Wednesday Group 3

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A11 Final Report

Initial Design Analysis:

We went through numerous iterations before coming to the final design.

We initially started by discussing the three different design options from the preliminary design review.

Saumya and Gabe's preliminary design idea was a double acting cylinder with a scotch yoke. Some advantages of this design were that it allowed for direct conversion of rotary into linear motion, had fewer moving parts, and allowed for smoother operation than the slider crank. The main disadvantage was that over time, the slot in the yoke would get worn down due to sliding friction and high contact pressures.

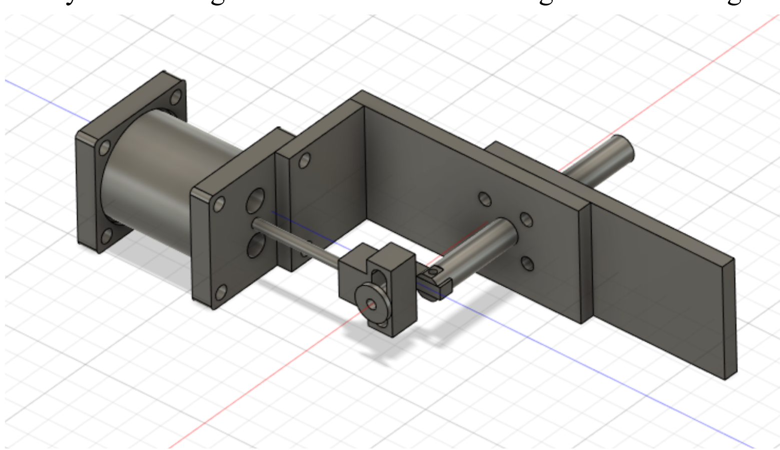


Fig 1. Double acting cylinder with a scotch yoke

Allie and Ryan's preliminary design idea was a single pump with a slider crank. We didn't find many ways to optimize the pump through our initial design so we ended up deciding to go for what we thought would be the simplest to design and build.

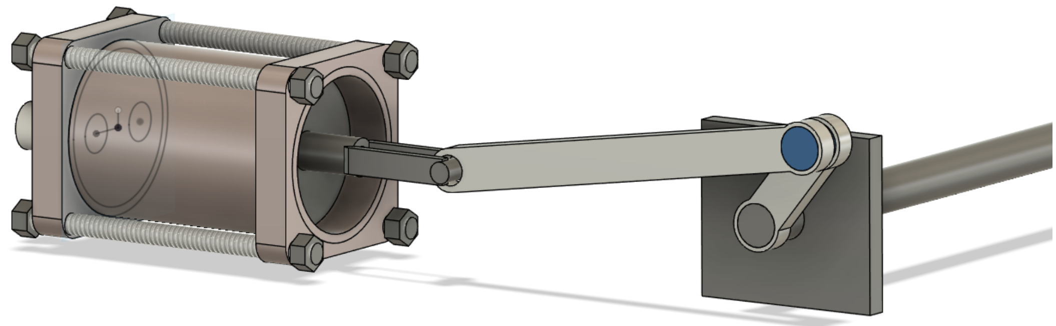


Fig 2. Simple 1 cylinder crankshaft pump

Isaac and Chris's original design was a single pump with a modified slider crank arm. The modified arm component converts the rotary motion from the shaft to linear motion, but allows for the piston to move straight in and out with minimal leaking. The modified component essentially has the same outcome as the scotch yoke, but would be slightly less complicated to manufacture.

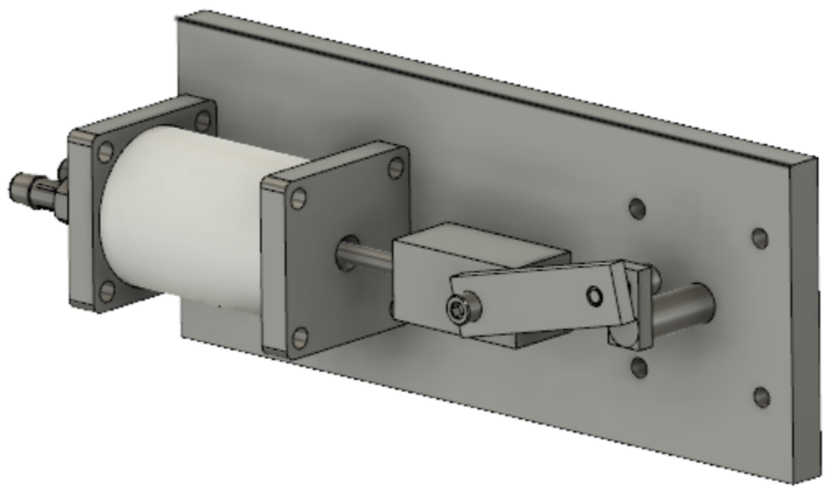


Fig. 3 Modified slider crank

After discussing the three design ideas as a group, we all agreed to go forward with the double acting cylinder with scotch yoke. The double acting cylinder with two input and two output valves allowed us to maximize the work being done by the pump, as the pump would be doing useful work during the entirety of its cycle, not just half. In addition, the scotch yoke mechanism allowed for smoother operation and reduced manufacturing cost from less moving parts.

<u>Further Design Considerations:</u>

We then discussed how we could optimize the double acting cylinder with scotch yoke design. Drawing inspiration from past years' pumps we saw in the lab, we thought we could further maximize our use of valves and power output by adding a second cylinder to the design.

We started working on a design with two cylinders, one on either side of the scotch yoke. However, when working on this design, we discovered that this design was not meeting the 14" x 14" constraint while leaving enough clearance for the knob on the face plate. With this in mind, we discussed further as a group and thought of other ways we could mount the two cylinders to the faceplate. We decided to split up into two groups to work on two different designs utilizing two cylinders. One group worked on modifying the either side design to meet the constraints and the other group worked on mounting the cylinders in a stacked design.

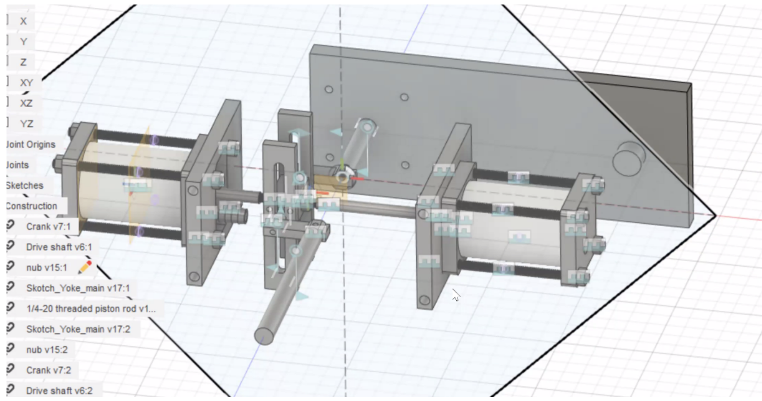


Fig 4. Design with two cylinders, one on either side of the scotch yoke

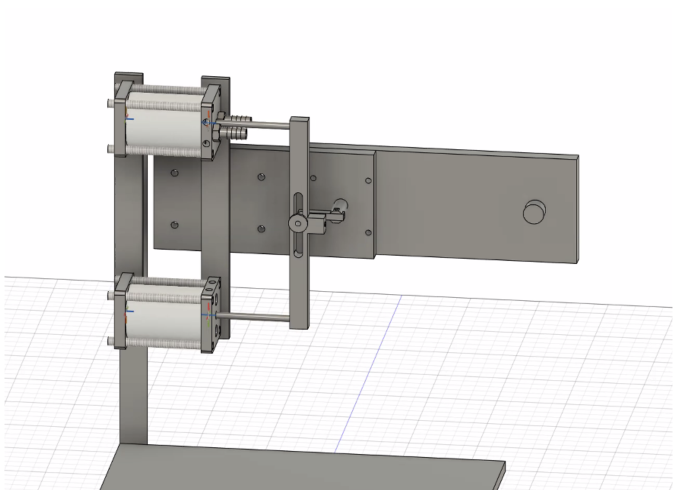


Fig 5. Design with two cylinders stacked

We ultimately went with the side by side option. We were originally concerned that the side by side design would be unable to fit within a 14” box, but we addressed that issue by rotating the box 45 degrees so that the length of the side by side pump was along the diagonal of the box. There were therefore no longer any issues with two double pumps on either side of the scotch yoke. We did however see some issues with the stacked design. Our main concern was that the yoke and cylinder mounts needed to be longer than before: this meant the parts were more subject to bending, and they were going to be more expensive to buy. With these drawbacks in mind, we decided against the stacked design and went instead with two double acting pumps on either side as our final design. Furthermore, for the long term use the symmetrical design with cylinders positioned across from each other may be more stable and witness a longer lasting usable lifespan.

Final Design Choice & Justification:

Our final design choice for the water pump is a double action pump with two cylinders using a scotch yoke mechanism. It uses four input valves (two on each cylinder) and four output valves (two on each cylinder). We chose this design for the advantages it provides. The first thing was that it maximizes the use of input and output valves. This allows us to double the amount of water flowing at a time and increases the efficiency of our pump. In our final design, we also decided to purchase our own bent valves for the inner end caps facing the scotch yoke. During the design process, one of the challenges we faced was making sure that there would be enough clearance between the ends of the valves with tubing and the scotch yoke to ensure that they don't interfere. By having the bent valves, we were able to make sure that the tubing would go out to the sides instead of the center so that the scotch yoke movement would not be hindered. For the mechanism to convert rotary into linear motion, we decided on the scotch yoke for two main reasons. The first is that it has less moving parts than the traditional slider crank. This would help reduce cost and increase ease of manufacturing. The second is that the scotch yoke provides smoother conversion of rotary into linear motion, which would make our pump work more smoothly without getting stuck. The last notable design decision we made was to include a bushing in our mounting place in which the drive shaft would mount. We implemented the bushing to ensure that the drive shaft could rotate with as little friction as possible. We decided against a bearing, as we thought that assembly (notably press fitting the drive shaft to a certain axial position) would be too inconvenient. Below is a render of our pump when our design was almost in its final stage. The only small changes we later made were after assembly.

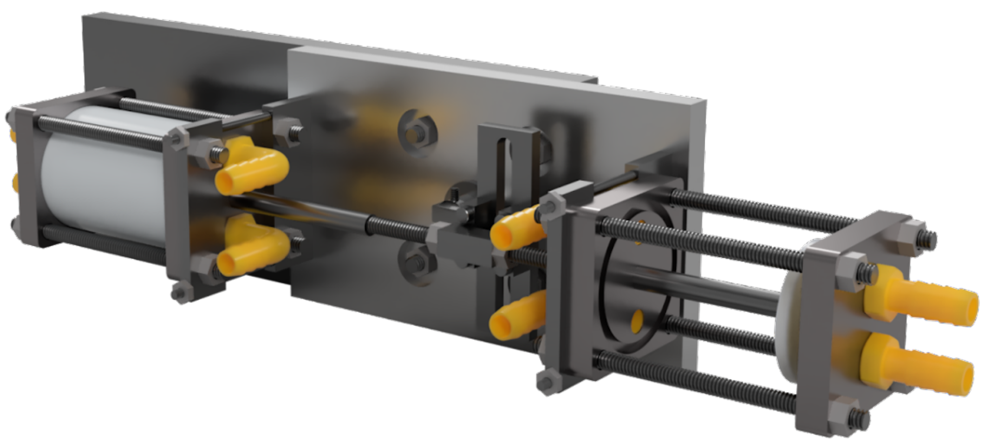


Fig 6. Water pump render before manufacturing changes

Challenges:

We faced many challenges during the fabrication process. One was that our original design for the rod collars was unrealistic. The diameter of these combined with the size of the hole required for the piston rod meant it was impossible to machine. The walls were too thin and would have collapsed had we continued drilling. We solved this by using the stocks OD rather than reducing it. That created another problem in that they did not fit in the holes we made in the cylinder endcaps. In order to fix this, we had to redrill the center holes with a larger drill size to ensure that the rod collars would fit well. We also had to sand down multiple parts (piston heads, rod collars) to ensure that they would slide smoothly in the pump.

A major challenge we faced after assembling the pump was that the scotch yoke portion (crank shaft, scotch yoke, nub) did not line up properly because of too much spacing between the parts. As a result, when we tried to turn the drive shaft, the scotch yoke would not move. We brainstormed different ideas to help remedy this problem. One thing we tried was 3D printing a part that would fit into the extra gap we had in the drive shaft. We also tried adding washers in between the crank and the scotch yoke to keep them at a constant distance apart. While both of these solutions provided a small improvement in rotation, neither was enough to allow for a smooth, full rotation of the scotch yoke. So, we decided to manufacture a part with a piece of stock that was left over from previous manufacturing. We removed our outside-top threaded rods and replaced them with the longer leftover portion. This rod acts as a guide for the new part which is a simple rectangle with one through hole and one threaded hole. The threaded hole attaches firmly to the piston rod while the through hole runs along the new threaded rod. What this part does is prevent the piston rod from rotating which was causing the scotch yoke to rotate. It is very important that the scotch yoke does not rotate as when it does, the crank presses into the yoke, preventing operation and putting stress on both pieces.

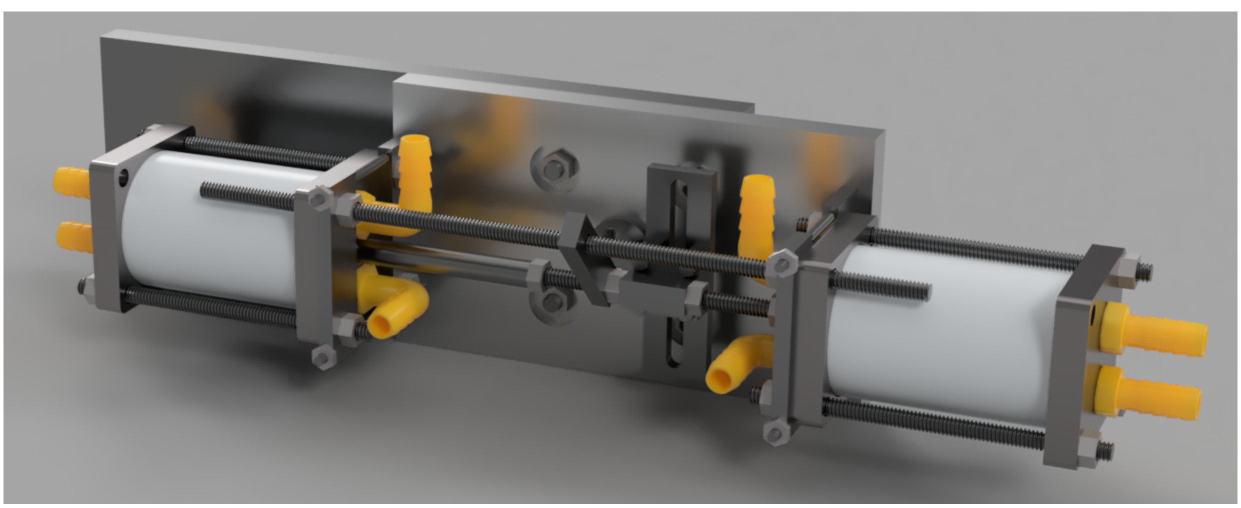


Fig 7. Water pump render including the modifications made during manufacturing.

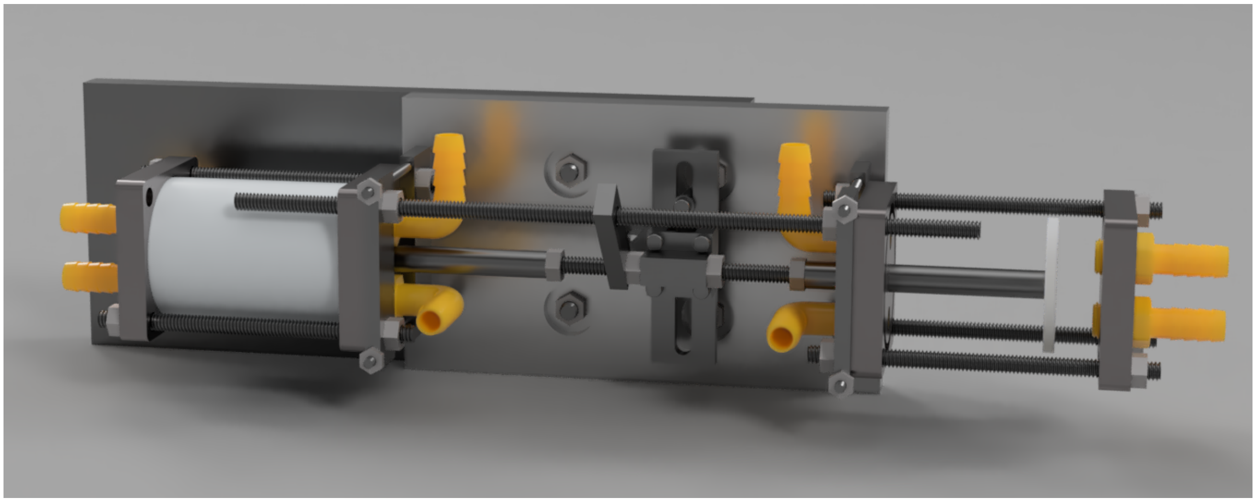


Fig 8. Water pump render including the modifications made during manufacturing at a different angle and with a cylinder hidden.

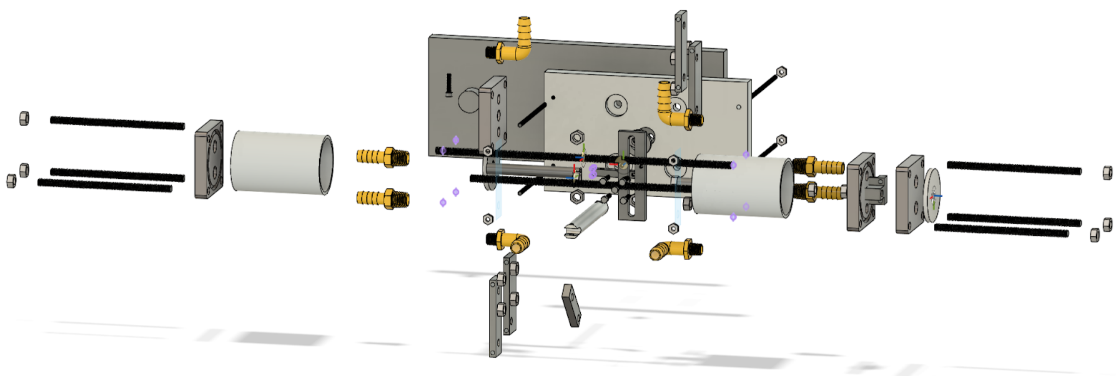


Fig 9. Exploded view of our water pump design

Ordering Analysis:

When our team was deciding which parts to use, we were looking for the right combination of cost, reliability, and performance. Selecting a component that is very reliable and high performing may have resulted in a cost that would not fit our budget requirements. Therefore, balancing these three factors together was integral in our ordering analysis of finding the most suitable parts for our water pump. First, ordering most of the components from Emerson made the most sense with certain components such as shaft, cylinder bore, and mounting plates. However, with the McMaster parts, we had much more flexibility and options with certain pieces. For example, with the 90 degree hose fittings, we could have selected the same part with different materials such as nylon, brass metal, polypropylene, and many others. Ultimately we went with the polypropylene material for the 90 degree hose fitting mainly because it provided satisfactory corrosion and abrasion resistance. It was also lighter weight and cheaper compared to the metal hose fittings but was still able to withstand the pressures that it would be exposed to. This is just one example of the extensive thought process that went into each component when we made the decision to execute a purchase for our pump. In the end, we want to find the right balance of cost, reliability, and performance. Sacrificing one of these variables to achieve the two other variables would not be ideal because we would fail to meet the objective goals of our mission. If this was a real life situation of designing a pump in a developing country where cost constraints may be a critical factor, designing a highly robust and high performing pump that is expensive and over budget would fail to meet the needs of a given population. This is why we must find the right balance between all three variables in the order analysis. Every engineering project is different with different objectives and challenges. Designing a pump for an aircraft may require higher levels of reliability and performance because the consequences of a failing pump mid air in flight can be more disastrous compared to a water pump in a camping RV vehicle. With all these key considerations in mind, with our double action pump in this particular instance, we felt a combination of all three factors was most ideal since extreme reliability or an extremely cheap price was not needed. A nice balance of all three variables was likely the best decision in the given circumstances.

<u>Parts list:</u>

Emerson

Machined End Caps Without Holes	2
Machined End Caps With 2 Holes	2
Piston Head(1 7/8" Diameter Plastic Rod)	2
Mounting Plate(1/2" x 4" Aluminum Bar)	7in
Nylon pipe fittings (3/8" barbed x 1/4"NPT)	4
Shaft (1/2" Diameter Steel Rod)	5in
Guide (1/4" x 2.25" Aluminum Bar)	3in
Scotch Yoke, Endcap Mounting, Crank (1/4" x 1" Aluminum Bar)	16in
1/4 - 20 threaded rod	5
1/4 - 20 hex nuts	26

Scotch yoke extrusion (1" x 2" Aluminum Bar)	1in
Bored Cylinder	2

McMaster

Bearing	6338K418	1
Plastic Barbed Hose Fitting	5218K788	4
6-32 nut pack of 10	91841A007	1
6-32 screw pack of 25	92185A149	1
6-32 threaded rod, 24"	98804A007	1
3/8" Al rod, 12” long	88615K12-88615K121	1

Total Prototype Cost: $4359.20

Product Cost(single): $4551.20

Product Cost(1000): $196.36

Fabrication timeline:

Part	Stock	Description	Team Member	Machined on
Endcap Modified	Machined Stock	Drill one through hole, tap two holes ¼ NPT on mill.	Saumya	5/1, 5/11, 5/12
Crank	1/4" x 1" Aluminum Bar	Band saw cut, face off six sides with mill, drill two holes, tap one using	Allie	5/1, 5/8

		mill.		
Drive Shaft	1/2" Diameter Steel Rod	Face off, mill in slot, mill in clamping surface, drill two holes, tap one.	Ryan	5/1
Mounting Plate	1/2" x 4" Aluminum Bar	Face off six sides on mill, counter sink 4 holes, drill 9 holes, tap 2 holes, ream one hole on mill.	Saumya	5/8
Nub	3/8” Al rod	Face off, turn both ODs to size, drill through hole, cut from stock.	Ryan	5/7
Piston Head	1 7/8" Diameter Plastic Rod	Face off on lathe, turn to size, drill one hole, tap hole on lathe.	Chris	5/10
Rod Collar	3/8” Al rod	Face off, drill through hole, sand.	Ryan	5/8
Scotch Yoke extrusion	1" x 2" Aluminum Bar	Band saw, face off six sides, mill out a lot of material, drill 5 through holes.	Gabe	5/2, 5/8
Scotch Yoke Main	1/4" x 1" Aluminum Bar	Band saw, face off six sides on mill, mill a slot, drill and tap four holes.	Gabe	5/8, 5/11
Vertical Mount Inside	1/4" x 1" Aluminum Bar	Band saw, face off six sides, drill two holes on mill.	Isaac	5/8
Vertical Mount Outside	1/4" x 1" Aluminum Bar	Band saw, face off six sides, drill two holes on mill.	Isaac	5/1, 5/8
Guide	1/4" x 2.25" Aluminum Bar	Bandsaw, face off cut side, drill two holes, tap one.	Ryan	5/17

Miscellaneous tasks:

Task Description	**Team Member**	**Machined on**
Cut and sanded threaded rods	Allie	5/8
Polishing interior of piston cylinder	Chris	5/10

Completed Assembly:

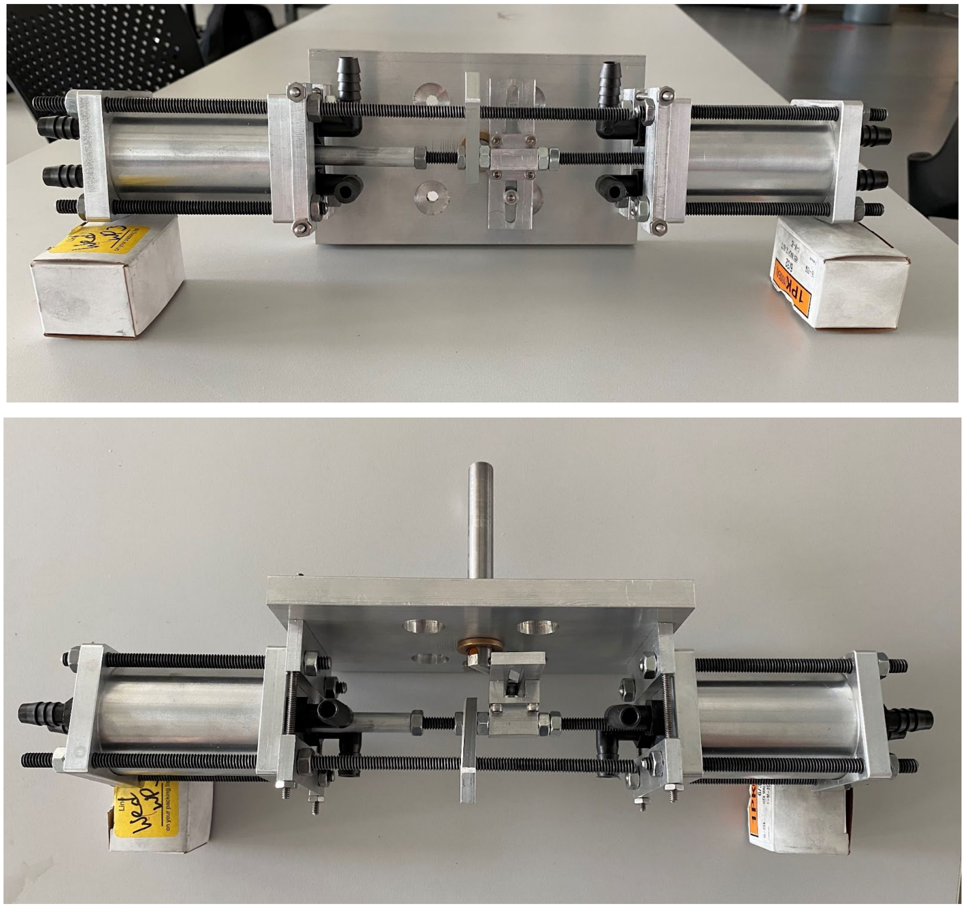


Fig. 10 Pump Assembled

Power Calculations:

First we take the equation for flow rate: $\dot{Q}$

$$\dot{Q} = \frac{AR\omega}{\pi}$$

Then we plug that into the equation for power: P

$$P = \rho_w g h \dot{Q}$$

Then, using these values:

Variable	Formula	Value
A	$\pi(\frac{D_p}{2})^2$	$0.00178 m^2$
D_p	-	0.0476 m
R	-	0.0272 m
ω	-	115.7 rpm
ρ_w	-	$1000 \frac{kg}{m^3}$
g	-	$9.8 \frac{m}{s^2}$
h	-	1.5 m

We can calculate flow rate and power usage. Multiplying each by 4 then gives the total flow rate and power use for both double action pumps combined:

$$\dot{Q} = 0.000119 \frac{m^3}{s} = 7.154 \frac{L}{min}$$

And that:

$$P = 1.751 W$$

Since the provide motor has a given power of 559 W. Assuming an efficiency of $\geq 1\%$ we have a functional pump.

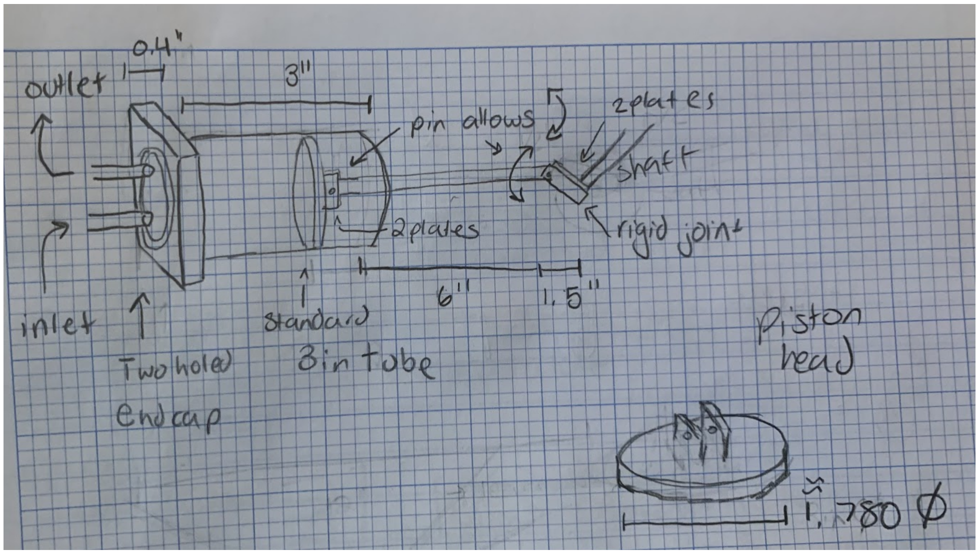
Performance Analysis:

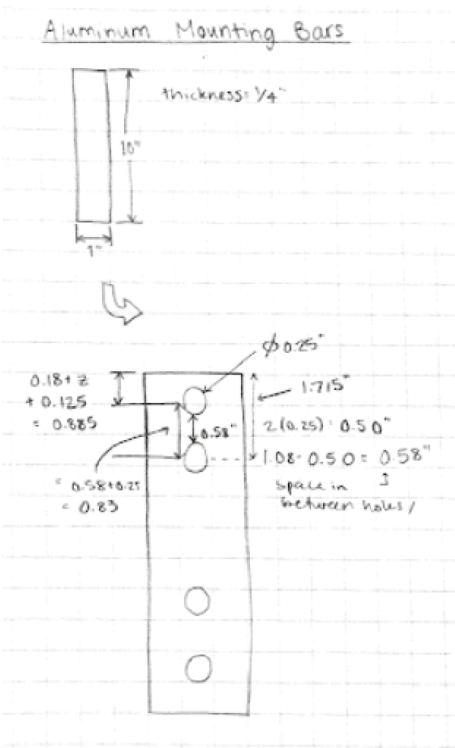
The pump was allowed to run for 1 minute. According to our calculations, that means the pump should have pumped 7.154 L. However, during testing, only 1.8 L of water was pumped in the one minute run time. The large discrepancy between the theoretical and actual volume of water pumped can be attributed primarily to the removal of one rod collar, which was necessary for the dynamical components to move without substantial friction. Removing the rod collar created a very large gap between the piston rod (a threaded rod) and the gap through which it passed into the cylinder. During each cycle, a substantial amount of water could be seen squirting out of this hole. Furthermore, the output tube attached to the cylinder cap with the large gap moved very little while the pump was running. This indicates that little if no water at all flowed through that output tube.

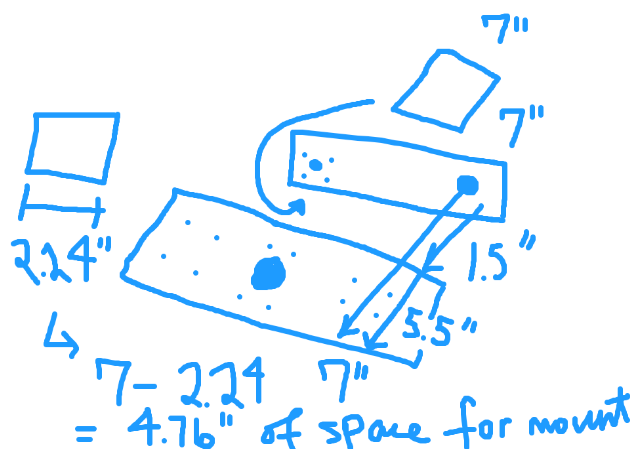
However, even if no water flowed through the output tube attached to the gap with the gap, that means the theoretical flow rate becomes 5.3655 L/min, meaning the pump should have pumped 5.3655 L in the one minute that it ran. This means that other components in the pump substantially deviate from their theoretical behavior. Such deviations include power being used to overcome friction between dynamical components. There was relatively minor friction between the pistons and cylinder. However, there was a fair amount of friction that existed between the one remaining rod collar and the cylinder cap, the crank and the yoke, and the guide and the threaded rod. In our calculations, we assumed no power losses, so the discrepancies between the pump in theory and reality can be partially attributed to this simplification. Another source of error in our calculations was the assumption that our pump would not leak at all. Leaking from the inner cylinder cap without the rod collar has already been discussed, but leaking from other parts of the pump was visible as well, including the connection between the caps and the cylinder and the connection between the nozzles and the caps.

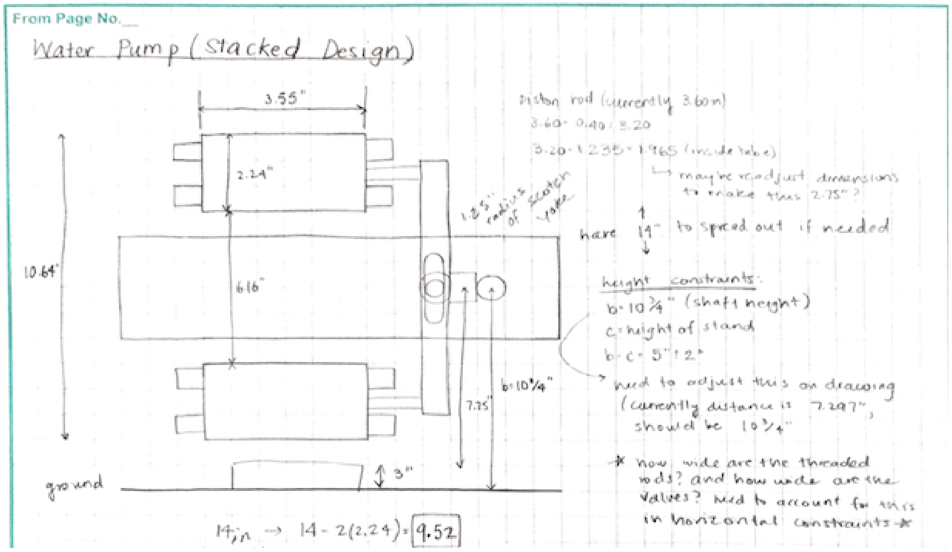
Despite the large gaps between the expected and actual performance of the pump, our group still met the requirements of pumping one liter of water in one minute. We knew coming into this design process that our pump would not live up to its theoretical performance due to issues such as leaking. Accordingly, we over engineered the pump to pump much more water than necessary, thus giving us a large margin of error. Subsequently, errors during the design, analysis, manufacturing, or assembly process did not cause our pump to fail its requirements.

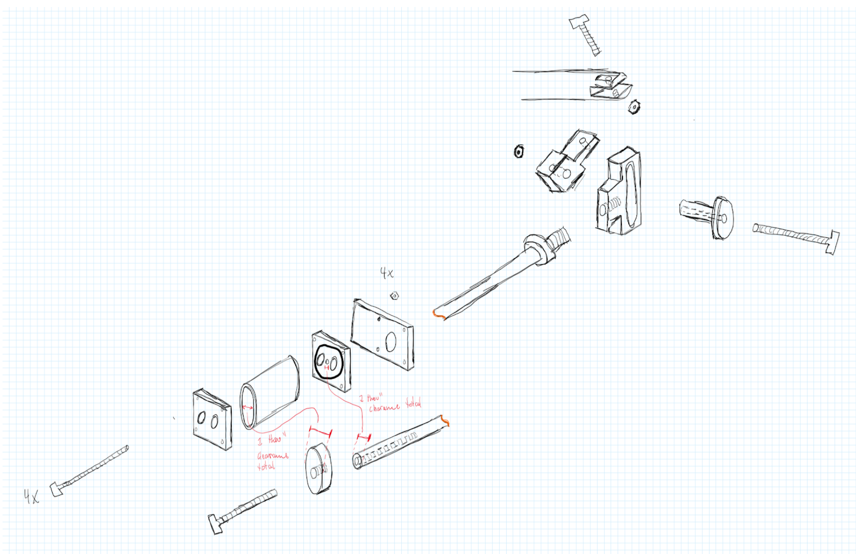
<u>Sketches:</u>


0.4"
outlet
3"
pin allows
2 plates
shaft
2 plates
rigid joint
inlet
Two holed
end cap
standard
3in tube
6"
1.5"
piston
head
1.780 Ø

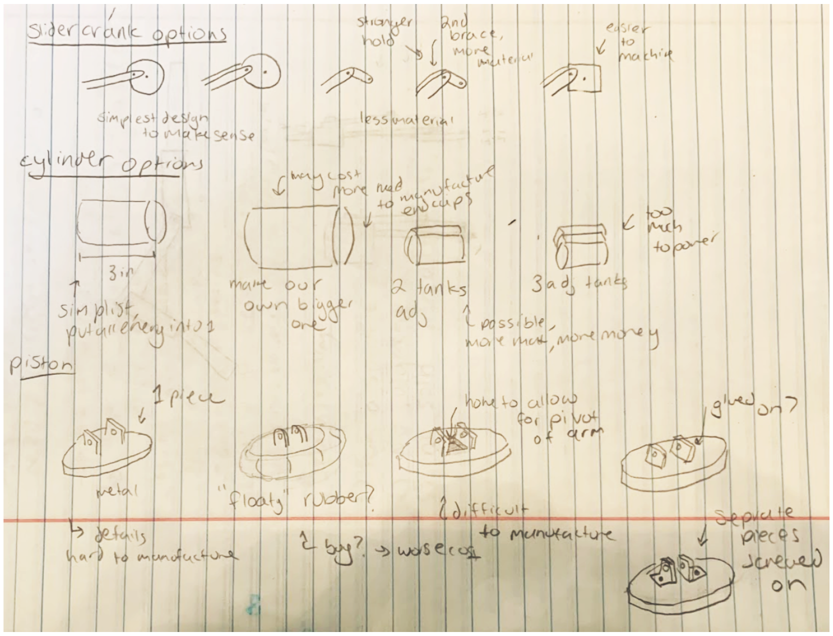

Aluminum Mounting Bars
thickness = 1/4"
10"
1"
Ø 0.25"
0.18 + z
+ 0.125
= 0.885
1.715"
2(0.25) = 0.50"
0.58"
1.08 - 0.50 = 0.58"
space in
between holes
0.58 + 0.25
0.83

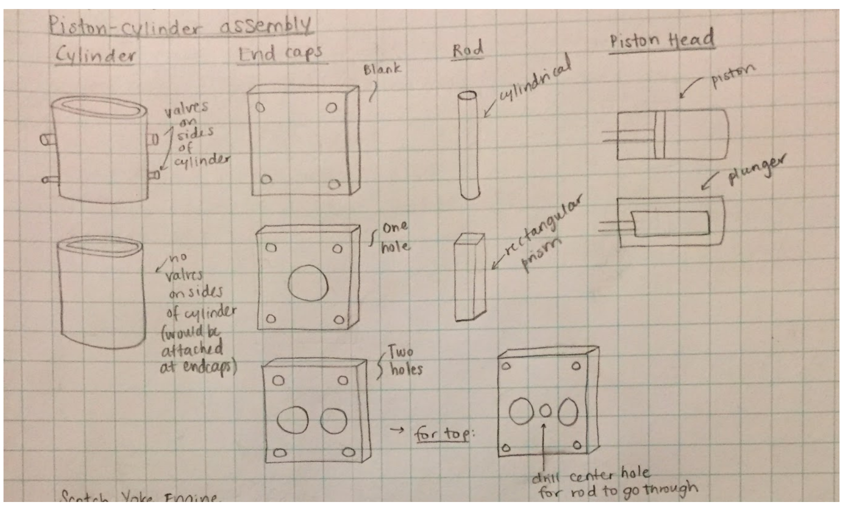

7"
7"
2.24"
1.5"
5.5"
7 - 2.24 7"
= 4.76" of space for mount

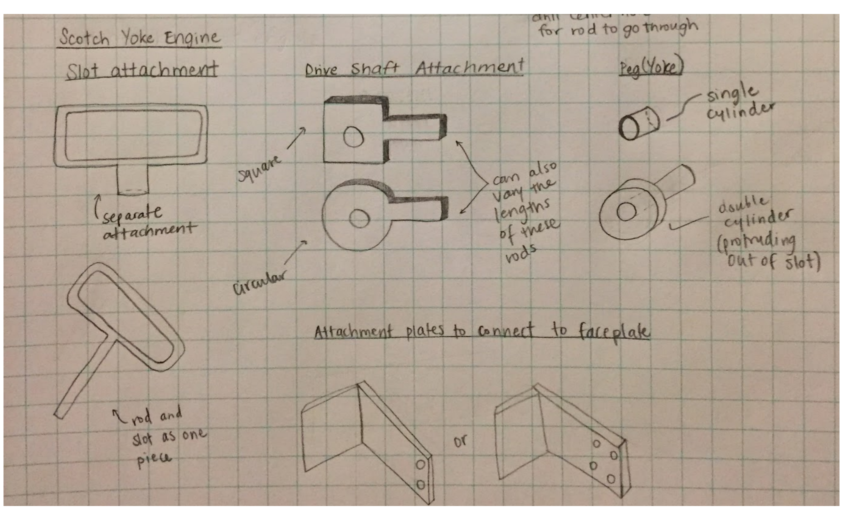

From Page No.__
Water Pump (Stacked Design)
3.55"
2.24"
10.64"
6.16"
7.75"
b=10¼"
3"
ground
14in → 14 - 2(2.24) = 9.52
piston rod (currently 3.60in)
3.60 - 0.40 = 3.20
3.20 - 1.235 = 1.965 (inside tube)
maybe readjust dimensions to make this 2.75"?
1.25" radius of scotch yoke
have 14" to spread out if needed
height constraints:
b = 10¼" (shaft height)
c = height of stand
b - c = 5" ± 2"
need to adjust this on drawing (currently distance is 7.297", should be 10¼"
how wide are the threaded rods? and how wide are the valves? need to account for this in horizontal constraints


4X
4X

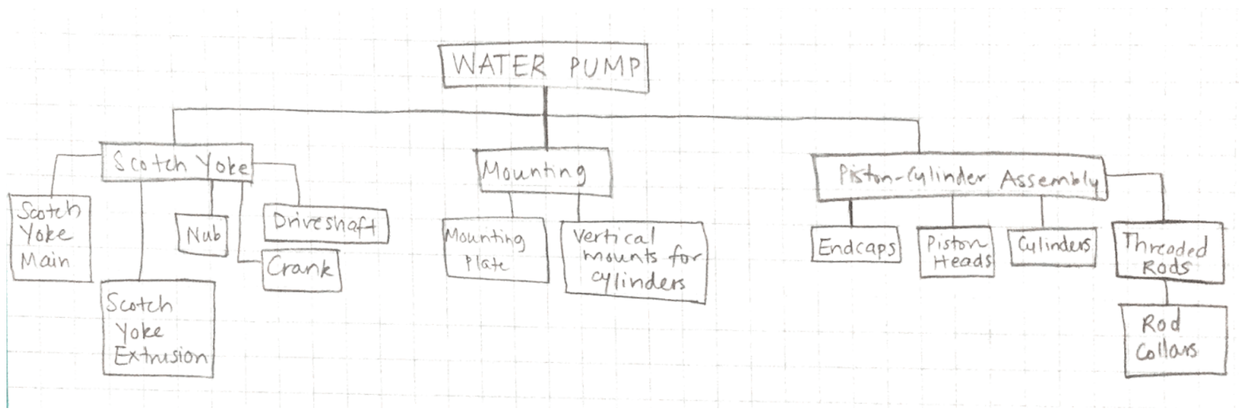
Morphological Charts:







<u>Functional Decomposition:</u>



PROJECT	Water Pump
PROJECT MEMBERS	Allie Voltagio, Ryan Begin, Isaac Beaton, Saumya Mehta, Gabe Mitchell, Christopher Levine

TASK ID	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	Project Conception and Initiation					
1.1	Team Charter	Team	3/31/2021	4/4/2021	5	100%
1.1.1	Completed CAD	Team	4/4/2021	4/11/2021	7	100%
1.2	Complete Parts List/Manufacturing Analysis	Christopher, Isaac	4/11/2021	4/28/2021	18	100%
1.3	A9 (Final Design + Paper Prototype)	Team	4/11/2021	4/28/2021	18	100%
1.4	Machining	Team	5/1/2021	5/12/2021	12	100%
1.5	Assembly	Team	5/12/2021	5/12/2021	1	100%
1.6	Final Report	Team	5/12/2021	5/21/2021	9	100%
3.3						

PHASE ONE			PHASE ONE			PHASE ONE	
WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8
M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F

Appendix:

note that since everything was made on a red machine, all part dimensions have tolerances of ±0.0005