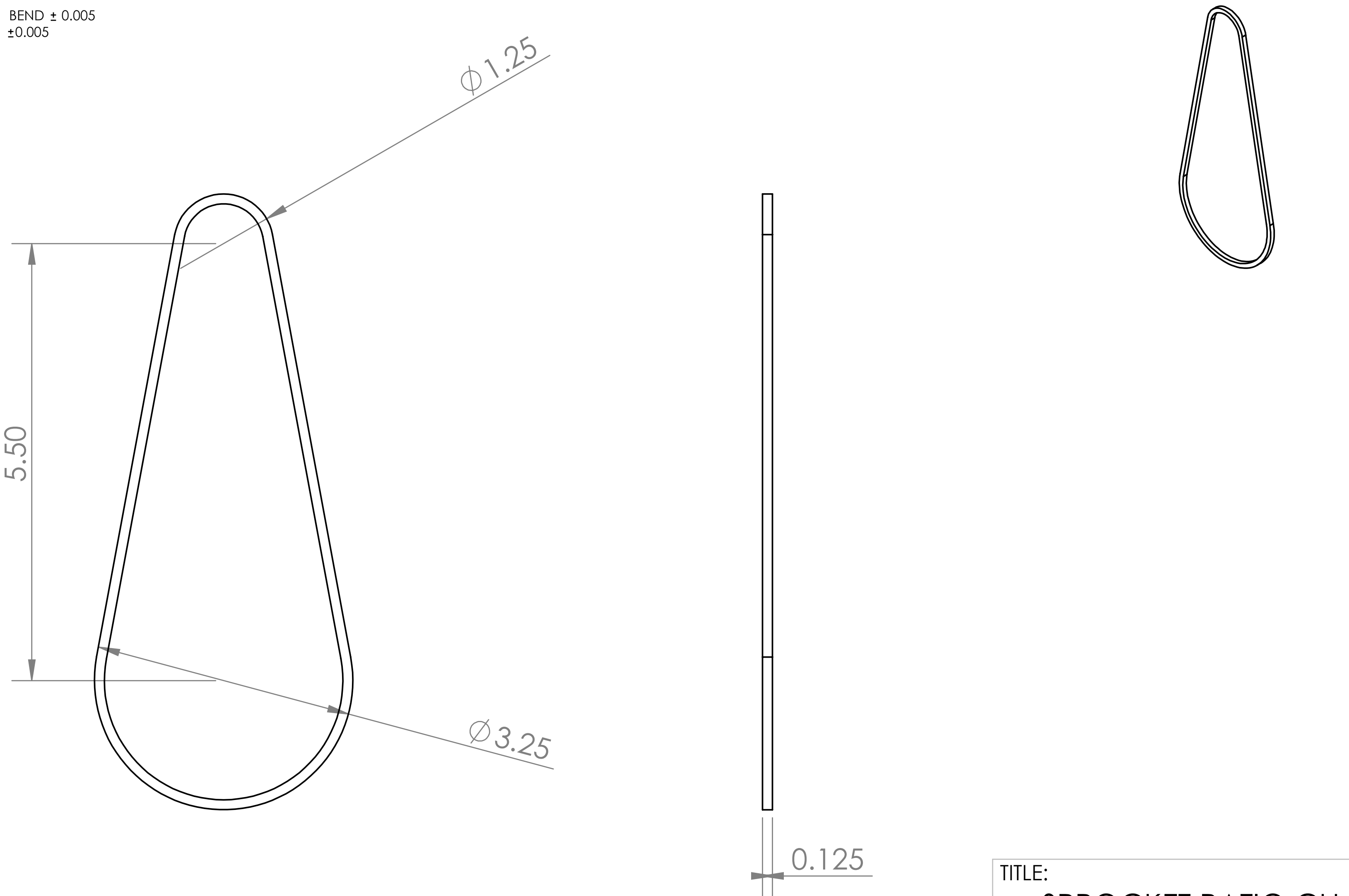
		NAME	DATE
MATERIAL: POLYCARBONATE	DRAWN	KS	1/30/17
FINISH	CHECKED		
	ENG APPR.		
DO NOT SCALE DRAWING	MFG APPR.		

TITLE:

SPOOL SUPPORT RAIL

SIZE	DWG. NO.	REV
A	MB_023	0
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



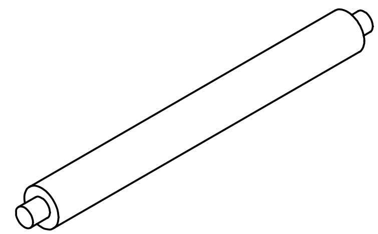
TITLE:	SPROCKET RATIO CHAIN	
SIZE A	DWG. NO. MB_025	REV 0
SCALE: 1:4	WEIGHT:	SHEET 1 OF 1

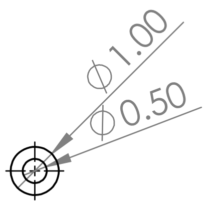
	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		

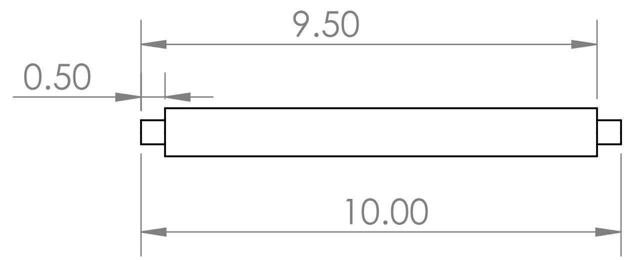
MATERIAL NYLON
FINISH
DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005







MATERIAL: SS 316

FINISH:

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		

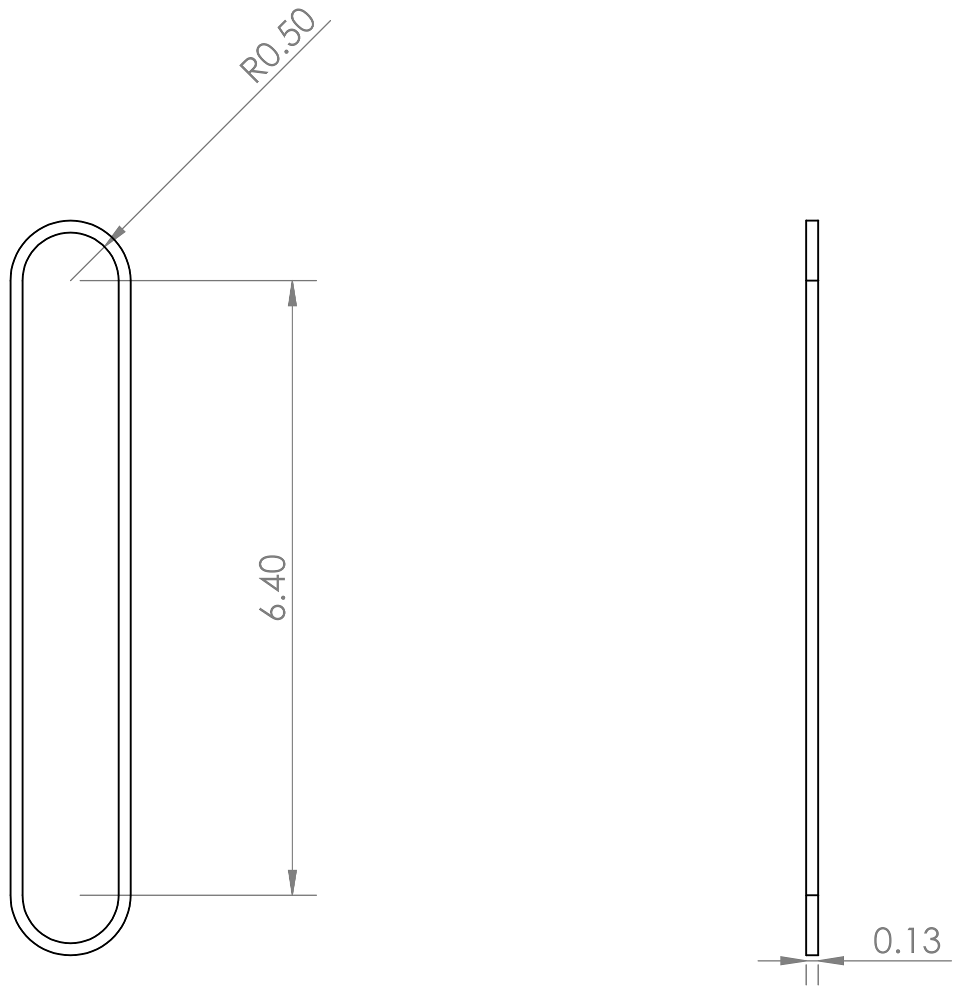
TITLE: TOP MILL

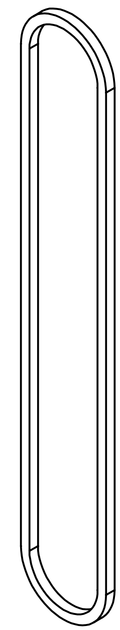
SIZE	DWG. NO.	REV
A	MB_026	0

SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005





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MATERIAL: NYLON

FINISH:

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		

TITLE:

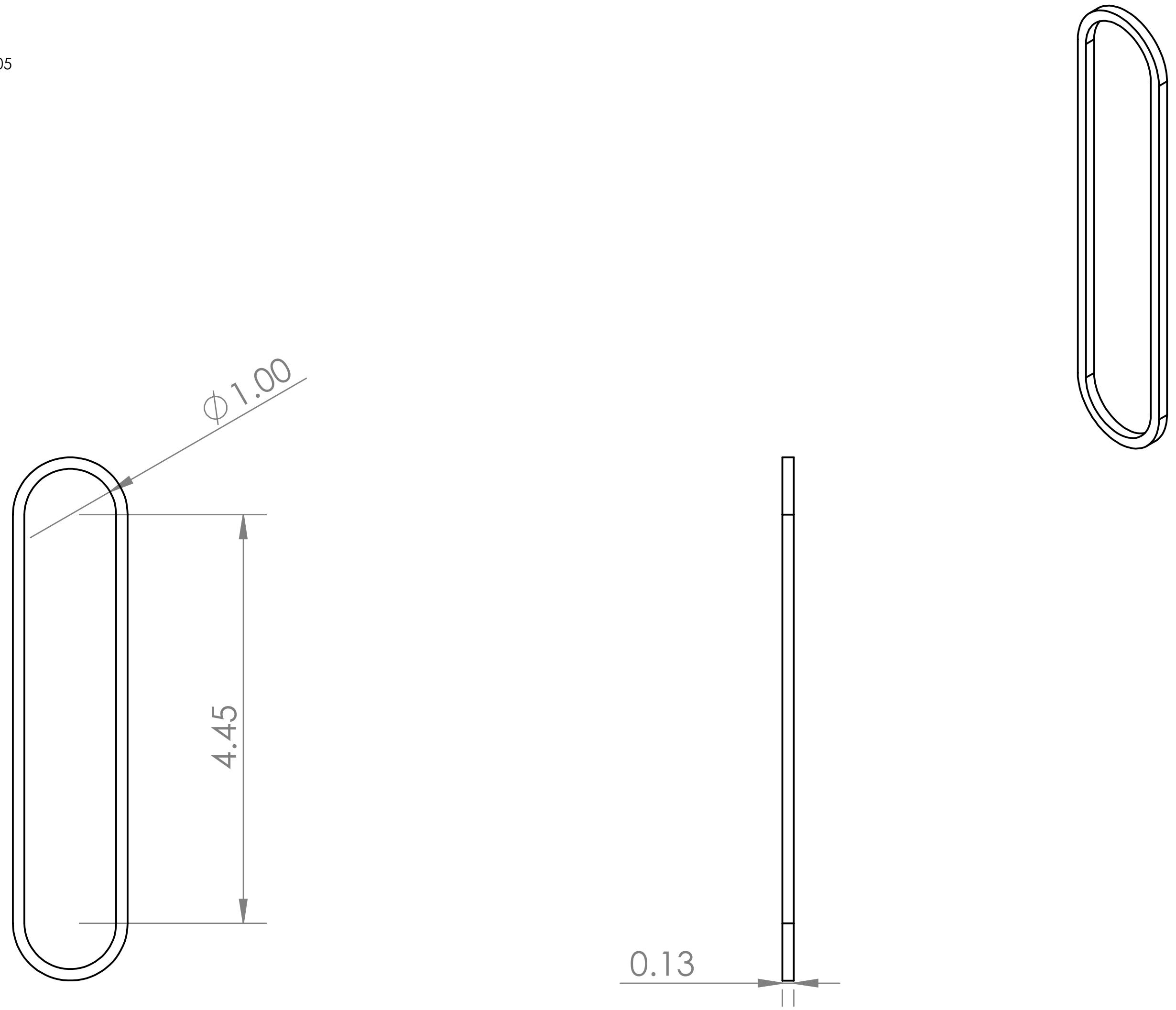
LONG CHAIN

SIZE	DWG. NO.	REV
A	MB_027	0

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



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MATERIAL
PLASTIC ROD

FINISH

DO NOT SCALE DRAWING

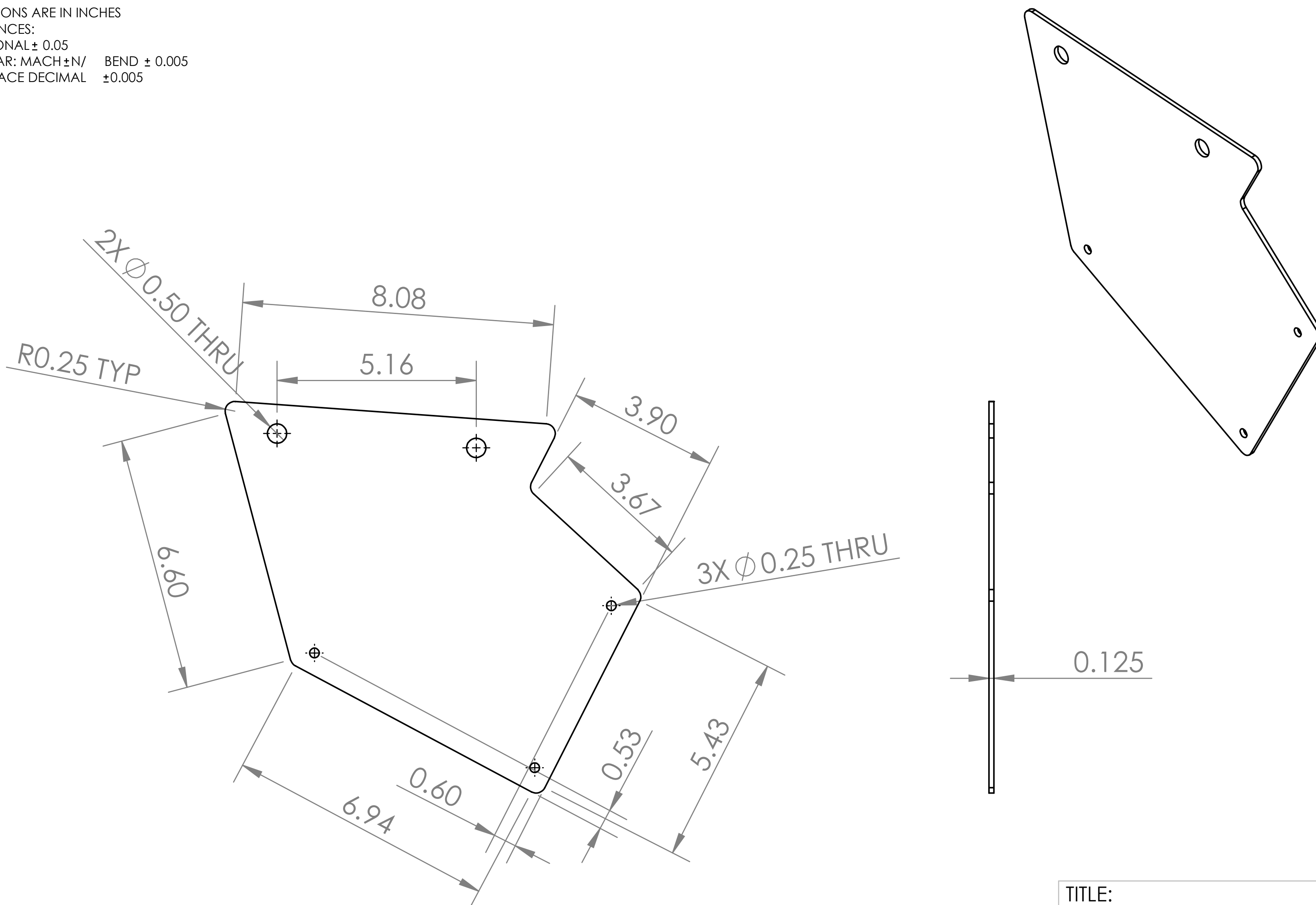
	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		

TITLE:
LONG CHAIN X

SIZE	DWG. NO.	REV
A	MB_027_X	0

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



MATERIAL: ACRYLIC		
FINISH		
DO NOT SCALE DRAWING		

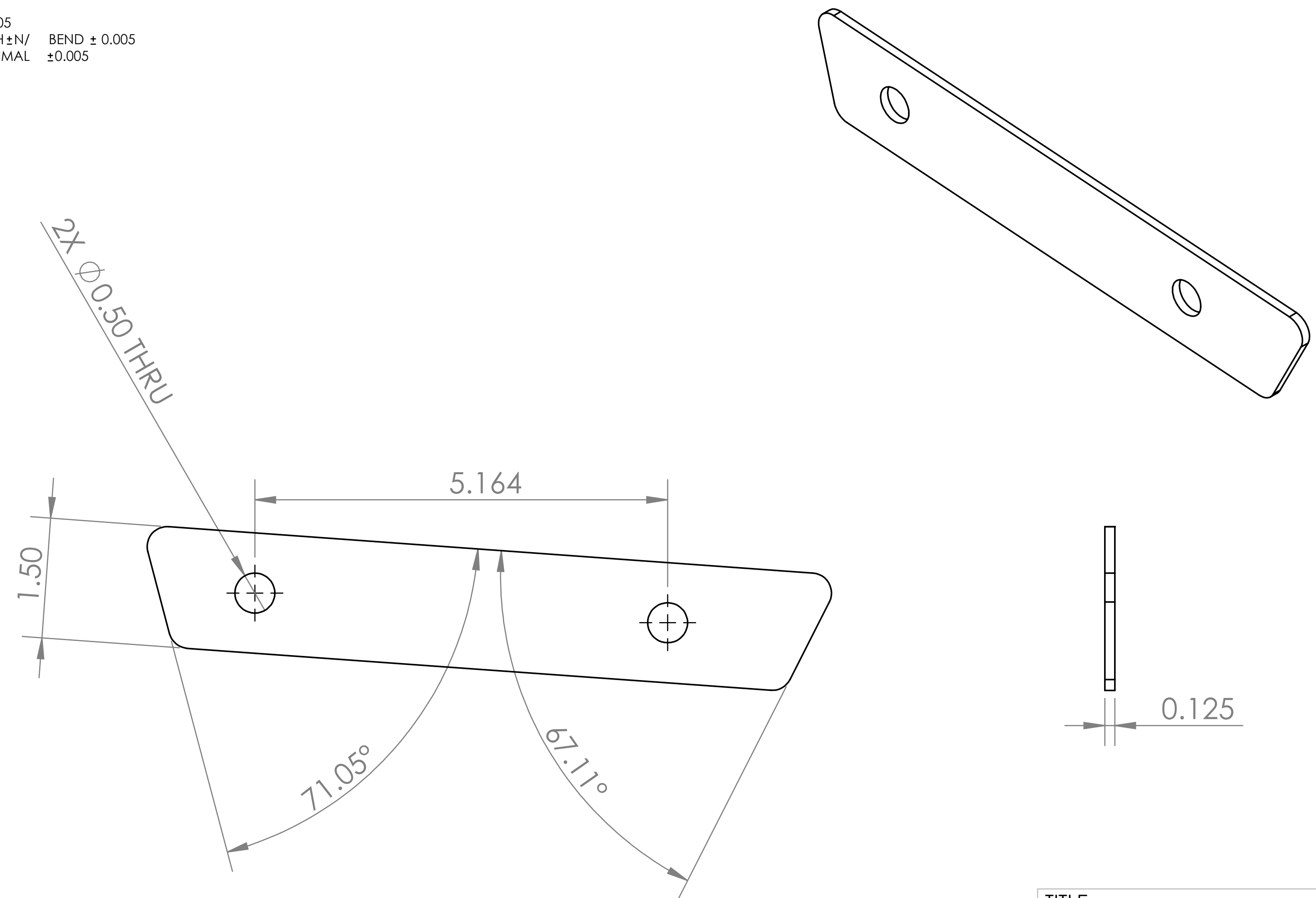
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		

TITLE: CONTAINMENT WALLS

SIZE	DWG. NO.	REV
A	MB_028	0
SCALE: 1:8	WEIGHT:	SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ±N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



TITLE:

TREATMENT DIVIDER

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		

MATERIAL
ACRYLIC

FINISH

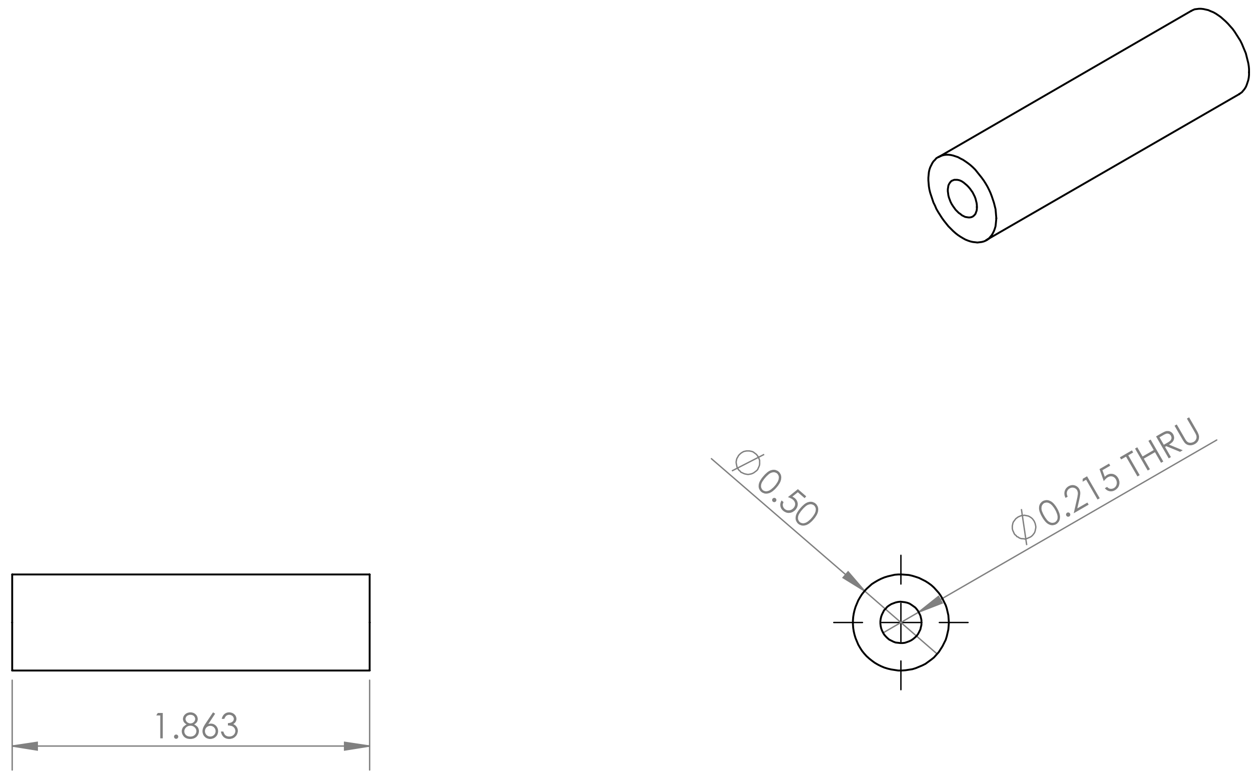
DO NOT SCALE DRAWING

SIZE	DWG. NO.	REV
A	MB_028_X	0

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



MATERIAL
POLYCARBONATE

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		

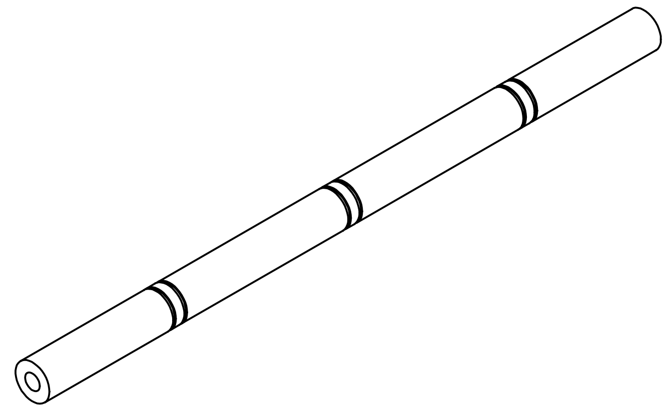
TITLE:
CONTAINMENT STANDOFF SHORT

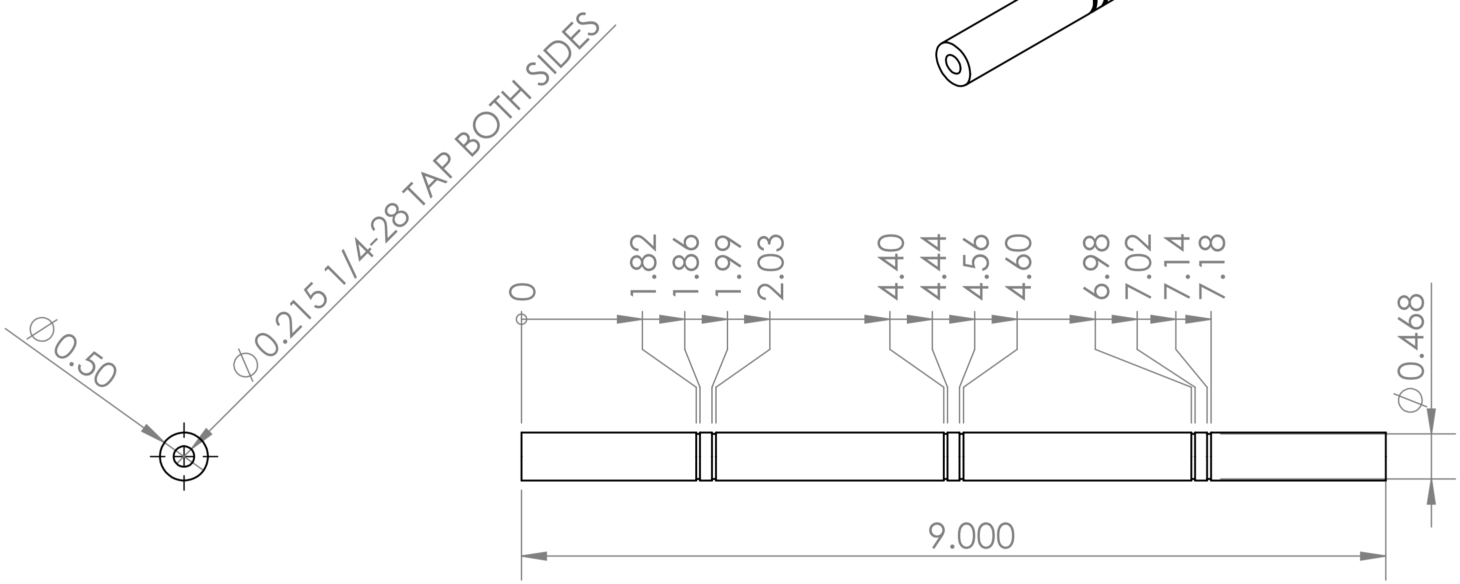
SIZE	DWG. NO.	REV
A	MB_029	0

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005





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MATERIAL
POLYCARBONATE

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		

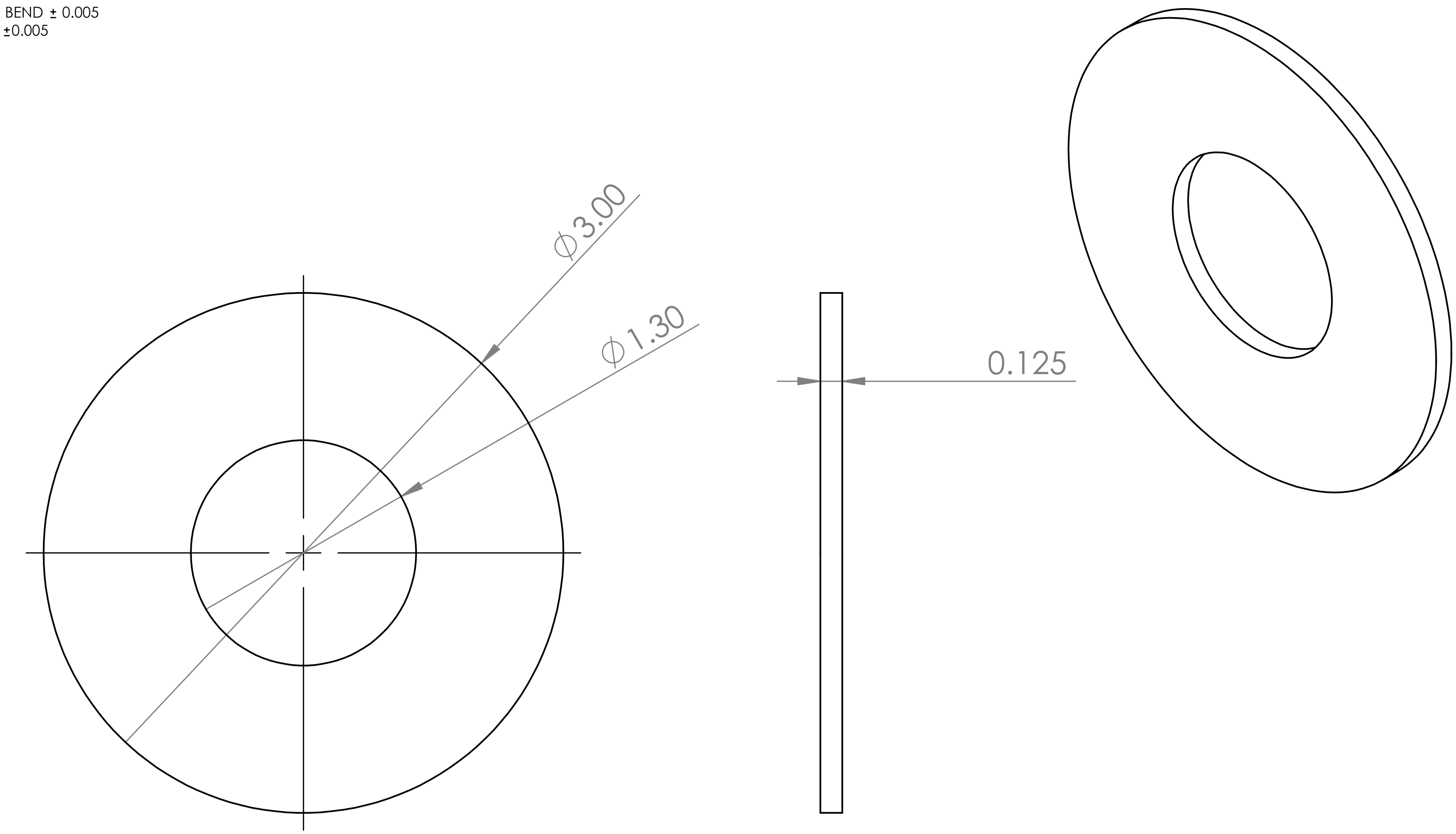
TITLE:
CONTAINMENT STANDOFF LONG

SIZE	DWG. NO.	REV
A	MB_032	0

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005



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		NAME	DATE
MATERIAL: ACRYLIC	DRAWN	KS	2/6/2017
FINISH	CHECKED		
	ENG APPR.		
DO NOT SCALE DRAWING	MFG APPR.		

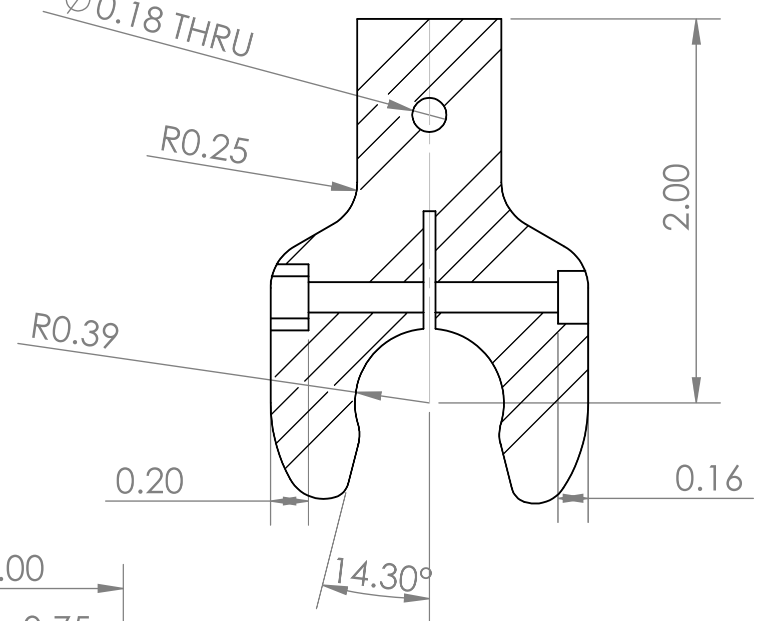
TITLE: BELT MATERIAL GUIDE

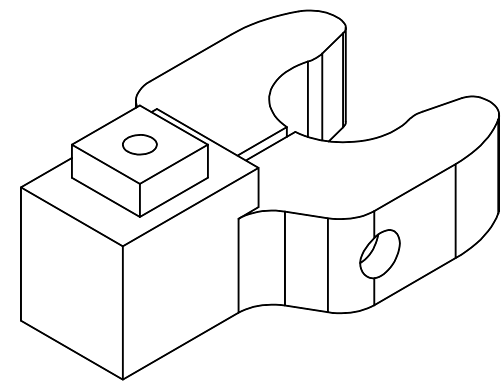
SIZE	DWG. NO.	REV
A	MB_033	0
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

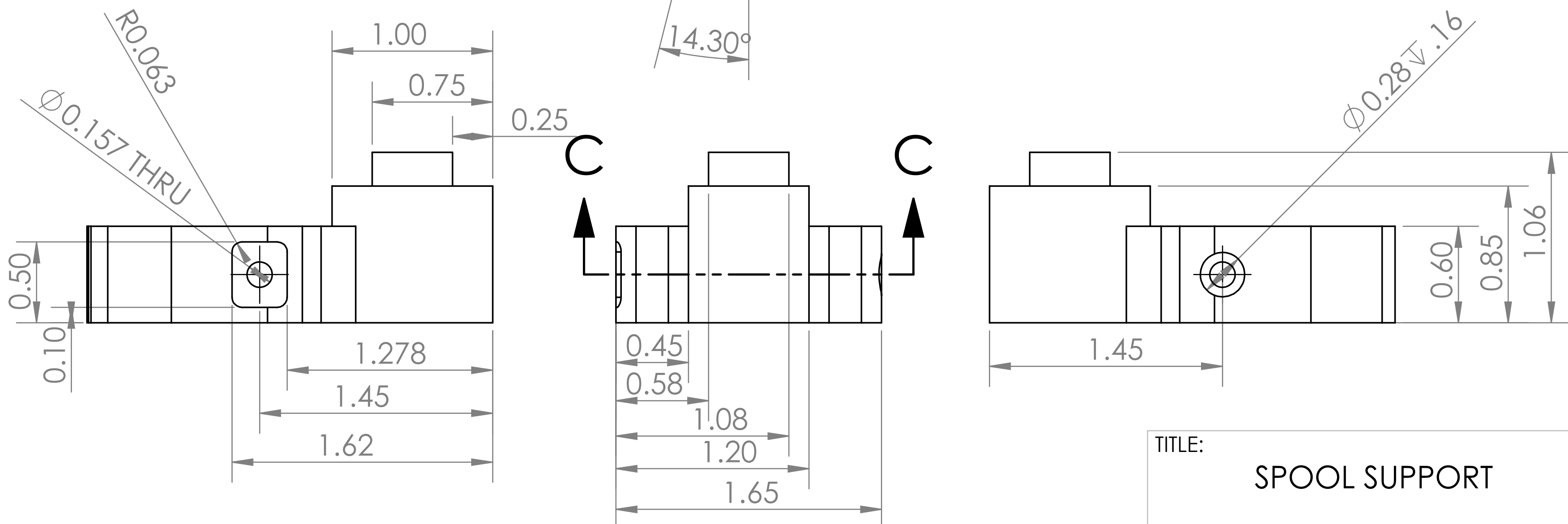
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005

SECTION C-C
SCALE 1 : 1







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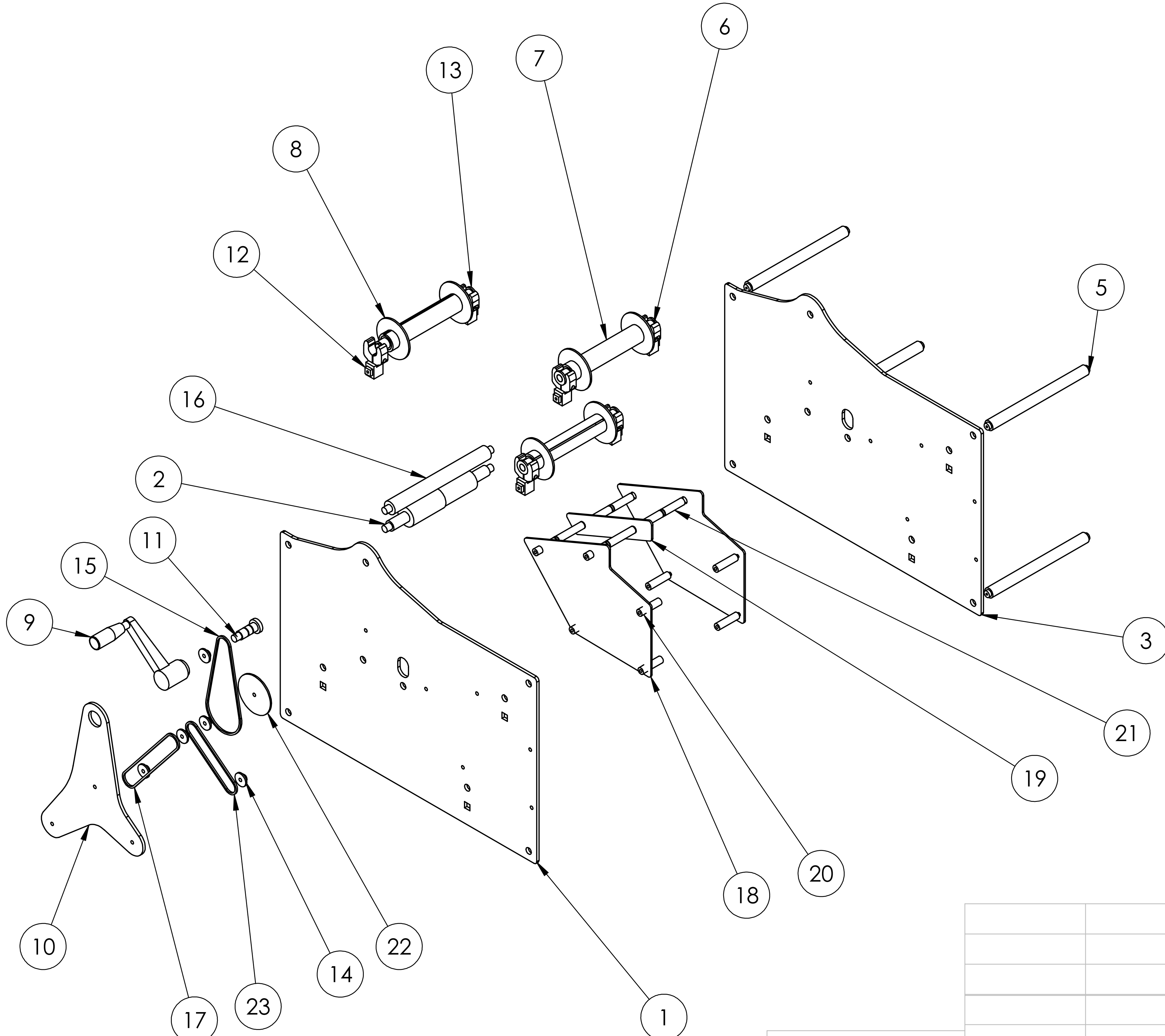
		NAME	DATE
MATERIAL: ACETAL	DRAWN	KS	1/30/2017
FINISH	CHECKED		
	ENG APPR.		
DO NOT SCALE DRAWING	MFG APPR.		

TITLE: SPOOL SUPPORT

SIZE	DWG. NO.	REV
A	MB_BP_Mk1_001	0
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	MB_001	FRAME	1
2	MB_003	BOTTOM MILL	1
3	MB_001_m	FRAME MIRRORED	1
4	MB_TANK	TANK	1
5	MB_018	FRAME STANDOFF SUPPORT	5
6	MB_020	SPOOL CORE	6
7	MB_004	BELT ATTACHMENT CORE	3
8	MB_033	BELT MATERIAL GUIDE	6
9	6129K6	HAND CRANK	1
10	MB_021	GEAR HOUSING PLATE	1
11	MB_022	HAND CRANK SUPPORT	1
12	MB_BP_Mk1_001	SPOOL SUPPORT	6
13	MB_023	SNAP IN GUIDE	6
14	12tSprocket	SPROCKET	5
15	MB_025	SHORT CHAIN	1
16	MB_026	TOP MILL	1
17	MB_027	LONG CHAIN	1
18	MB_028	CONTAINMENT WALLS	2
19	MB_028	Treatment Divider	1
20	MB_029	CONTAINMENT STANDOFF SHORT	6
21	MB_032	CONTAINMENT STANDOFF LONG	2
22	60tSprocket	SPROCKET	1
23	MB_027	LONG CHAIN	1

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± 0.005
TWO PLACE DECIMAL: ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

EXPLODED VIEW OF MARK I TEST BED ASSEMBLY

SIZE B | DWG. NO. MB_ROV_EXPLODED_MARK | REV

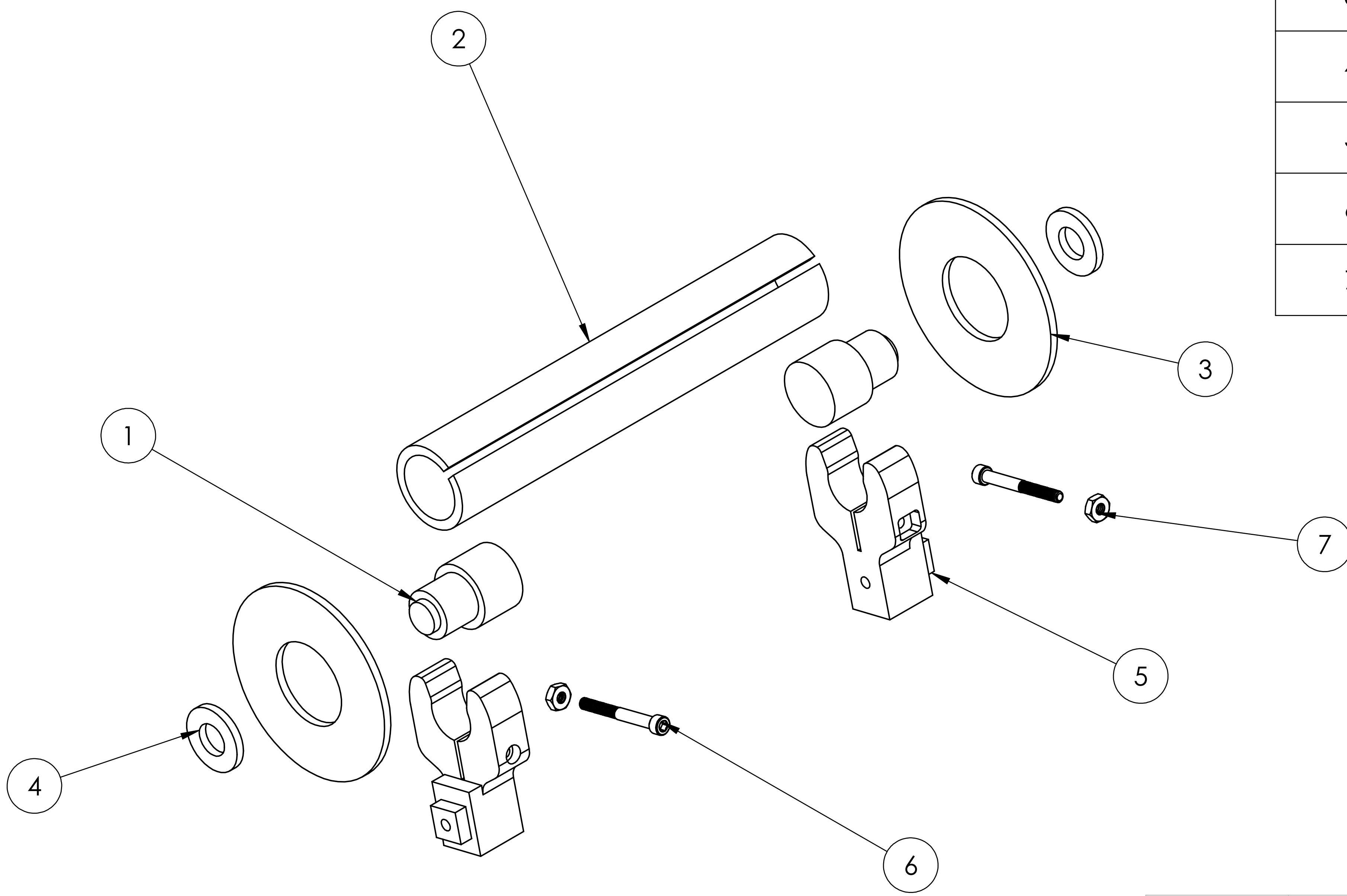
SCALE: 1:24 | WEIGHT: | SHEET 1 OF 1

4 3 2 1

B B

A A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	MB_020	SPOOL CORE	2
2	MB_004	BELT ATTACHMENT CORE	1
3	MB_033	BELT MATERIAL GUIDE	2
4	MB_023	SNAP IN GUIDE	2
5	MB_BP_Mk1_001	SPOOL SUPPORT	2
6	92185A203	8-32 BOLT	2
7	91240A009	8-32 SS NUT	2



PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SPOOL SUPPLY SUB ASSEMBLY

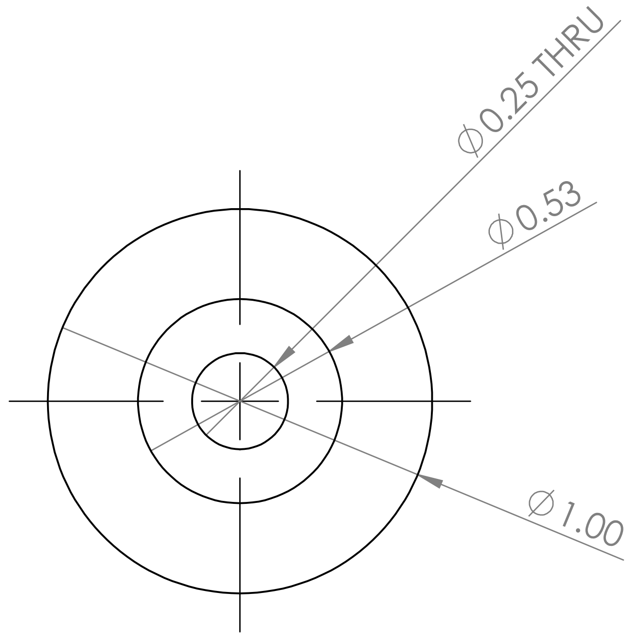
SIZE **B** DWG. NO. SUB_SPOOL_ASSY REV

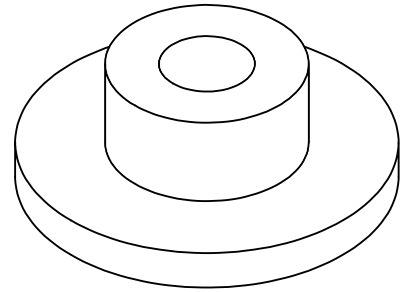
SCALE: 1:8 WEIGHT: SHEET 1 OF 1

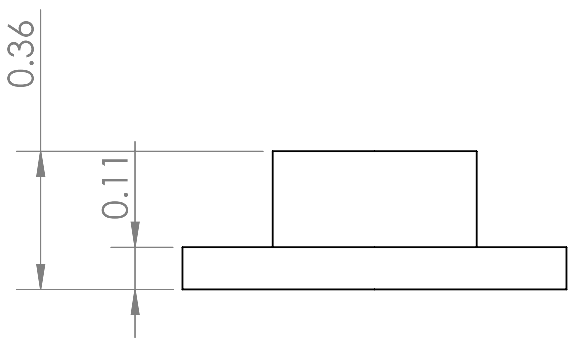
4 3 2 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005







PROPRIETARY AND CONFIDENTIAL

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		NAME	DATE
MATERIAL: NYLON	DRAWN	KS	2/6/2017
FINISH	CHECKED		
	ENG APPR.		
DO NOT SCALE DRAWING	MFG APPR.		

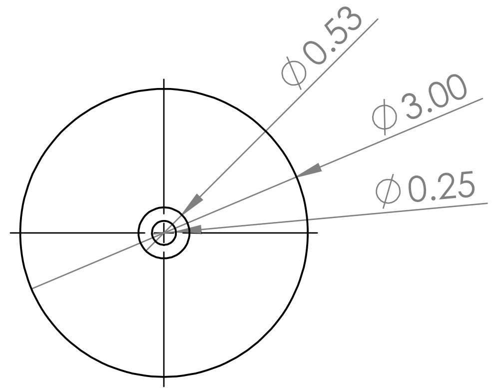
TITLE:
12 TOOTH SPROCKET

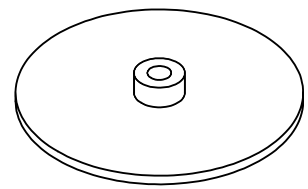
SIZE	DWG. NO.	REV
A	10tSprocket	0

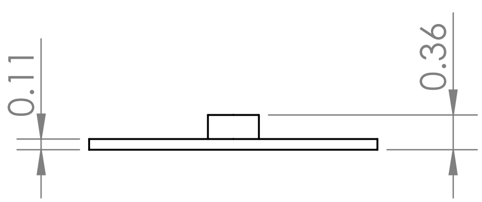
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.05
ANGULAR: MACH ± N/ BEND ± 0.005
TWO PLACE DECIMAL ±0.005







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MATERIAL: NYLON

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KS	2/6/2017
CHECKED		
ENG APPR.		
MFG APPR.		

TITLE:

60 TOOTH SPROCKET

SIZE	DWG. NO.	REV
A	10tSprocket_60	0

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

Appendix F: Bill of Materials

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	MB_001	FRAME	1
2	MB_001_m	FRAME MIRRORED	1
3	MB_TANK	TANK	1
4	MB_018	FRAME STANDOFF SUPPORT	5
5	MB_020	SPOOL CORE	6
6	MB_004_DS	DRIVEN COLLECTION SPOOL	3
7	MB_033	BELT MATERIAL GUIDE	6
8	MB_021	GEAR HOUSING PLATE	1
9	MB_BP_Mk1_001	SPOOL SUPPORT	6
10	12tSprocket	SPROCKET SMALL	5
11	MB_025	SHORT CHAIN	1
12	MB_027	LONG CHAIN	1
13	MB_028	CONTAINMENT WALLS	2
14	MB_028	TREATMENT DIVIDER	1
15	MB_032	CONTAINMENT STANDOFF LONG	2
16	60tSprocket	SPROCKET LARGE	1
17	MB_027	LONG CHAIN	1
18	MB_CX_01	MILL SLIDER BLOCK	4
19	MB_CX_02_DS	SLIDER RAIL - DRIVE SIDE	1
20	MB_CX_02	SLIDER RAILS	1
21	MB_CX_04	TOP MILL	1
22	57785K99	MILL TOP HAT BUSHING	4
23	MB_CX_04_DM	Drive Mill	1
24	MB_CX_07	SS MILL SHEATH	2
25	MB_CX_03	TAP	2
26	MB_CX_03_NT	NO TAP	2
27	91585A374	METRIC DOWEL PIN	4
28	93285A316	NYLON TIP SET SCREW	4
29	MB_036	MILL DRIVE SHAFT	2
30	MB_035	DRIVE STANDOFF R_L	1
31	MB_034	DRIVE STANDOFF R_S	1
32	MB_037	DRIVE STANDOFF L_L	1
33	MB_038	DRIVE STANDOFF L_S	1
34	MB_039	DRIVE STANDOFF M_S	1
35	MB_036_MDS	MIDDLE DRIVE SHAFT	2
36	MB_040	DRIVE HOUSING STANDOFF	3
37	MB_041	FRAME BACK	1
38	MB_042	FRAME BOTTOM	1

39	MB_029	CONTAINMENT STANDOFF SHORT	6

Appendix G: Potential Hazards Checklist

Checklist of potential hazards

Y	N	
Y		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	N	2. Can any part of the design undergo high accelerations/decelerations?
	N	3. Will the system have any large moving masses or large forces?
	N	4. Will the system produce a projectile?
Y		5. Would it be possible for the system to fall under gravity creating injury?
	N	6. Will a user be exposed to overhanging weights as part of the design?
	N	7. Will the system have any sharp edges?
	N	8. Will any part of the electrical systems not be grounded?
	N	9. Will there be any large batteries or electrical voltage in the system above 40 V?
	N	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	N	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	N	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	N	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	N	14. Can the system generate high levels of noise?
	N	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
Y		16. Is it possible for the system to be used in an unsafe manner?
Y		17. Will there be any other potential hazards not listed above?

Appendix H: Design Verification Plan Checklist

Verification Plan				Verification Report	
Test #	Test Name	Test Method	Acceptance Target/Criterion	Results **P**ass/**F**ail/**U**ntested	Comments
1	Collection Test	Prototype/Mk. I	90%	P	Currently at 96%, can be improved to 99%.
2	Biomass Test	Prototype/Mk. I	Thickness: .25mm	P	
3	Spool Replacement Timing	Prototype/Mk. I	5 minutes	P	
4	Undamaged Specimen	Mk. I	Visual Inspection	P	Passes with intermediary bar removed.
5	Grit Failure	Mk. I	Passes Biomass Test w/ grit <10mm D	U	Unable to test due to time constraints.

Appendix I: MATLAB Imaging Code

```
%% Analogue Image Processing
% Current code uses a color threshold to convert an image to a binary image
% It then filters out noise based on the size of the boundary surrounding
% the blobs. It then finds the area of the remaining blobs and places a
% border around them.

% CODE STILL NEEDS CALIBRATION FOR A SCANNER, IMAGES VARY DEPENDING ON
% SHADOWS AND HOLES IN THE FABRIC

% Improvements to the code include:
% - Using area to filter blobs. Depending on size of rocks entering, area
% may be a better method of filtering since area scales differently than
% perimeter.
% - Cut down on bwboundary command, used twice, should be able to do
% filtering and boundaries in one go.

% Tyler Cottle
% Brian Paris
% Kai Staal
% Last edited: 3/23/17

%% Clear Section

close all
clear all
clc

%% Set-up Parameters
% ppi = ; %[pixels per inch]

%% Read in Image

Photo = imread('Test_6.JPG'); %reads in stock image

figure; %creates figure window
imshow(Photo); %displays stock image on figure 1

%% Convert to Black/White image

BWPhoto = im2bw(Photo, .8); %converts image to black/white given brightness
threshold value

figure(2) %creates second figure window
imshow(BWPhoto) %displays black/white image on figure 2

%% Find Area (Threshold only, NOT Accurate)

% totalPixels = numel(BWPhoto);
% numWhitePixels = sum(BWPhoto(:));
% Area = totalPixels - numWhitePixels;
```

```matlab
%% Invert to White/Black
%Makes image easier to work with other commands

WBPhoto = imcomplement(BWPhoto);

%% Filter by Size and Find Area
% Finds border of white "blobs"

%Traces boundaries, stores in variables.
%B holds matrices of the boundary locations in the plot
%  each matrix is Nx2, holding the X and Y locations of each bounday point
%L is large matrix showing where boundaries are stored w/ parent/child
%N holds the number of "blobs" outlined (also is length of B)
[B, L, N, A] = bwboundaries(WBPhoto, 'noholes');

figure(3);
imshow(WBPhoto);
hold on;
%Filters the "blobs" based on the length of their border
for k = 1:length(B),
   boundary = B{k};
   if length(boundary) > 100;    %Tests length of border
      ;                         %If greater than above, do nothing
   else
      WBPhoto(boundary(:,1),boundary(:,2)) = 0; %Otherwise change boundary
   end                                          %pixels to black
end
hold on;
imshow(WBPhoto);

Area = sum(WBPhoto(:)); %Sums remaining white pixels.

%% Add Borders
%Plots a blue border around the remaining white "blobs"

[B, L, N, A] = bwboundaries(WBPhoto, 'noholes');

figure(4);
imshow(WBPhoto);
hold on;
for k = 1:length(B),
   boundary = B{k};
   plot(boundary(:,2),boundary(:,1),'b','LineWidth',2);
end


%% Potential Code

%Finding Centroids of White Regions
%s = regionprops(WBPhoto, 'centroid');
%centroids = cat(1, s.Centroid);
```

Appendix J

Operators' Manual

This owner's manual is provided to aid you in the safe and reliable operation of the Marine Biomass Analyzer. Read and understand this document in its entirety before operating the device.

Safety Precautions

Personal Attire

- Remove all jewelry (watches, bracelets, rings, etc.). These items may inadvertently get snagged in the device or destroyed by water.
- Roll up sleeves before operating the device to ensure they cannot get snagged in the device.
- If the operator has long hair, tie it up and place behind the head before using the device.

Operation

- Only allow one individual to operate/interact with the device at any one time.
- Aside from assembly when the device is inoperable, never place appendages in the mill subassembly, spools and material guides.
- When operating the device, keep all limbs and appendages outside of the superstructure and drive train zones. Only one hand is required to operate the device, on the operator's turn crank handle.
- If resistance to cranking becomes excessive, stop cranking and examine the drive train. Through use, the rubber collars can shift, causing sprockets to slide and altering the tension in the chain. Ensure all respective sprockets are in-line and rubber collars are shifted back to their correct position to prevent the chain from derailing or breaking.

Insertion/Removal of Spools and Material

The device should arrive partially disassembled, whereas the three spools will be removed from their holders and placed inside the device.

Inserting Material and Winding the Supply Spools (May Require Two Persons)

1) Take a free end of the white fabric or clear film material from the spools they came delivered on from the manufacturer and insert several inches of it into the slot on the supply spools. If desired or required to prevent the material from coming loose, use masking tape to hold it in place in the spool.

2) Begin winding the material onto the supply spool, transferring it from its original packaging spool until you have transferred sufficient material for your test(s) (No more than 30 feet). To apply maximum tautness (ideal), this may require two people.

3) Cut the material with scissors when sufficient material has been spooled.

Installing the Supply Spools and Attaching to Collection Spool

1) Insert the spool ends into the yellow spool holder clips. Even if the screws in the holder clips are tightened, you should still be able to insert the spools. If too much force is required, loosen the screws until the spool can be easily inserted.

2) Completely loosen or remove the nylon-tipped set screws in the slider caps of the mill subassembly. This will allow you to lift the top mill and maximize the gap in the mill allowing you to feed the spool materials through.

3) Take the free ends of the white fabric and clear film, and simultaneously feed them both through the large mill gap you just created. If the gap is still too small, you may completely remove the slider caps and top mill. Replace these items and fasteners once the spool materials are through the mill subassembly and resting on the opposite side.

4) Now that the spool materials are through the mills, simultaneously put several inches of both free ends into the slot in the collection spool. Use masking tape if necessary to affix them in this position.

5) While looking at the hand crank, turn it counter-clockwise to induce tension in the system. This may require holding onto the spool materials at the collection spool to insure they don't become loose or fall out. Rotate the crank until the collection spool has turned approximately ½ to one full revolution. The system is now ready for test use.

Operating the Device for a Test

Adjusting Spool Material Tension Before Operating

1) Simply loosen/tighten the screws in the yellow spool holders and turn the crank slightly to induce tension until you reach your desired level of tension.

Performing a Test

1) Begin slowly turning the crank counter-clockwise as before. It is recommended to turn the crank one revolution every six seconds approximately to have a linear conveyor speed of 2 inches per second.

2) Inject filtered samples into the containment area as you continue to slowly crank. The specimens should naturally float up and become loosely attached to the white fabric as they feed into the mill.

3) Continue cranking and injecting as desired until you run out of supply material. Crank the collection spool until all material is wound up on it.

4) Remove the collection spool for analysis. This may require loosening the screws in its yellow spool holders.