Redesign of a Peristaltic Pump for Additive Manufacturing

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AMFG 401: Term Project

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Executive Summary

In this investigation the components of a peristaltic pump are evaluated and re-designed such that they can be additively manufactured in a single process. This will greatly reduce the time needed to be spent on assembly and the manufacturer's labor costs. This report contains four parts; understanding of traditionally manufactured part, redesigning the assembly for additive manufacturing, first design analysis and design iteration, evaluation and redesign of the iteration.

In part one the design of peristaltic pumps was investigated to give a knowledge basis for how to redesign the part. It was determined that in order for a Peristaltic pump to operate there needed to be an airtight compression within the hose that creates suction through pressure differentials to get liquids from one end of the hose into the other. The traditional assembly did this with rollers that rotate through indirect torque application from the pulley belt to compress a hose. Once the fluid has passed the midpoint of the pump, water flow will begin through a process called peristalsis, which will "push" fluid through the hose.

In part two, the peristaltic pump is re-designed for functionality with the additive manufacturing process performed by the Markforged printers. Taken into account are the reduced strength levels of the Markforged trademark material Onyx to create a part that can still function. It was determined that the hosing could be properly compressed within a helical gear design which could be printed as one part instead of as individual parts that are then assembled. The design was then printed.

In part 3 of the project the additively manufactured, redesigned peristaltic pump print is analyzed in terms of dimensional accuracy, delamination, surface finish, mechanical and structural properties. The insight gained from this analysis led to a redesigning of the part. The redesign included removal of support material, insertion of a gap between gear surfaces and an increase in the size of the part.

In the final part of this investigation, the next iteration of the additively manufactured design was printed and inspected. The pump was again evaluated for dimensional accuracy, delamination, surface finish, mechanical and structural properties. Printing without support material was a success, taking less than five minutes to have the part fully assembled by installing tubing.

It is the conclusion of this investigation that additively manufacturing peristaltic pumps can be done in an economical fashion by reducing assembly time drastically.

Part 1: Understanding an Existing non-AM-Produced Assembly of Components

Executive Summary;

We have decided to take the components of a peristaltic pump and re-design them such that they can be additively manufactured in a single process. This will eliminate the time needed to be spent on assembly and the manufacturer's labor costs. Peristaltic pumps operate by creating suction through pressure differentials to get liquids from one end of the hose into the other. The rollers in the assembly seen below will rotate through indirect torque application from the pulley belt, and "suck" liquids through the hose. Once the fluid has passed the midpoint of the pump, water flow will begin through a process called peristalsis, which will "push" fluid through the hose. The only requirement for the operation of a peristaltic pump is that there needs to be an airtight seal at the entrance of the hose. As is seen in the chemistry stockroom, one core advantage of a peristaltic pump over others is that the fluid never leaves the rubber or plastic tubing. This ensures that corrosive chemicals that might otherwise degrade the pump system will never come into contact with metallic pieces. The system we design will hold strongly within the bounds of that design philosophy, and will ensure that our pump won't be weakened even in an instance of catastrophic failure. Unfortunately, the lab coordinator did not approve of us disassembling his pump since it's currently being used throughout the whole day for chemical transfers, but we took pictures to scale, and used calipers to measure component sizes.

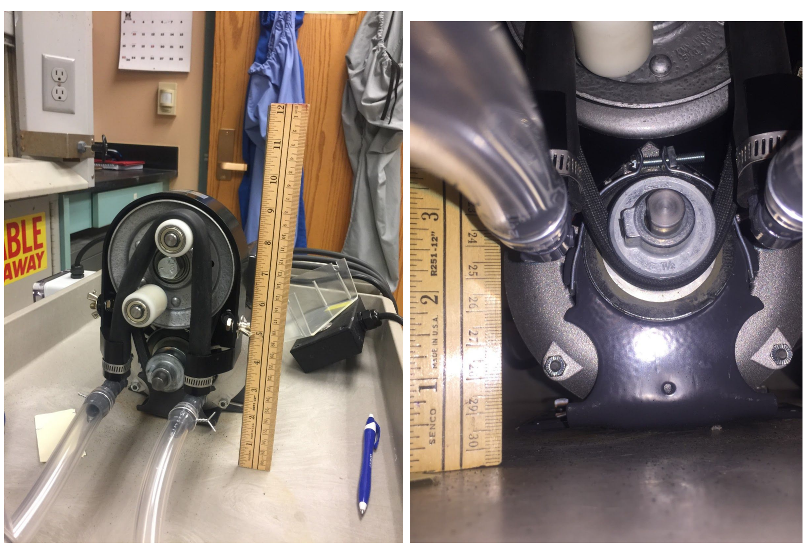


Figure 1: Front and Detail View of Pump

With this pump being printed and functional, the intent is to attach it to a motor of the same size/fitting as the one currently being used in the Chemistry lab for the fluid transfer of corrosive materials. Thus proving our solution viable and effective.

Figure 2: Side View of Pump

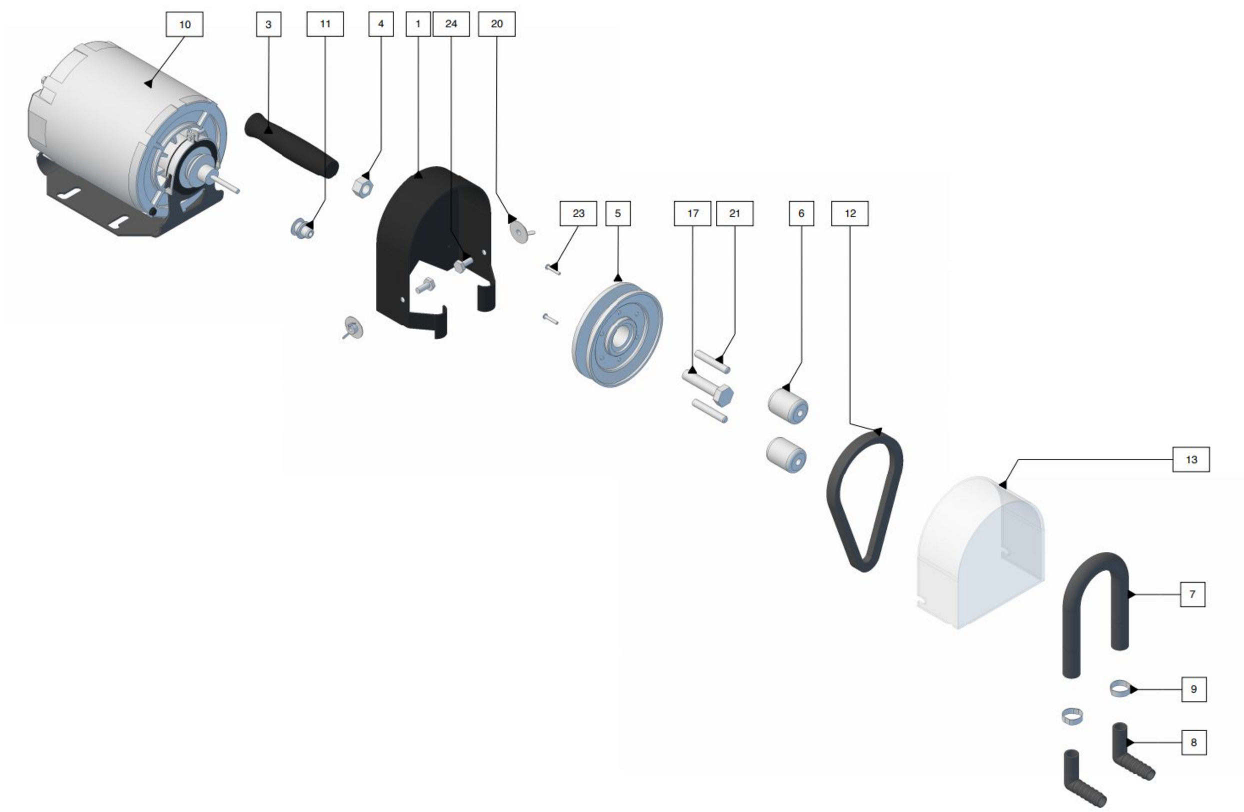
Peristaltic Pump;

The peristaltic pump was designed to minimize contact between a pump and the harsh fluids that it is pumping. It works by creating a pressure differential and then pushing fluid through a hose similar to squeezing toothpaste out of a tube. It has rotating parts which compress a section of hose and run along the length. These compression points cause fluid to flow through suction caused by pressure differentials. The pressure differentials are a result of the tube expanding back to its resting cylindrical shape creating a lower pressure section just behind the roller. When this happens fluid flows from the higher pressure to the lower pressure area. This pump requires at least two rollers to keep a constant flow moving through it. This is due to a possible loss of pressure when a section of the hose is not being compressed which would allow for atmospheric gas to get into the system. This project's objective is to redesign the interface between the motor and tube.

Component Breakdown:
The peristaltic pump consists of 17 different parts in total, however, the scope of this project is to redesign the mechanical interface between the motor and the tube. This mechanical interface consists of 10 main parts. These parts are:

1. (1) Structural Housing Unit
2. (5) Pulley and Bearing
3. (7) Tubing
4. (8) 90 deg. ½” PVC elbow
5. (11) Pulley Motor Drive
6. (12) Drive Belt
7. (17) Axial Bolt
8. (21) Shaft Roller Axle
9. (23) Screws, Roller Shaft
10. (6) Roller Assembly with Bearings

The numbers listed in parenthesis are corresponding to the manufacturer’s assembly drawing;



[http://www.greylor.com/files/parts/model200-exploded-parts.pdf]

Part 1: Structural Housing Unit

This is the part which contains and secures all other parts to the motor. It has several attachment points which require screws to secure. This part was most likely formed from sheet metal and welded together.

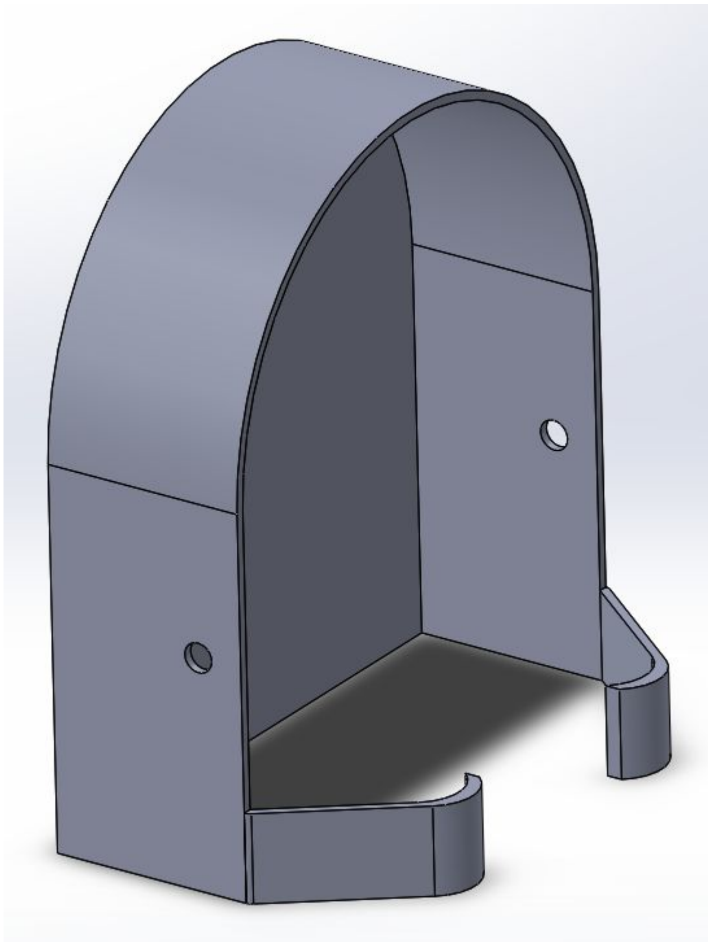


Figure 3: Housing Unit

Part 2: Pulley and Bearing

This is the part which rotates inside of the housing. It connects to the pulley motor drive for rotational motion delivery. This plate allows for rotational energy to be supplied to a wider radius. This part was most likely cast through injection molding due to tight require geometric tolerancing. There was little or no machining after due to no need for threads in this part.

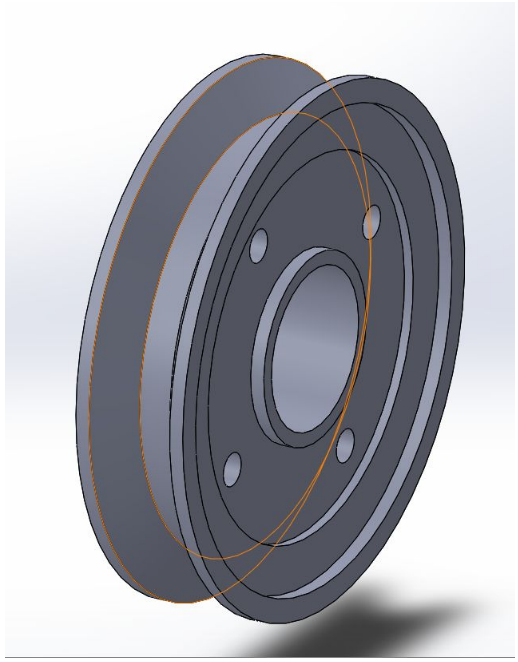


Figure 4: Pulley

Part 3: Tubing
This is standard ½” rubber tubing. The fluid being pumped flows through the tubing as it is compressed. The tubing was likely extruded.

Part 4: 90 deg. ½” PVC Elbow
This piece connects the tubing of the pump to any tubing that the user installs. It is made from PVC with an injection molding process.

Part 5: Pulley Motor Drive
This part is what transfers power from the motor to the Pulley and Bearing. The motor drives a belt which wraps around this piece causing it to rotate with the motor. This piece is attached to the Pulley and Bearing plate and transfers the rotational energy to it. This part could be made through lost wax casting or injection molding. It would require post processing to have correct dimensional tolerancing to fit on the Axial bolt and properly connect to the Pulley and Bearing.

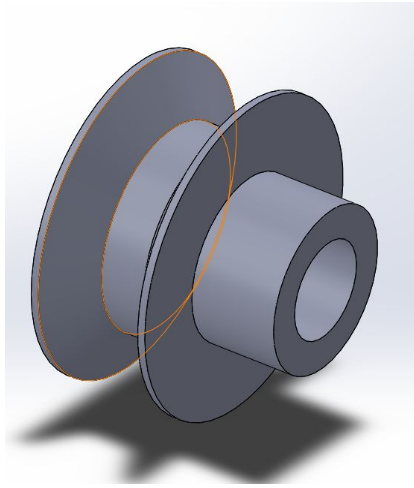


Figure 5: Pulley Motor Drive

Part 6: Drive Belt
This is a V-Style rubber drive belt which possibly has fiber reinforcement. It transmits energy from the pulley motor drive to the larger pulley.

Part 7: Axial Bolt
This bolt serves as the axis about which the Pulley and Bearing plate and the Motor Drive piece rotate. It takes any loading imparted by pressure applied to the hose and transfers it to the housing. Due to load applied to this bolt being relatively low it could be made from a casting process and then machined. If the loads it would see were high it would be best to forge it and then machine it. This process could be more expensive than a wire drawing and forming process followed by a machining for threads, so that process may have been used.

Part 8: Roller Shaft
This part serves as a shaft to transfer load from the Roller to the Pulley and Bearing. It could be made through a wire drawing process and then have the center machined with threads.

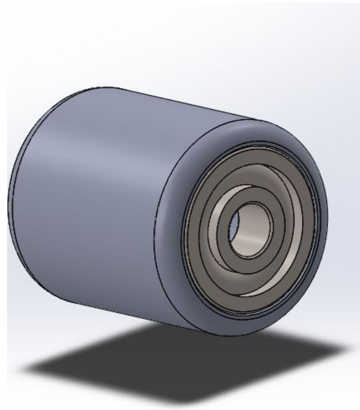


Figure 6: Roller

Part 9: Screws, Roller Shaft

These are fasteners which connect the Roller Shaft to the Pulley and Bearing. These could be made from a wire drawing process as well. The screw will be drawn to slightly over diameter then the head will be formed and the threads machined.

Part 10: Roller Assembly with Bearings

This part includes both a flat large surface to interface with the hose and the bearing inside. The outer shell is made of a polymer formed through die casting. It is then finished so the surface won’t cause damage to the hose during operation. The bearings are made from metals and include balls and housing to tight tolerances. These must be machined and greased.

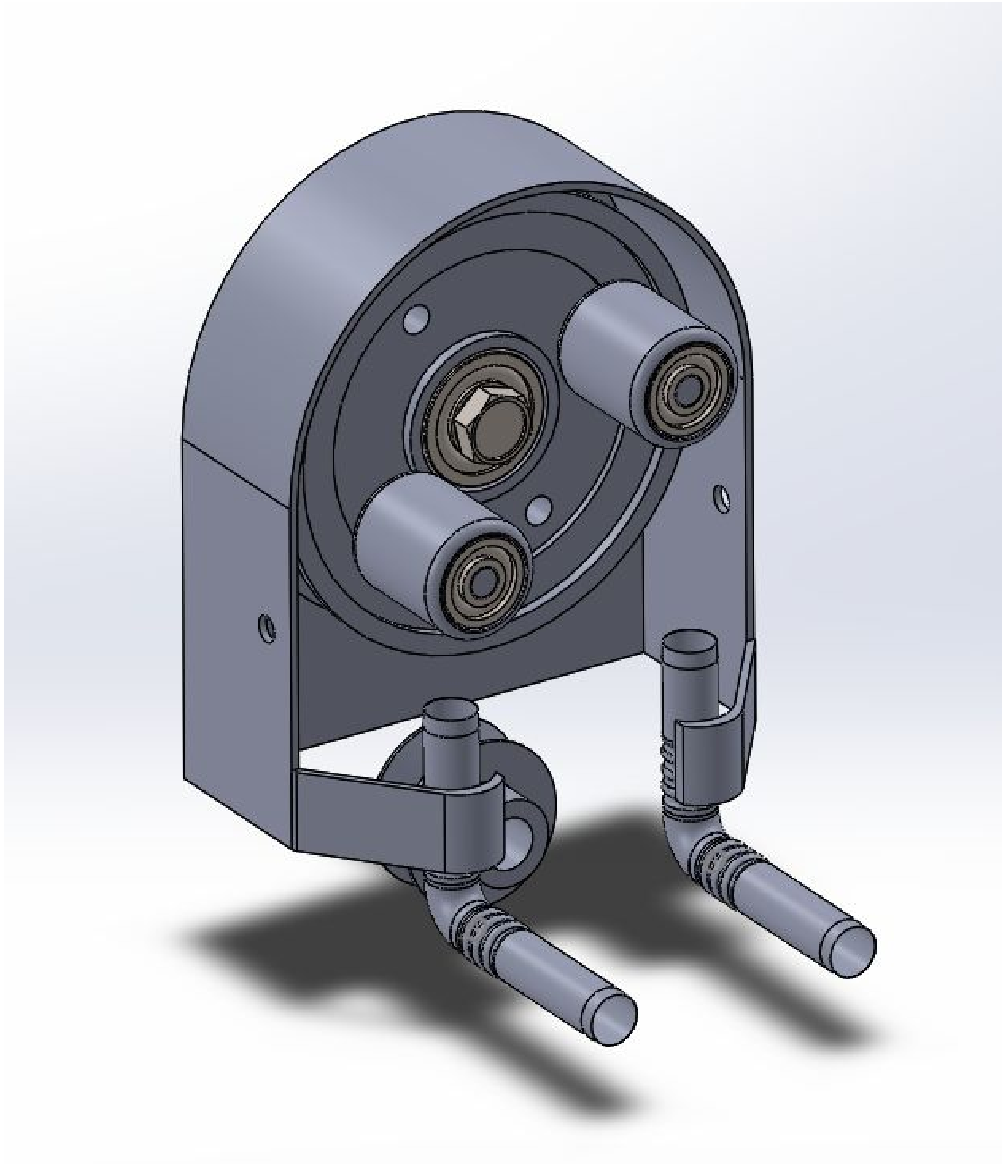


Figure 10: Full Assembly (tubing and belt not shown)

Part 2: Redesigning an Assembly of Components for AM Processes and Print

Executive Summary:

In step 2, the peristaltic pump is re-designed for functionality with the additive manufacturing process performed by the Markforged printers. Taken into account are the reduced strength levels of the material used in Markforged printers to create a part that can still function. This iteration of the design is currently not functional due to underestimating support removal and an oversight of gap tolerancing. We are confident these issues can be resolved in the next iteration of development for this part.

In this step the peristaltic pump is re-designed for functionality with the additive manufacturing process performed by Markforged printers. As improvement to the inspiring planetary gear system, we've also made changes related functionality (implementation of canal for tubing) and also to gearing system such that it may best be printed by an additive machine.Taken into account are the reduced strength levels of the material used in Markforged printers to create a part that can still function. Furthermore, another important point for the effectivity of the pump is, that we have a seamless engagement between the gear teeth and the surface of the tube. So, we want to make sure that this engagement can be found as a pump attribute after the printing process. The printing process in general was divided into eight steps. The first part included the planning and design of our building component, which then was implemented into a 3D-CAD software (Solidworks). After developing the pump and creating the drawings, a Conversation into STL was necessary for the printing. We decided to use the Markforged Onyx printer of our University and its associated Eiger software. The support material was placed for the printing process the way it was planned in part 1 of our project. Our setup was relatively straightforward (leveling building plate, changing material supply….) but it was time-consuming since another project build was already programmed and ready to start just before our design could be processed. Therefore, we had to start a second iteration including all individual set-up steps. Then, we could begin with our printing process: The actual printing took more than 6 hours. When the process was finished, the part was removed from the building plate by a paint scraper (see figure 3).In one of the last steps, we had to face a problem - the post processing was more challenging than expected, since we didn't want to damage the part. Our mistake was that we did not consider the sensitivity and vulnerability of the freshly printed component: This iteration of the design was/is currently not functional due to underestimating support removal and an oversight of gap tolerancing. We are confident these issues can be resolved in the next iteration of development for this part. In the new redesign one our focus will be to make the removal of the support material easier.

Redesign Process:

In the original assembly, the peristaltic pump was designed to operate via indirect torsion with the pulley belts operating in a circular motion to reduce the amount of shearing force/torque operating on the machine bolt that holds the pump's main pulley wheel in place. This is going to be the most prevalent issue we face when changing the material from a hard metal, to a softer, 3D Printed plastic. The Markforged machine prints with their proprietary Onyx material which is a composite made of nylon and chopped carbon fiber filament that is strong and flexible. This, in addition to its heat resistive properties, will make it a good option for a dimensionally stable part with industrial reliability. A metal material would've been stronger and more suitable, but due to our modifications to the manner in which the force is applied, our part will be functionally equivalent to the original assembly.

Table 1: Mechanical properties of Markforged's Onyx additive manufacturing material.

Property	Test Standard	Onyx
Tensile Strength (MPa)	ASTM D638	36
Tensile Modulus (GPa)	ASTM D638	1.4
Tensile Strength at Break (%)	ASTM D638	58
Flexural Strength (MPa)	ASTM D790	81
Flexural Modulus (GPa)	ASTM D790	2.9
Flexural Strain at Break (%)	ASTM D790	N/A
Heat Deflection Temperature (C)	ASTM D648	145
Density (g/cm^3)	N/A	1.18

Our proof of concept is inspired by a planetary gear system and can be seen in Figure 1. Cylindrical rollers are sandwiched between two sets of planetary gears to create a high strength part that eliminates the cantilevered rollers of the original pump (seen in Figure 2). Having the rollers supported by gears on both the front and back faces gives better support and means that a lighter, weaker material can be used in place of the steel parts in the original pump. Another change in the function of the piece is that the tube is compressed between the outer rollers and the large ring where in the original part the tension on the tube is what causes it to compress when the rollers rotate. Eliminating the tension on the tube increases the safety for the user by reducing the likelihood that the tube will break or pull free from its connection and release toxic or corrosive fluids. The parts in our design would be very difficult to subtractively manufacture because of the abundance of overhangs and sharp internal corners. Additionally, the parts would be impossible to assemble once fully formed.

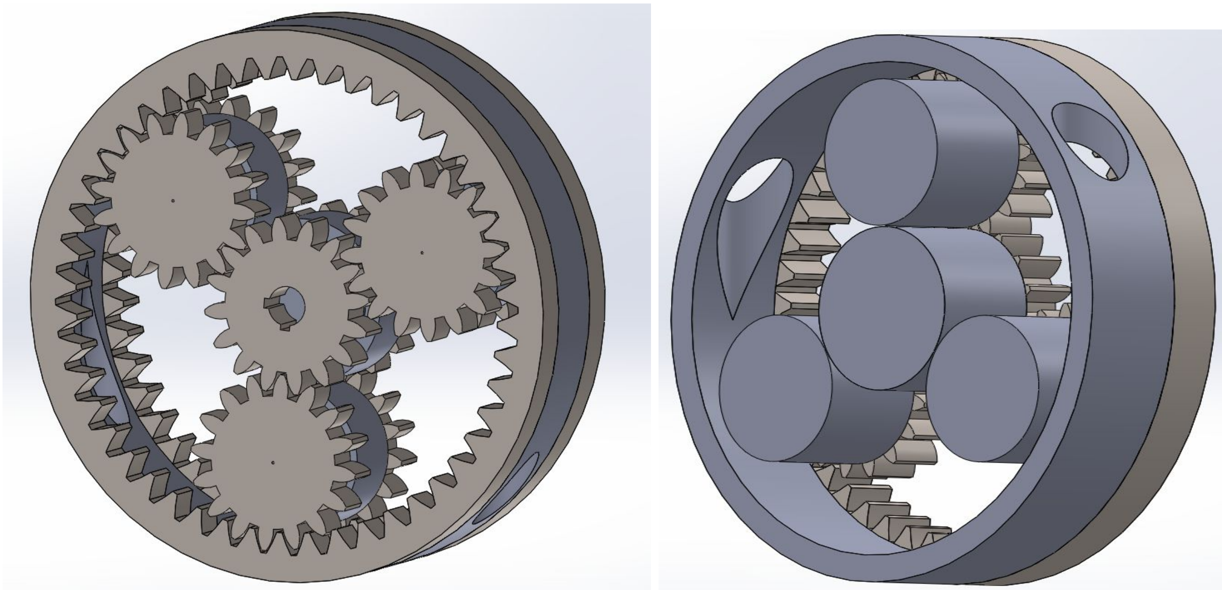


Figure 1.
***Left* -A redesign of the peristaltic pump for manufacturing with a Markforged machine.**
***Right* - Shows the inner ring of the sandwich design.**

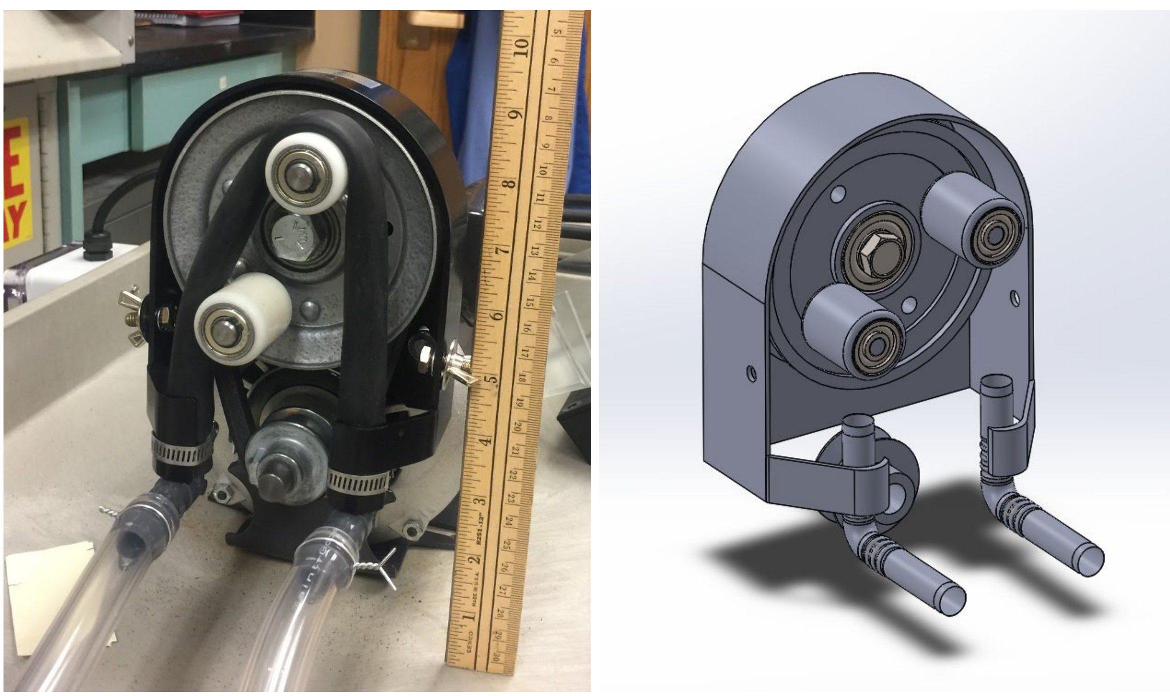


Figure 2. Original design for peristaltic pump.

This system was designed to accommodate ¾” surgical tubing with a ⅛” wall thickness but printed at 33% scale to prove the concept. The gap between the three outer rollers and the inner face of the ring was designed to be .1875”. This value was chosen Based on Eq. 1 below

$$Gap = 2 * wall\ thickness - tube\ compressibility$$

Eq. 1: roller gap calculation

where the tube compressibility was assumed to be 1/16”. This value should also compensate for any “slop” in the movement caused by printing inaccuracies. A view of the rollers as well as the inlet and outlet holes for the tube can be seen in Figure 3.

For an effective engagement within the pump, we will need to have seamless engagement between the gear teeth, and the surface that compresses the surgical tubing. Our gears are designed to have a slip-free rolling system with uniformly distributed gears. Our aim is to have this gear system driven by a ½” allen shape (subject to increase dependant on system reliability to increase surface area and reduce system stress). This will need to be the most accurate part of the entire print to ensure that any slip isn’t going to lead to our part being shredded when the motor exerts higher amounts of friction (fatigue failures), and we also need to ensure that the hole isn’t too small, or a forced insertion of the wrench/drill will be causing additional stress and could potentially crack the part (tensile failures). When considering the amount of torque that can be applied to our system (from a reliability standpoint) we’re currently confident in a ¼” tubing of a pliable nature (such as latex). This tubing size is dictated by the diameter and wall thickness of our gear system, because the rollers and their track will need to be able to accommodate the tubing width while it’s in full compression. To make our print truly a single piece we need to accommodate the amount of overhang on the gear teeth. The gear teeth overhang also prevents the torque from pushing the gears outside of their planetary housing, concentrating the torque and making a more efficient use of the gear’s rotational forces.

All of the above discussed topics will be contributing factors to the systems overall Bearing Stress. Due to the nature of the part (circular rotations) we believe that this will be the part’s weak point (as opposed to Shear Stress or Tear Out). These calculations will be done, and the area calculated such that we can create a part with an acceptable factor of safety.

$$\delta_b = P/A_b$$

$$\delta_b = bearing\ force$$

$$P = Axial\ forces\ acting\ on\ the\ plate$$
$$A_b = bearing\ area$$
Eq. 2 bearing force

The summary of the printing process broken into the eight basic steps of additive manufacturing

1. CAD modeling: The CAD model was created in SolidWorks by taking premade gears from the SolidWorks toolbox and adding the rollers between them. While building the model thought was given to how the piece should be oriented when printing. The obvious choice was to print with the large flat faces parallel to the build plate. This left a small amount of overhanging area on some of the gear teeth but these areas were left accessible for support material removal.
2. Conversion to STL: Conversion to STL format was very simple because we were using SolidWorks. The assembly was saved as a part file and all the rollers were merged with their respective gears to form only five distinct bodies. Then the part was simply saved as an STL file using the “save as” command in SolidWorks.
3. We chose to print our part using a Markforged Onyx printer. The process of transferring the file to the printer is relatively straightforward using Markforged’s Eiger software. The STL file is uploaded to the Eiger website using a login specific to the machine. Once uploaded the part can be oriented, scaled, sliced and support material can be added. Due to time constraints the pump was scaled down to 33% of its original size. Support material was added under the gear teeth as planned in step 1 due to the
4. Setup: Setup included leveling the build plate, changing material supply for the system to ensure there was an adequate amount for the build, and preparing the build plate surface to make for easier removal of the part. This step also included a second iteration of setup on a new printer due to having a build start just before ours.
5. Build: The build took a little over 6 hours.
6. Removal: Figure 3 below shows the removal technique used.

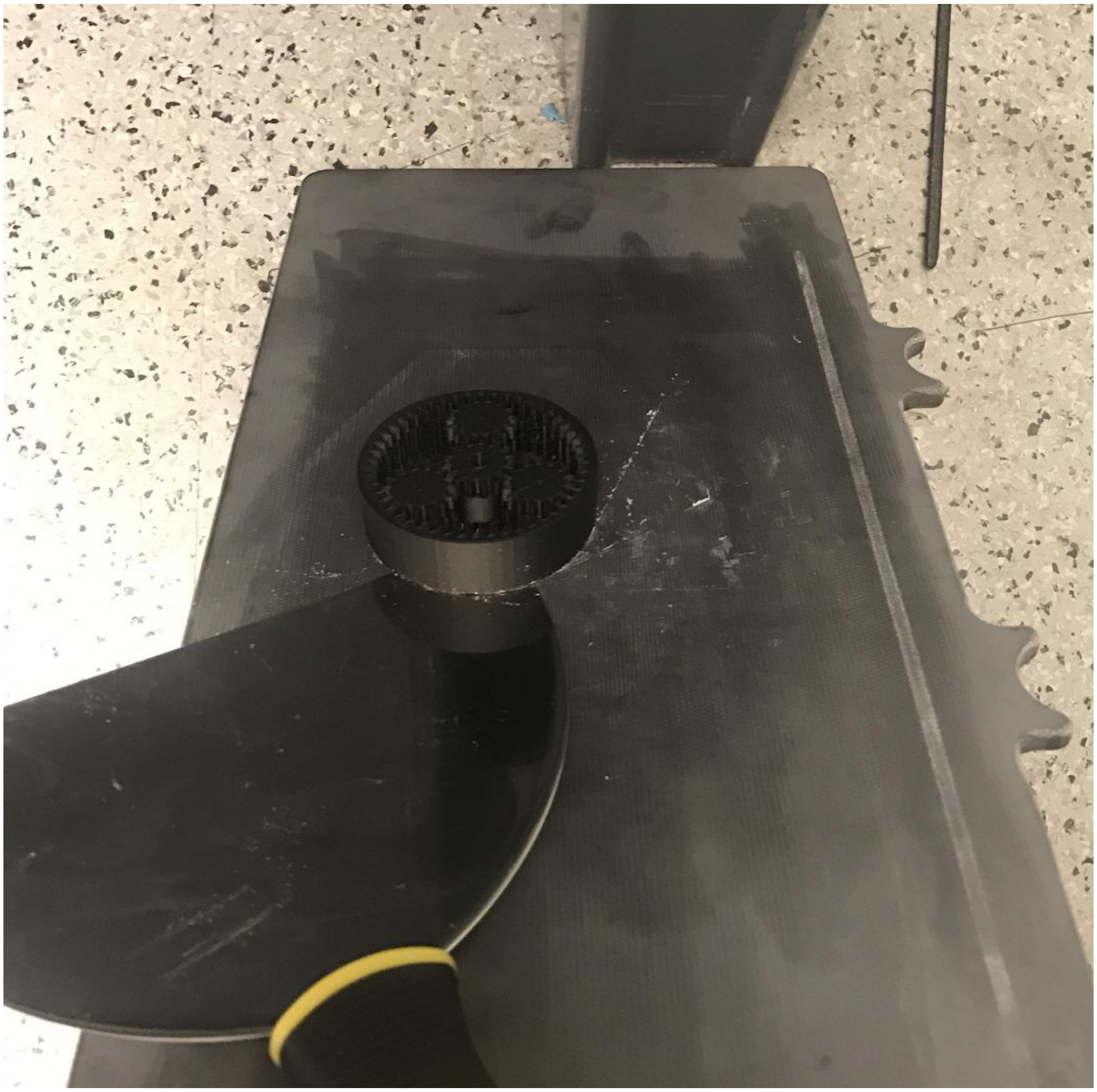


Figure 3. Removal technique for getting the part off of the build plate using a paint scraper.

7. Post processing: This step was found to be more difficult than anticipated and was not able to be completed with several hours of work. This will warrant a redesign of the part to make the support material easier to remove or have none at all. Specifically the material between the gears and outer shell was nearly impossible to remove without damaging the part.

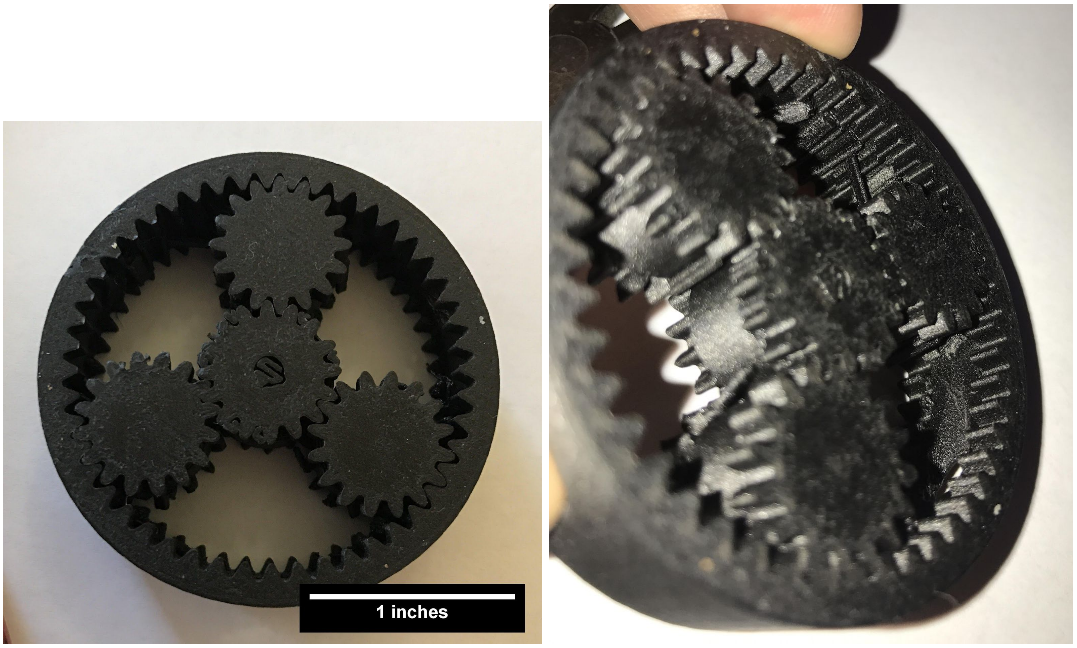


Figure 4. Pictures of the final part during support removal.

8. Application: The part is currently not in a functional state due to recessed support material and inadequate gaps between gears and the center ledges of the part. Also, the hole in the middle does not take to an allenhead very well to transfer rotational energy due to deformation of the material upon force application.

In conclusion, the next iteration of design for this part will be to minimize support material and address tolerancing between the teeth and inner shelf of the part such that the part will require less than one hour of post-processing to become functional.

[Appendix A]

ASTM Specifications for Material Testing

ASTM D638

Is the standard testing method for tensile properties of plastics

ASTM D790

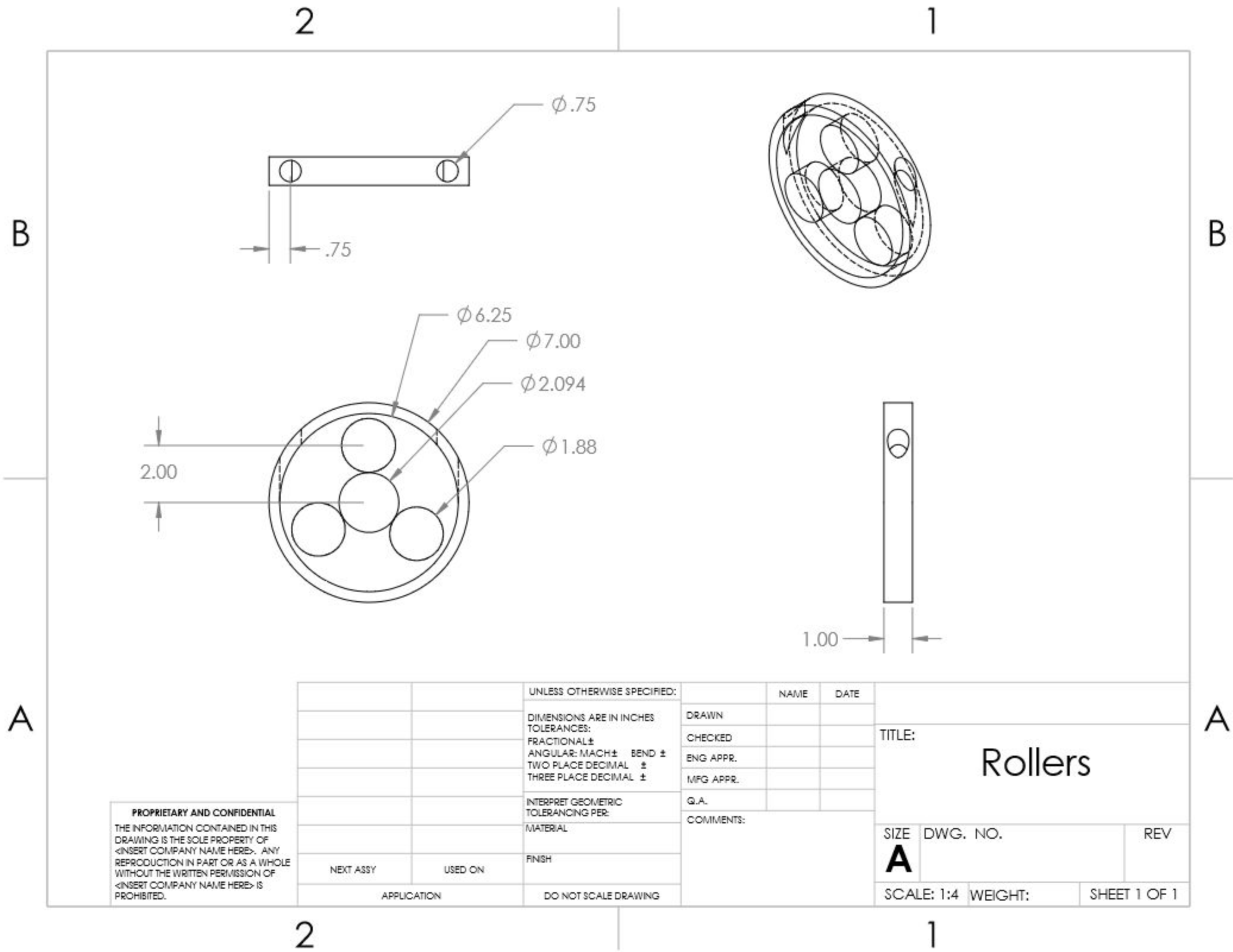
Is the standard testing methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

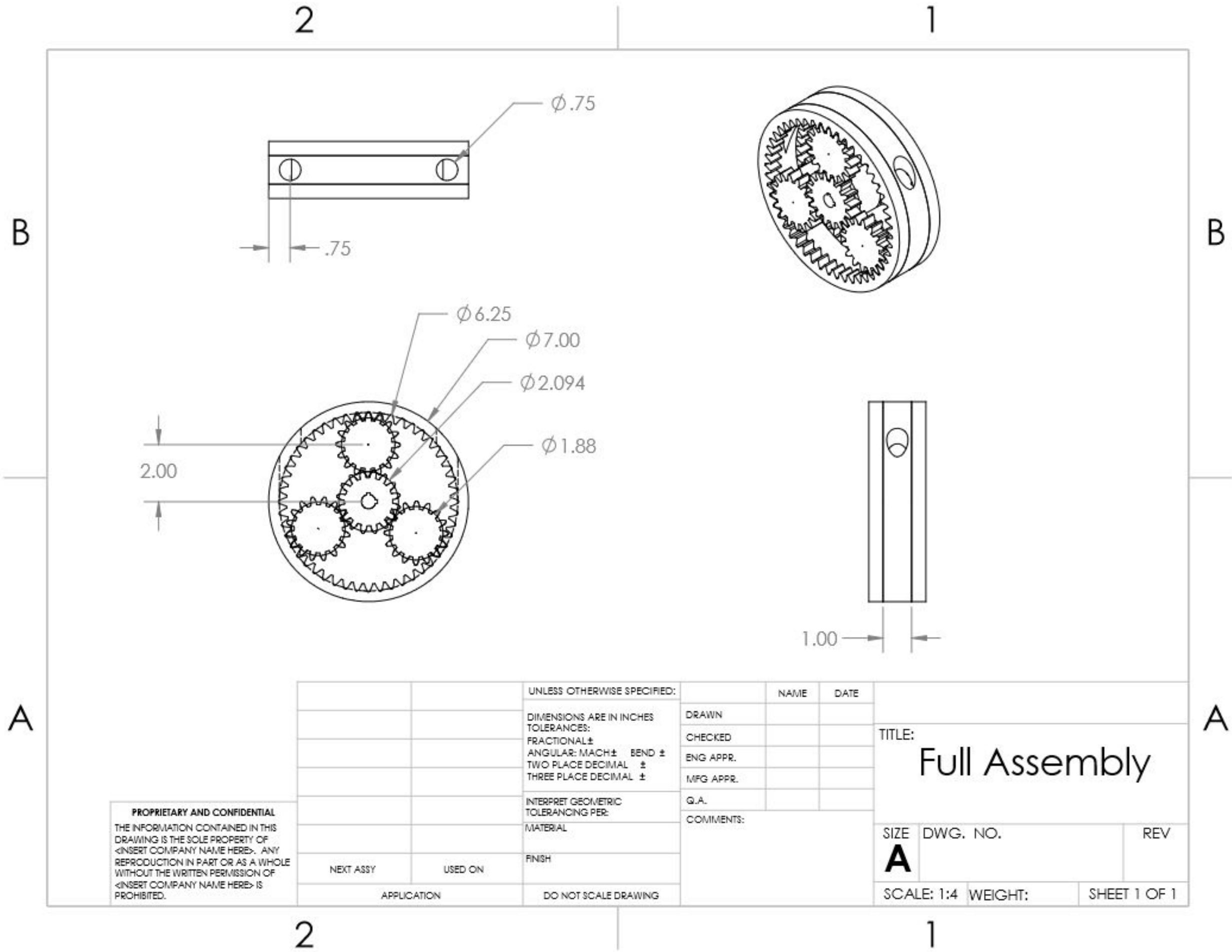
ASTM D648

Is the standard testing Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position

[Appendix B]

Engineering Drawings of Redesigned Part





Ring Gear:
Pitch Diameter = 6 in
Diametral Pitch = 8 teeth/in
Pressure Angle = 20 deg
Face Width = .5 in

Internal Gears:
Pitch Diameter = 2 in
Diametral Pitch = 8 teeth/in
Pressure Angle = 20 deg
Face Width = .5 in

Citations:

"ASTM D638." *ASTM International - Standards Worldwide*, www.astm.org/Standards/D638.

"ASTM D648." *ASTM International - Standards Worldwide*, www.astm.org/Standards/D648.

"ASTM D790." *ASTM International - Standards Worldwide*, www.astm.org/Standards/D790.

"Epicyclic Gearing." *Wikipedia*, Wikimedia Foundation, 9 Oct. 2018, en.wikipedia.org/wiki/Epicyclic_gearing.

Part 3: Analyze Printing Results and Redesign for Increased Yield and Printability

Executive Summary:

In part 3 of the project the redesigned peristaltic pump print is analyzed in terms of dimensional accuracy, delamination, surface finish, mechanical and structural properties. The insight gained from this analysis led to a redesigning of the part.

Due to the amount of print time projected for a full sized pump, the part was scaled to 33%. Analysis of the pump's mechanical and structural properties of torque were completed without a full assembly involving a motor and tubing, however, insight into its functionality was gained. The action of torquing the center gear allows for rotation of the gear system, but there are issues experienced due to the inexact nature of printing gear teeth. The part, having been shrunk to a smaller scale experienced much tighter tolerances between the gears and individual teeth. For this reason, it is projected that the full sized part will experience less resistance, despite the increase in surface area contact between the now larger gears. In the initial print, the use of support material required post-processing to a degree that resulted in damage to the structure of various components. The outer gear experienced deforming that resulted in oblong rotation of the gears, the internal gears experienced substantial wear to their individual gear teeth during the re-installment of the internal gears to their housing in the outer gear. This damage resulted in an increased amount of resistance in the movement for the planetary gear system and over time will increase the amount of damage the part will see due to stress. As such, an upgrade to various components was necessary.

Analysis of Printed Part

After the part was printed it was visually inspected to verify its functionality and to check for defects in the design and with the print. The part was assessed on support structure, dimensional accuracy, lamination and bonding, surface finish, mechanical and structural properties. The part was printed at a smaller scale to save on time and cost. As a result proper sized tubing could not be located for full operational testing. The part was still tested to make sure the gears meshed correctly and spun effectively around the center.

Upon removing the part from the print bed it was found that the support material would be difficult to remove. The abundance of small, internal overhangs meant that the support material was very hard to to reach, even with tweezers. These overhangs can be seen in Figure 1. It took approximately 4 hours to remove the support material. Once the support material was removed the team attempted to rotate the planetary gears only to find that some of them were fused together. This can be attributed to not adding a gap between the gears in the SolidWorks model. The team was unable to free the gears while they were still assembled so the internal gears were removed from the housing. Once this was done the gears were separated and the remaining support material was removed. The need to disassemble the part for post processing and then reassemble it is unacceptable as it defeats the purpose of additively manufacturing the part.

Figure 1. Image showing overhangs on printed part.

After post processing the dimensional accuracy and functionality of the part was assessed. The first issue that the team noticed was the keyway that was designed into the central gear was too small to print accurately. This keyway is essential to delivering power to the system. It was observed that the edges of the keyway were rounded too much and deformed when used. This can be seen in Figure 2. This could be from excessive heat causing the material to sag in this area or the machine reaching its dimensional limits. This warranted a redesign of the keyhole. The gears were turned by hand to check that they meshed correctly and rotated smoothly. Some grinding and resistance was encountered. It is unclear if this is from an error in the print or from disassembling and reassembling the system. Additionally, some bulging of the outer ring gear was observed. Dimensions were distorted at the start/stop points of each layer. This could be due to overlapping in the tool path or inadequate stopping of the flow at the end of each layer.

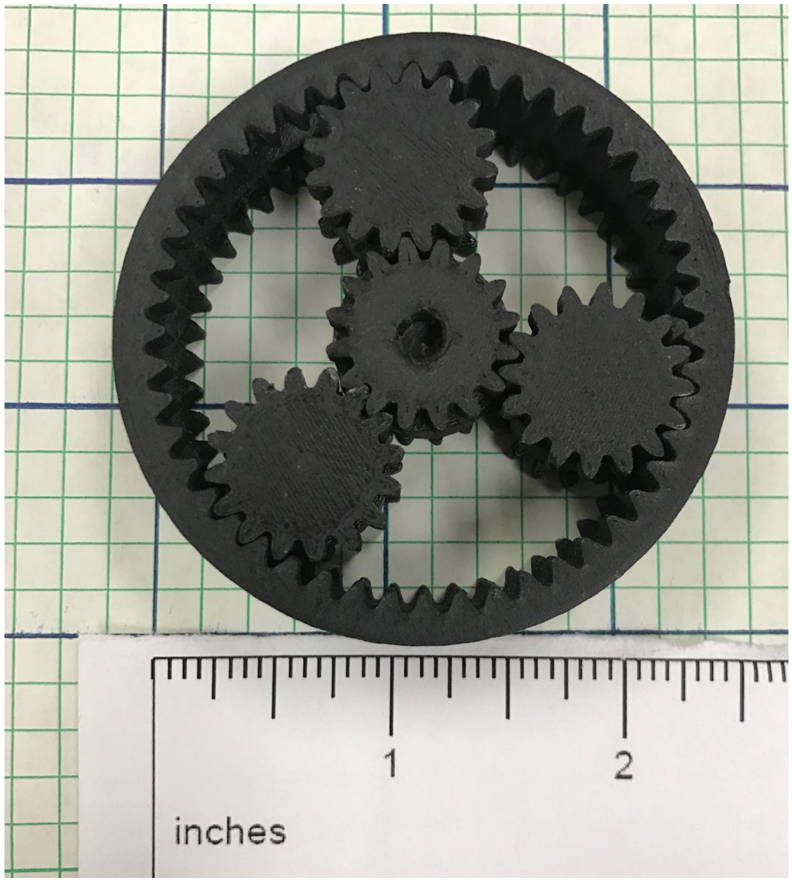


Figure 2. Full part with deformed keyway.

There was some delamination and bonding problems seen in the part within the gear teeth. This was most likely caused by the fine detail of the teeth compared to layer thickness. Since the path was too large to fit more than one layer in the tip of the tooth it delaminated towards the center of the tooth. Some of these unbonded regions are 1/16 of an inch. The delamination can be seen in Figure 2.In the holes for the tube irregularities could be observed. In detail: the holes could not be printed continuously so that some spots of the surface are uneven and the bonding between the layers is not seamless. Also there are accumulations of material at two spots, which has no danger for the tube. This is the main observed issue in comparison to the iterations on the teeth. The challenge for the printing of the teeth was the small size and should be improved when printing the part without scaling it down.

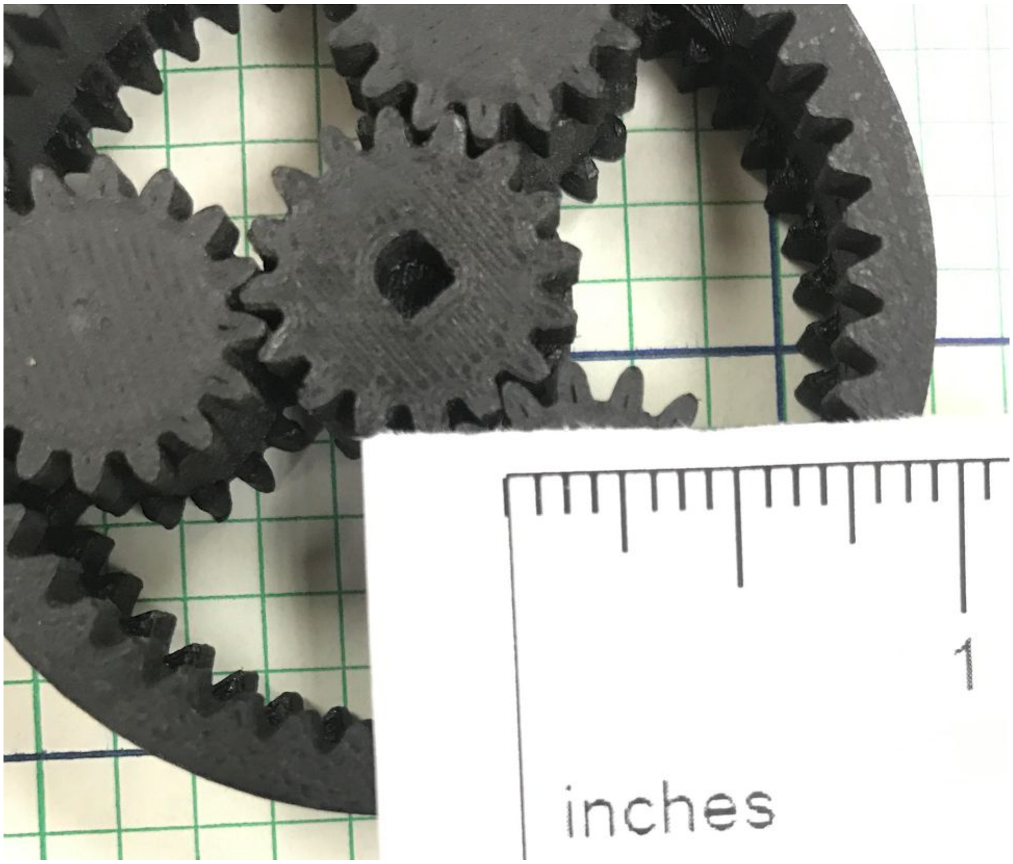


Figure 3. Image showing delamination issues observed in gear teeth.

The optical surface properties from the outer surface of the main wheel is printed consistent and without any irregularities. The surface finish for this part is not a major concern. Parts will need to be inspected for any sharp protrusions that could cause damage to the polymer tube which transports liquid. There are no sharp points noticed that could damage the tubing. There is minor surface damage from support material removal due to extra force being used. The damage can be seen in Figure 4 below. This damage is only cosmetic and will not impact the performance of the part.

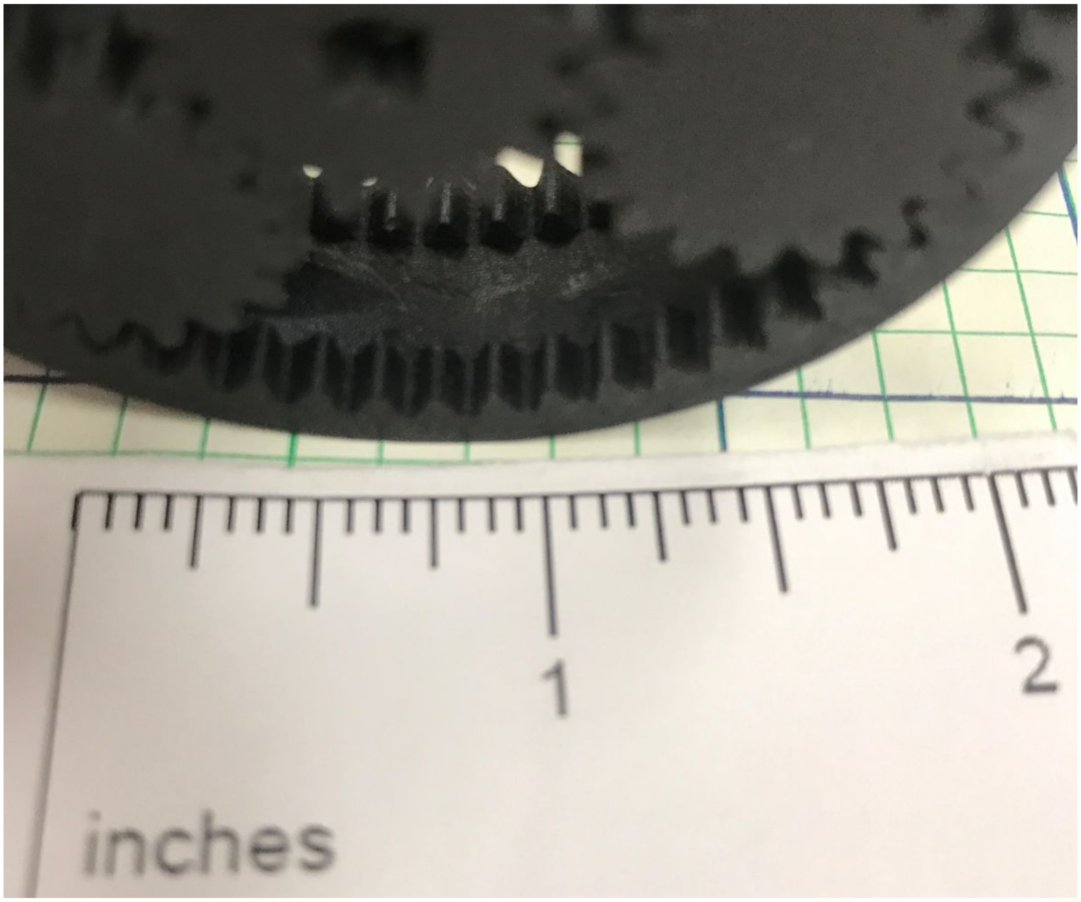


Figure 4. Image of damage caused during support removal.

The mechanical properties of the part are adequate to perform in this pump. The nylon material is strong enough to withstand operating forces and has a low stiffness such that the part can be deformed to insert a tube. Stiffness could be a problem during operation but it is thought that it will not be. This is due to the 3 internal gears applying pressure at points equidistant from each other. However, if it does become a problem a fourth gear could be added to create another point for load distribution or more material added to the exterior of the part.

Redesign of the Assembly

The problems with the first iteration stated above were the main focus when redesigning the part. The problem of the keyway not being useful was fixed in two ways. First, the keyway was changed from a circular hole with two square key notches to a ¼" hex. This change can be seen in Figure 6 . Additionally, if the part is printed at full scale the dimensional accuracy will be improved because there will be less fine detail for the printer to replicate. The next problem that was addressed was the fusing of the teeth. A gap of .025" was added between the horizontal faces of the gear teeth to provide enough space for the two faces to remain independent as seen in Figure 5.

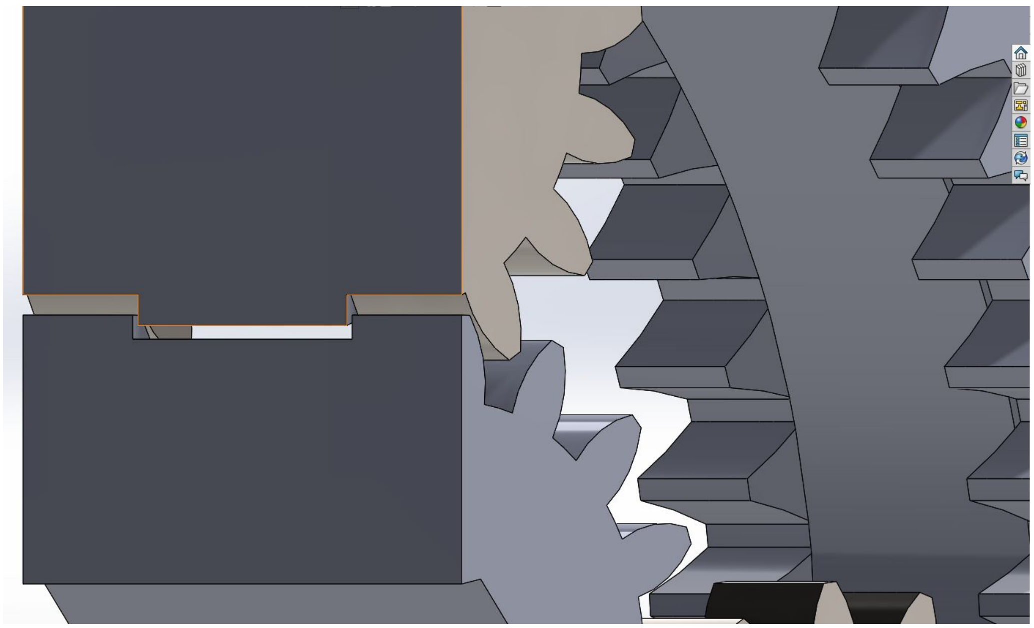


Figure 5: Gap of .025" between flat tooth faces

In this iteration the aim is to create a part that does not require support material. This will save time on post-processing and save the part from possible damage. This will also allow the part to be taken directly off the build plate and put into service. No support material will be used on the next print. The maximum overhang is ¼" which should be small enough for the Markforged Onyx 2 to print without support material.

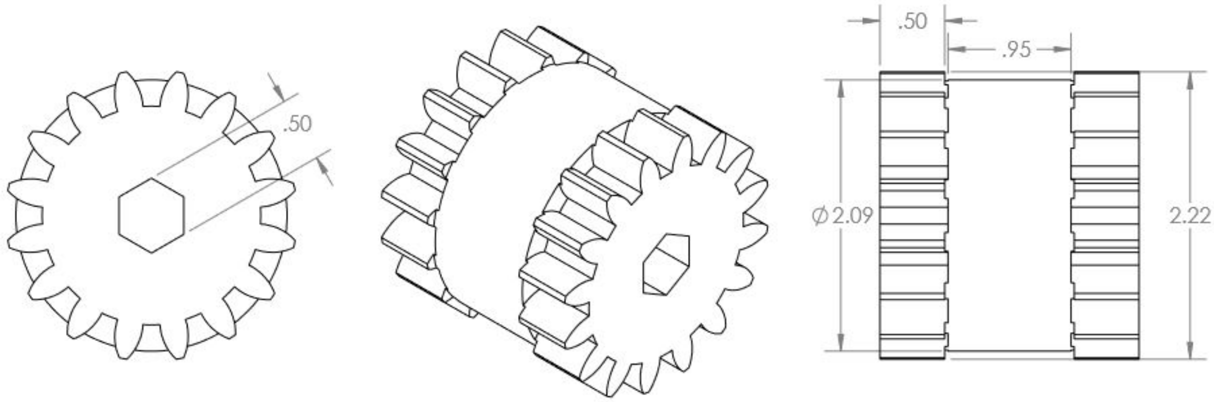


Figure 6: Redesigned Center Gear [IPS]

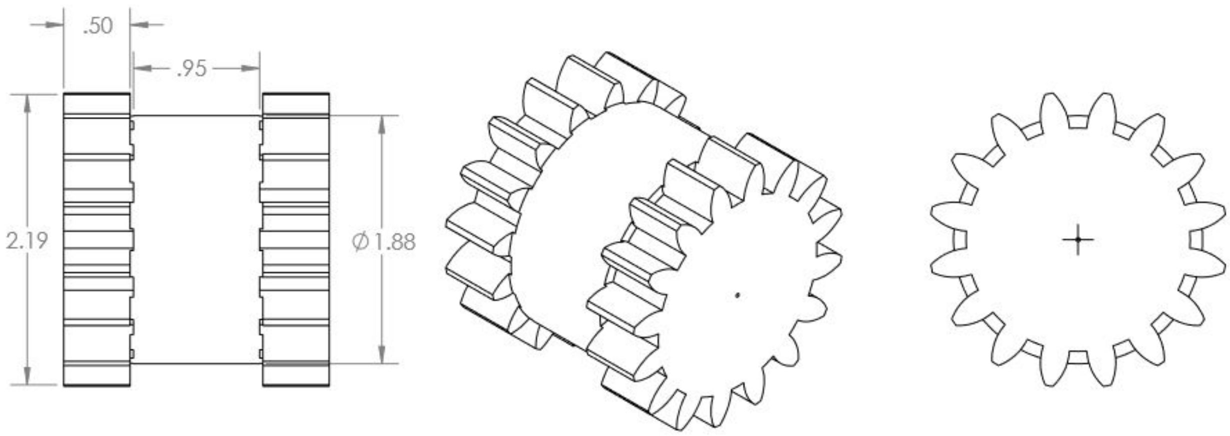


Figure 7: Redesigned Internal Gear [IPS]

In addition to the upgrades to the gear design, there has been the installment of a mounting bracket (as can be seen in figure 8) to increase the part's all around utility. Testing of the initial iteration exposed a very apparent flaw wherein the planetary gear system would not be able to spin without the outer gear system being fixed. The system would sooner undergo complete circular rotation before the teeth's friction would give. This has been combated through a mount, and the introduction of gaps. With this new design, the hope is that the mounted gear system will be able to undergo testing with complete autonomy through the implementation of the hex-drive and a motor. This will open the door for more potential tests on the additive process, and the onyx material such that the final iteration specifications may be compared to the inspirational system designed by Greylor. Testing could encompass various topics such as wearing, fatigue, and a volumetric comparison of water in a given amount of time.

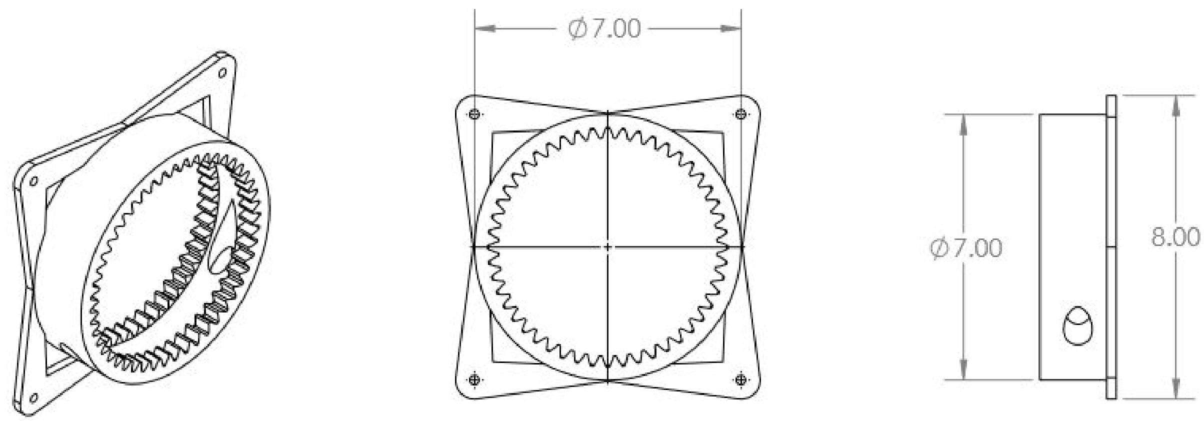


Figure 8: Redesigned Outer Gear & Mounting Bracket [IPS]

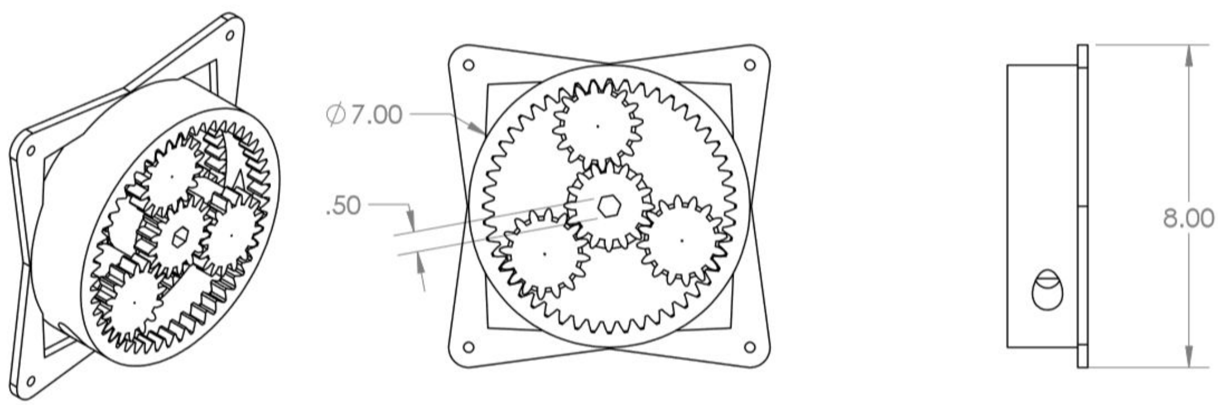


Figure 9: An Assembly of the new pump [IPS]

Part 4: Print Redesign and Analyzing the Result

Executive Summary

In the final part of this investigation, the next iteration of the additively manufactured design was printed and inspected. After this inspection future design recommendations are made to improve the part. The pump was again evaluated for dimensional accuracy, delamination, surface finish, mechanical and structural properties. Printing without support material was a success, taking less than five minutes to have the part fully assembled by installing tubing. The part was printed at larger scale this time, .65 instead of .33, due to the availability of tubing. This increased printing time to 30 hours but alleviated some of the problems discovered in the previous iteration. Half inch tubing was utilized to fully test the part and it was found to be non functional. This was due to tolerancing in the part and can be solved in future design iterations. There are several design paths suggested which can lead to a fully functional part. It is concluded that with design iteration the tolerancing can be fixed such that the part will function as a pump.

Analysis of Reprint

To complete the print for this part of the project, the various parts were turned into an assembly via SolidWorks, and then exported as an STL file, which was uploaded to the Markforged Eiger website. Before the print process began the print bed was cleaned. This was done because poor adhesion to the print bed was observed on other prints happening at the time. The print bed was removed and wiped thoroughly with acetone and a shop towel. A small amount of black oily substance was removed, but for the most part, the acetone seemed ineffective. The removal of the bed warranted a re-leveling per the Markforged machine's specifications. Unlike the previous iteration, it was deemed unnecessary to activate the support material feature in the Eiger software. This led to a part that was ready to work as printed, a complete elimination of post-processing time. The original part was designed to accommodate a ¾" tube. Unfortunately only ½" tube was readily available for the team to use so the intention was to print the part at 66% scale to fit the new tube size. The larger part can be see in Figure 1. This proved to be a convenient problem to have since the full size part would not have fit on the print bed. In fact the maximum size that fit on the print bed was 65% scale so that is what was used. The automatically generated settings were used for material settings. This means a 33% fill density was used with four floor layers and two wall layers. At this scale, with the set parameters the part took roughly 30 hours to print.

Figure 1. Image of second iteration of part design

Once printing was complete the part was removed from the print bed. During this process the putty knife used to pry the part up slightly damaged some of the gear teeth, delaminating the first layer. As can be seen in Figure 2 this damage is minor and did not affect the functionality of the part.

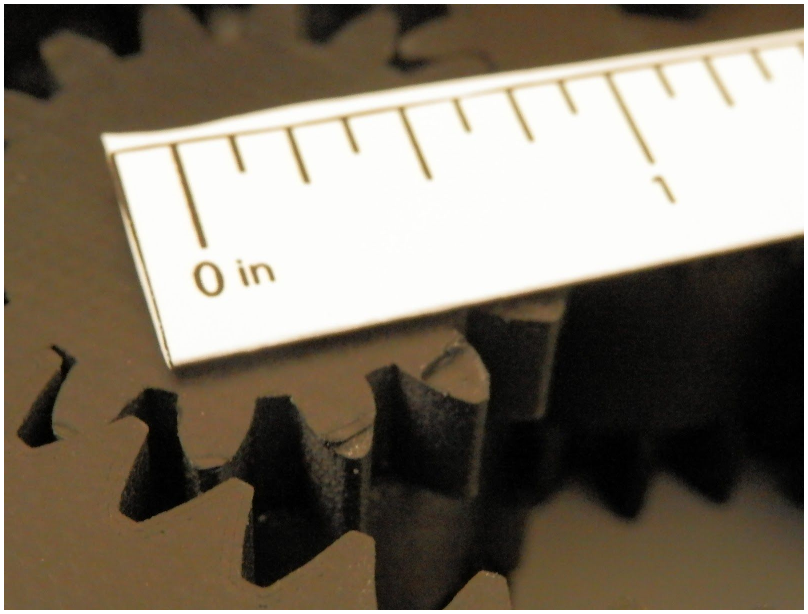


Figure 2: Delamination of gear teeth

The elimination of support material greatly reduced post-processing time and slightly reduced print time. As a result of this change, the overhangs printed with slight filament drooping. This was expected and is relatively minor as the largest overhangs are approximately ⅛”. Within several layers the print is back to normal as seen in Figure 3.

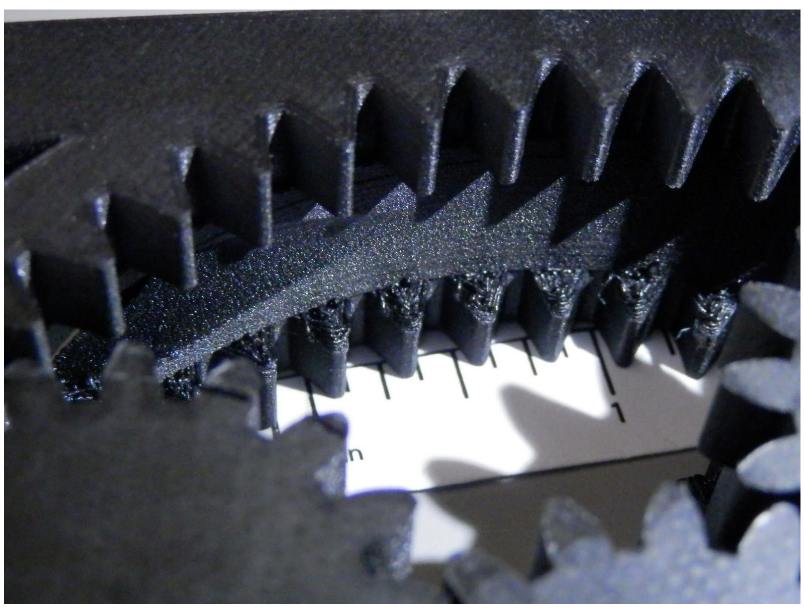


Figure 3: Filament drooping on overhangs

Once the part was removed from the print bed it was immediately ready to have the tubing inserted. This process was relatively easy and only took about a minute. The tube was threaded through the inlet hole and the gears were rotated until the tube could be threaded back through the outlet hole. The tube was then adjusted so it layed snugly inside the groove between the gears. With the tube inserted the pump was ready to be tested. It can be seen from Figure 4 that the dimensional accuracy of the keyway was greatly improved in this iteration.

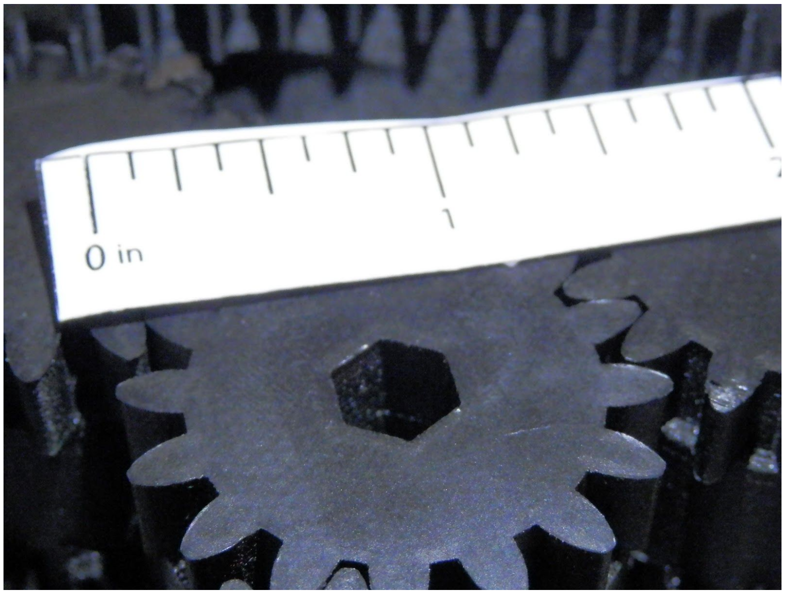


Figure 4: Center gear keyway

A hex key was easily able to fit snugly in the keyway and provide consistent power to the device. The pump was brought to the machine shop to test the pump with an electric drill providing power. An image of this testing can be seen in Figure 5.

Figure 5. Image of testing performed to determine functionality when pumping water.

Upon testing it was observed that the pump ran smoothly with little grinding or vibration, even at high speed. The drooping filament on the overhangs had no adverse effect on the functionality of the pump. This can be attributed to the channel for the tubing being large enough that the loose filament ends did not drag on the tubing. The only aspect of operation that the pump failed in was the most critical; it did not pump water. Upon investigation it was found that the rollers were not compressing the tubing enough to create a complete seal and so all pressure was lost. Several hypotheses were put forth as to why this was. It is possible that the ring gear deformed slightly during operation and did not provide the resistance needed to compress the tubing. This is unlikely, however because the increased size from the last iteration and addition of a mounting bracket adds significant rigidity to the system. Another reason could be that the assumptions made about how much the tubing needed to be compressed to create a full seal were incorrect. It is possible that the there were gaps at the edge of the seal as shown in Figure 6 that allowed pressure to escape.

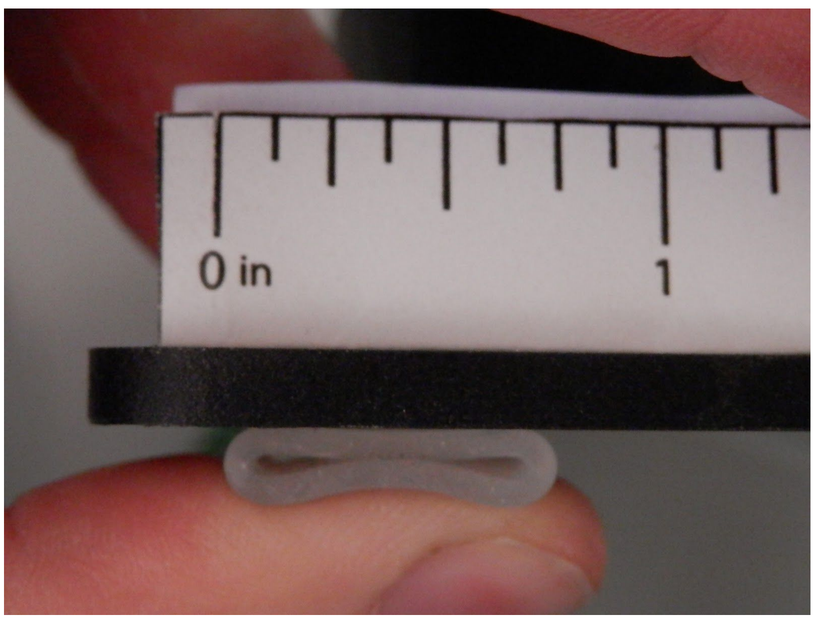


Figure 6: Gap at corners of tubing

Finally, dimensional accuracy in the interface between gear teeth may be to blame. A small amount of play was observed in the gear teeth meshing that may have caused inadequate compression of the tubing. This play was present in the SolidWorks model but may have been accentuated by slight inaccuracies in the print. The gap between gear teeth can be seen in Figure 7.

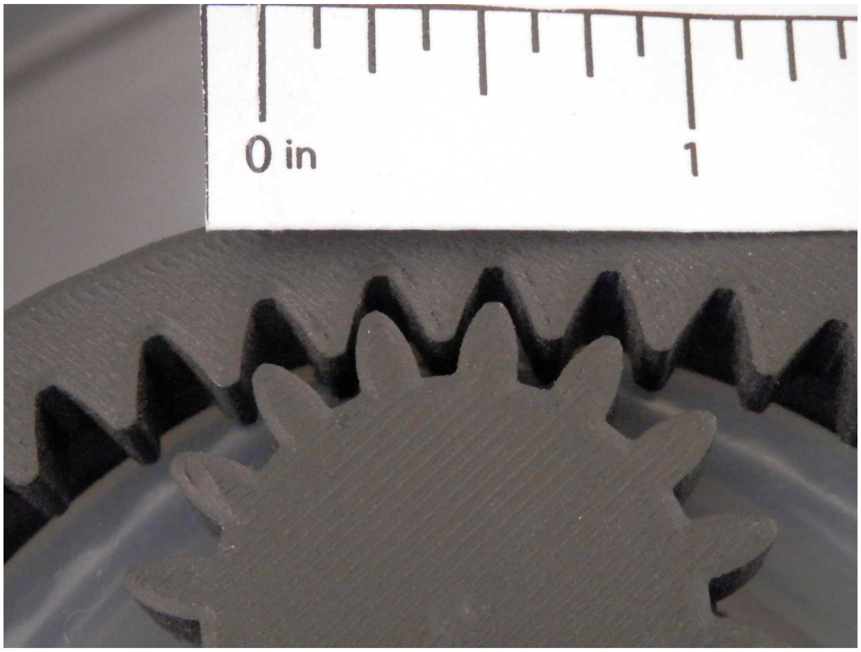


Figure 7: Gap in gear teeth caused by tube resistance

Next Iteration

The next iteration of the pump design would have create greater compression on the tube in order to achieve an airtight seal, and properly maintain the pressure differential needed to operate as a peristaltic pump. This could be done several ways, by addressing the problems outlined above.

The easiest solution would be to pick a tube with a greater wall thickness. This could solve the problem by increasing the required gap size to what the actual gap size already is between the rollers and outer gear. This would also not require any adjustments to the actual design of the pump, making it a favorable option. However, this solution is not guaranteed to work because tubing wall thickness is not infinitely variable. Increasing wall thickness would cause increased stress on the pump and could require an unfavorable amount of power to actually rotate the gears, and increase the amount of torque needed by the motor to the keyway. Thicker walled tubing would also result in greater stresses within the tubing material and potentially earlier failure of the assembly.

Another solution to create a complete seal in the tubing is to increase the roller size. This would create a smaller gap between the rollers and the ring and compress the tube more, creating a full seal. This solution would add the benefit of decreasing overhang size and lead to a cleaner print. An alternate to this solution that would essentially be the same is to decrease the ring size, achieving the same results.

Another solution considered was the addition of a fourth gear in order to mitigate play observed in the gears creating a tighter gap to better compress the tubing. By having four equally spaced gears, each gear would have another directly across from it to better translate load into the outer ring. This load path would better transfer compression and result in less play within the gear interface. This is thought to be the best option due to the greatest predictability of the tubing gap. This predictability is the result of mostly elastic deformation of the material instead of dimensional realignment of the assembly. Less play will also increase the life of the pump by ensuring smooth meshing of the gears and a reduction in the amount of grinding.

Our final consideration was increasing the gear size slightly in our 3 gear planetary system in order to attempt to eliminate play in the system and create a better seal in the tube. This solution, however, may cause problems as the diametral pitch of the internal gear would be slightly different than the diametral pitch of the ring gear and introduce a new means of grinding to the gear teeth.

Whichever solution is decided on, the complete sealing of the tube is essential to the function of the pump. In the next iteration of the pump it would be useful to research motors and pick one to design the mounting bracket around. The motor should be as inexpensive as possible while still delivering the necessary amount of power to the pump. It may be helpful to measure the amount of torque needed to spin the pump and use that along with the desired speed to find a motor with the right power. From there the mounting bracket design can be tweaked to securely fit on the selected motor while being strong and easy to print.

Along with with this research, parallels could be drawn to the functionality of the initial peristaltic pump the design was based off of. Fluid volume specifications could be derived from the initial pulley compression system, and motors with speeds that lead to comparable pumping results could be considered for a full cost-benefit analysis of the additively manufactured part, and the cost of the standard Greylor model initially studied.

Another improvement that can be made in future iterations is the addition of selective support material. In the Eiger software used, support material could only be turned on or off. It was turned off in the second iteration because in the first iteration the support material was generated in very hard to reach places and took an unreasonable amount of time to remove. If a different software was used, support material could be added only to the overhangs that are accessible. Although the drooping material on the overhangs did not affect performance in testing it is unclear if it would negatively impact long term durability. Adding support material to easily accessable overhangs would clean them up while keeping post-processing time low.

Finally, the fill density of the part could be optimized to reduce the print time as much as possible while retaining strength. A lattice could be added to the top and bottom faces of the pump like spokes on a wheel to allow for very low fill densities. This is something that would have to be applied over many iterations to achieve the lowest possible print time while keeping deformation minimal.

Conclusion

It is the conclusion of this investigation that with proper tolerancing determined through design iteration this part could be fully functional and adaptable to different size motors and tubings which would allow for customization of flow rates. This product could offer economic alternatives to traditionally manufactured peristaltic pumps due to the ability to use less expensive materials and greatly reduce assembly time.