Design and Construction of a Filamentous Algae Harvester Prototype

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science degree in Physics from the College of William and Mary

by

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Final Report on the Design and Construction of a Filamentous Algae Harvester Prototype

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1 Background

Algal-based bio-fuels present a great alternative energy source. However, using current production methods the land, water, carbon dioxide, and nutrient requirements for growing the algae limit potential cultivation sites so severely that these fuels cannot sustainably supply a significant portion of our current energy consumption. It is estimated that to produce enough algal based fuel to supply 5% of the U.S.'s current transportation needs would require as much as 15 million tons of Nitrogen, and as much as 2 million tons of Phosphorous. This represents as much Nitrogen as is currently use in all of U.S. agriculture, and half the amount of phosphorous already used in U.S. agriculture (Committee on the Sustainable Development of Algal Biofuels, et al., 2012).

This project is one part of a larger effort, the ultimate intent of which is the optimization of algae production, drying, and pre-processing. Instead of using open land, we're trying to grow the algae on substrait plates in local rivers. By growing the algae on artificial surfaces in eutrophic rivers, we eliminate the need for large areas of land, large amounts of water and for carbon dioxide, nitrogen, and phosphorous input, all at no cost to the grower (Manos, N.D., Unpublished).

The substrait plates used collect wild local algae, and there is no outside input of nutrients. The site at the York River primarily collects the phototrophic algae *Berkelea* and *Melosira.*Using current techniques this site has produced up to 50gm per square meter of usable biomass daily, and could theoretically produce up to 2000 gallons of butanol per acre within one year. In addition to providing an inexpensive production method for bio-fuels, this method provides an ecological benefit to the river. The algae absorb the extra nutrients in the water from fertilizer run off and other agricultural sources that cause eutrophication and filter it out of the water by using it for their own growth (Manos, N.D., Unpublished).

For the algal growth to produce enough biomass to supply a significant portion of our energy consumption, we need to show that this in water growth can be done on a large scale economically and with minimal labor. To that end, the goal of this specific project is to design and develop a more efficient way to harvest the algae from the substrait than what is currently in use.

2 Current Harvesting Methods

Currently, the algae is harvested by scraping it off of the substrait plates it is grown on. Although this method does effectively collect and retrieve the algae, it has a number of problems that I am hoping to be able to alleviate with a new harvesting technique. The first problem is that it is a time and labor intensive process to remove the plates from the water and scrape the algae filaments off of them. This imposes limits on how quickly it can be harvested, and on how large the individual plates can be. Secondly, this process stresses the plates themselves, reducing their usable life span.

The current scraping method also reduces algal yield over time. Given sufficient biological resources, algae growth follows an exponential curve. The more algal mass is present the faster it grows until it reaches the limit imposed by the available space and nutrients(Australian National Algae Culture Collection, N.D.). By scraping the algae off of the plate, so little is left behind that regrowth is hindered. Recall that for very low input values exponential growth is slower than linear growth. This problem is illustrated by figure 1. This plate had 3 small sections harvested at four, eight, and sixteen days prior to the photo, and shows the regrowth of the algae over that time.

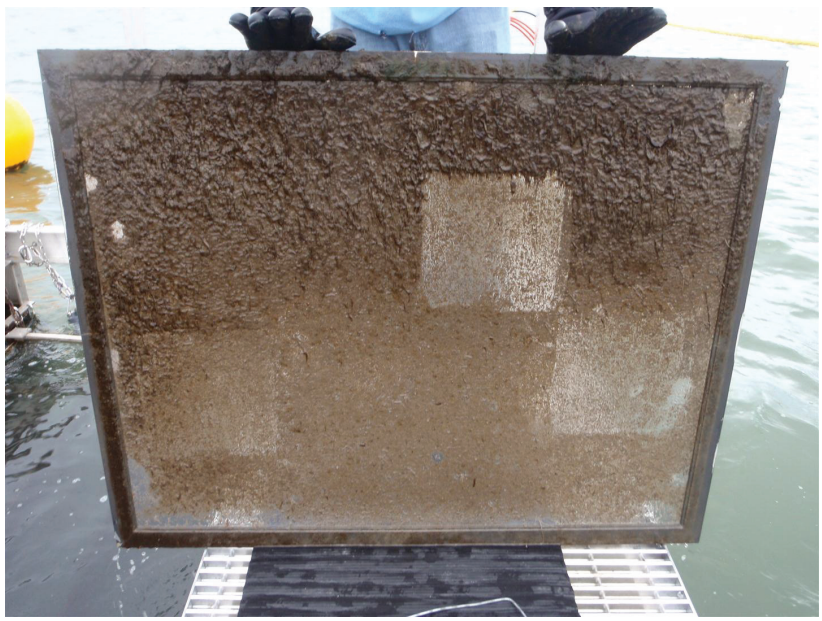


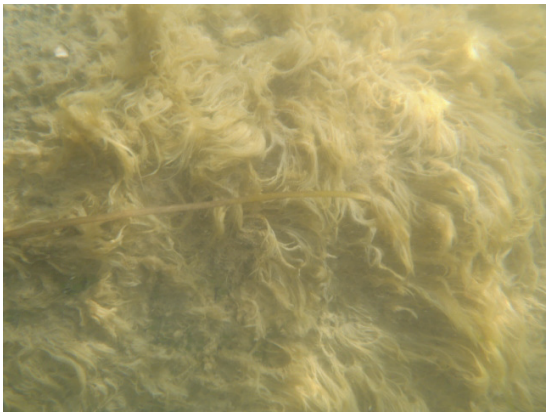
Figure 1: Photo of the York River site showing bare spots on substrait plates. These sections were respectively harvested 4 days prior (Top Center), 8 days prior (Lower Right), and 16 days prior (Lower Left) to the taking of this picture.

To address these problems, we decided to come up with a method to cut the algae filaments off several millimeters above the surface of the plate, and retrieve the cut stalks with mesh filter bags. This could potentially be much quicker than removing the plates from the water, and it will certainly reduce the stress on the plates during harvesting. We also suspect this method will have two other benefits to it. Firstly, we suspect it will increase the algae yield by eliminating that slow period of initial regrowth. When given sufficient natural resources algal growth is exponentially dependent upon the numbers of

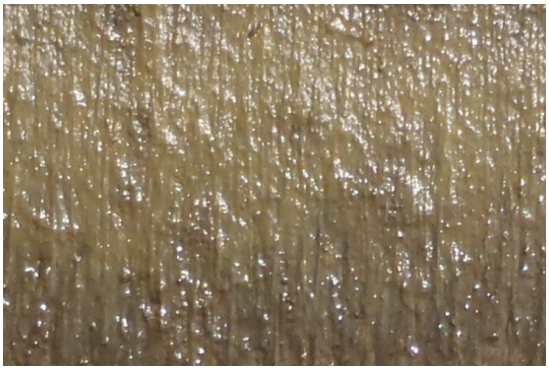
cells initially present in the stalk. By leaving a few centimeters worth of stalk behind, the growth should be much greater over the few days immediately after harvesting than it wold be if the plates had been scraped. We also suspect that the scraping process also picks up a significant amount of sediment and other non-algal mass. We hope that algae harvested with the cutting method will have less of this extra material, and as a result, produce a higher energy density in the mass that is harvested, allowing it to be more efficiently converted into fuel.

3 Early Design Ideas and the Problems with them.

3.1 Weed Trimmer Design



(a) Plate with algae in water



(b) Plate with algae out of water

Figure 2: Algae on substrait plates shown both in and out of the water

As you can see from Figure 1a, when the algae is in the water, it floats and drifts around. Like this, is feasible to cut off the filaments while still leaving some biomass on the plate. To that end,I considered several different designs.

One of the first designs that was considered was that of a spinning blade. Something that would work very much like a weed trimmer or lawn mower, with a thin blade that spun quickly enough to cut through the stalk. A quick calculation of the drag forces led me to discard this idea. Unbeknownst to me at the outset of this project, a group at Huntington Ingalls Industries had tried a similar approach, and built a prototype to test. According to Dr. Bill Cooke, the motor burnt out when they tried to run it at speed in the water (W. E. Cooke, Personal Communication, November 14, 2013).

Aside from the difficulty of getting something to spin quickly in water, this design would also stir up the water, and would push the stalks away from the blades. This would make it rather useless for cutting the flexible algae stalks.

3.1.1 Discussion of Drag Forces in Water

The drag force acting on anything moving in the water is probably the single biggest obstacle to various designs for cutting the algae. Although the drag force is the driving

element behind this problem, ultimately the most important number is the power required to overcome this force and keep the blade moving at speed. The following calculation assumes a single blade coming out in one direction from the axis around which it will rotate.

For most any object moving at high speed, we can ignore the linear friction term, and focus on the quadratic drag. That drag force is descried by Equation 1.

$$F_{Drag} = \frac{C_D}{2}\rho_0(dA)v^2 \tag{1}$$

Where C_D is the positive drag coefficient that varies with specific materials and configurations. $C_D \leq 2$. ρ_0 is the density of the fluid. In this case, with water, $\rho_0 = 1g/cm^3$. A is the cross sectional area perpendicular to the linear motion, and v is the magnitude of the linear velocity (Nave, 2012).

In the weed trimmer (and several subsequent designs) the cutting edge is spinning around a central axis. Because of this the linear velocity at any given point is dependent upon how far from that axis the point is. The linear velocity at any given point is $v = r\omega$ where r is the distance from the axis,ω is the angular velocity. Thus, the differential force at any given point along the cutting edge is

$$\mathrm{d}F_{Drag} = \frac{C_D}{2}\rho_0\mathrm{d}A(r\omega)^2 \tag{2}$$

From there we can separate the differential area into two terms, the width of the blade, which I will define as h, and a differential length.

$$\mathrm{d}F_{Drag} = \frac{C_D}{2}\rho_0 h\mathrm{d}r(r\omega)^2 \tag{3}$$

To calculate the power lost to drag, we need to find the torque caused by the drag force. $\tau = \int F \times r$. Since the velocity vector in uniform circular circular motion is always perpendicular to the radius, and drag forces directly oppose motion, we need not worry about the sine term of this cross product, as it goes to 1 with the 90 degree angle.

$$\tau = F \times r = sin(90)Fr = Fr \tag{4}$$

We only have the drag force for differential sections of the length, so we can only get the torque for differential sections. To get the total torque on the system we need to integrate over the distance from zero to L where L is the total length of the cutting edge.

$$\tau = \int_0^L \mathrm{d}\tau = \int_0^L (\mathrm{d}F)r \tag{5}$$

By plugging Eq. 3 into Eq. 5 we get

$$\tau = \int_0^L r(\frac{C_D}{2}\rho_0 h(r\omega)^2)\,\mathrm{d}r \tag{6}$$

We can then remove all the terms not dependent upon r outside the integral

$$\tau = (\frac{C_D}{2}\rho_0 h\omega^2)\int_0^L r(r)^2\,\mathrm{d}r \tag{7}$$

Evaluating this integral, we get

$$\tau = (\frac{C_D}{8}\rho_0)h(r^4\omega^2)|_{r=L} \tag{8}$$

Power is related to torque by $P = \tau\omega$. Therefore, the power required to keep the blade spinning at speed is

$$P = (\frac{C_D}{8}\rho_0)h(r^4\omega^3)|_{r=L} \tag{9}$$

The above derivation assumes only a single edge of length L coming out from the axis of rotation, but in an actual design, there would be at least two edges extending out opposite of each other. Therefore the power requirement would be the result of Eq 6 times the number of blades. Assuming a weed trimmer string of 1/10 inch (reasonable for a string, but too thin for any rigid blade), 1800 rpm (nearly a fifth of what an average weed trimmers run at), a radius of 10cm, and a drag coefficient of 1, the power requirements where around 12 horsepower ($13.4kW$). This is in the range of an outboard boat motor. Given a large enough motor this design could be used, but would be impractical and inefficient.

Although it is derived based on the idea of a string trimmer, the above model can be used to approximate power requirement of any rod that is symmetric about its axis of rotation with radius L. If the rod is symmetric about the axis of rotation but does not go all the way to the axis, re-integrate equation 3 using new boundary conditions, and this will still hold so long as drag from whatever is between the new boundary and the axis is minimal.

It should be noted that the power requirement can be reduced a factor of four without reducing the cutting rate by doubling the number of blades, and halving the angular velocity, but that cannot be done with this design, because the it will only cut when the blade hits a stalk at high speed.

This model was used to estimate drag forces on the design that was ultimately prototyped. The specifics of that will be discussed later.

3.2 bifurcating blade and single rotating blade designs

The next idea we discussed was a set of bifurcating blades. Two bladed combs would be placed over top of each other, and one would move laterally back and forth, cutting the stalks. This design is very similar to what is already used in some hand-held grass trimmers. A model of this blade design is shown in Figure 3.

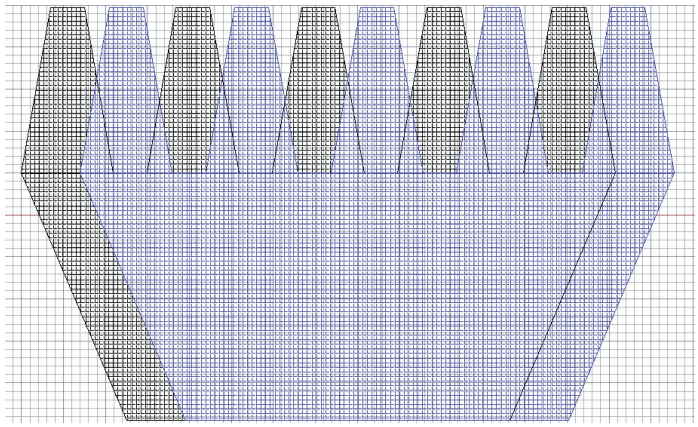


Figure 3: Design Model for Bifurcating Blades

Because of the two sided cutting action, the movement of these blades could be slow enough that drag would not be as large a concern, but it would likely still be enough to churn the water. We also suspect that many of the stalks would slip out of the blades rather than being cut. Further, this design only works well when it is being moved across the plate parallel to the direction of the comb.

To address this second problem, I briefly considered a bifurcating blade design with the comb going out radially, but this was quickly modified to a radial comb with a single scything blade spinning around the comb. See Figure 4.

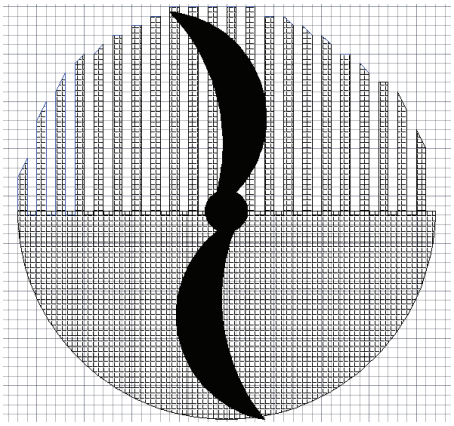


Figure 4: Design Model for the comb and blade design. The red is the blade. In this design it would rotate counter clockwise. The upper blue is a comb that would hold the stalks in place as the blade cut,and the lower blue section is part of the frame that would hold the apparatus together.

This design still only works well when moved parallel to the comb, and there is the potential for the stalk to get tangled around the comb and not get cut well, but it is still a design that might be returned to if the current design fails to perform.

4 Current Approach and Design Considerations

4.1 Approach

Our current design works on much the same principle as scissors. It has two blades rotating in opposite directions. Each blade will have a slight inward curve, like a very shallow sickle blade, or a pruning knife (see Figure 5). This will let the blades trap the stalks between them as they close. Since the cutting action comes from the two blades pushing past each other, and not the speed of the impact, it can be run at a speed slow enough that drag will be minimal, and the water will not be churned too much. I estimate that is the blades cut 2 to 3 ties per second, then the device could be moved over the plate at a reasonable speed without missing algae stalks. With two sets of blades this could occur with rotation of 60-100 RPM. Assuming that it only effectively cuts $\frac{1}{4}$ of the area that the blades circumscribe in a single pass, then the harvest rate R in square meters per minute would be equal to

$$R = (N/4)\omega\pi r^2 \tag{10}$$

where N is the number of times the device cuts per rotation)$N = 2$ for this design), and ω is in RPMs. Assuming blades with roughly a four inch radius, and the 60-100 RPMs give above, I predict a maximum harvest rate of one to two square meters per minute.

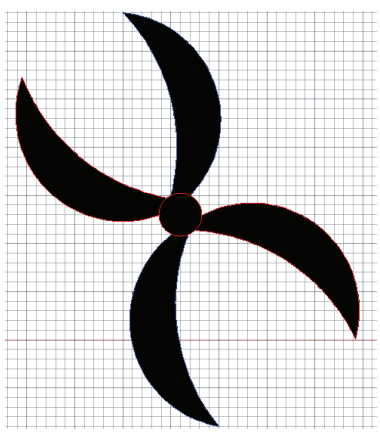


Figure 5: Design model for rotating blades. The cutting edge is the concave surface.

4.2 Design

In getting this approach to work, the biggest challenge has been creating a set of nested, counter rotating shafts. To do this, we initially created a design with single drive shaft that would be connected to a motor. This shaft would then be connected to the outer of the two shafts using a belt and pulley system, and connected to the inner of the nested shafts through a gearbox. The belt and pulley system would cause the outer shaft to turn in the same angular direction as the drive shaft, and the gearbox would allow the inner shaft to turn in the opposite angular direction. Figure 6 is a rough sketch of what this might have looked like.

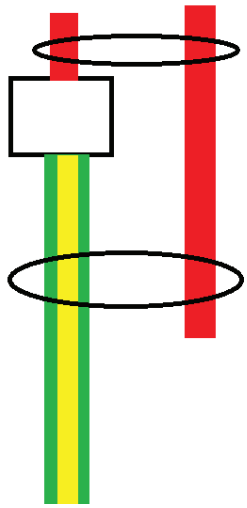
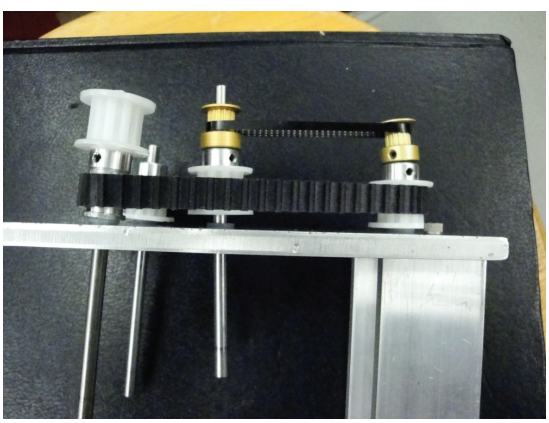
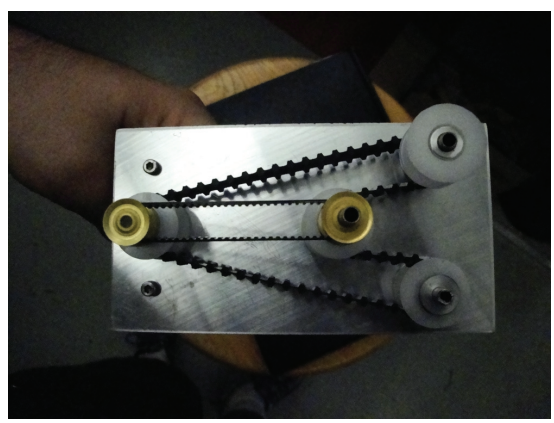


Figure 6: Nested Shafts: Yellow and green represent the two shafts, red represents the drive shafts (note that a second shaft would be needed in this setup to transfer power around the gearbox). The black loops represent the timing belts.

The original plan was to use a simple commercially available gearbox, but the ones I found were designed to transfer power at a right angle to the input direction. Instead I modified the design to use two separate sets of pulleys to create the counter rotation. With a two sided timing belt and two idler pulley the outer shaft can be driven in the opposite direction as the powered drive shaft while the inner shaft can be driven in the same direction as the drive shaft by a different belt. The pulley on the inner shaft will be above the pulley on the outer shaft. A picture of this layout in the prototype is shown in Figure 7. Figures 8 shows the nested shafts. Figures 9 and 10 are the schematics for the plates that hold the shafts and gearing system in place.



(a) Top Down View



(b) Side View

Figure 7: Photographs of the gearing system

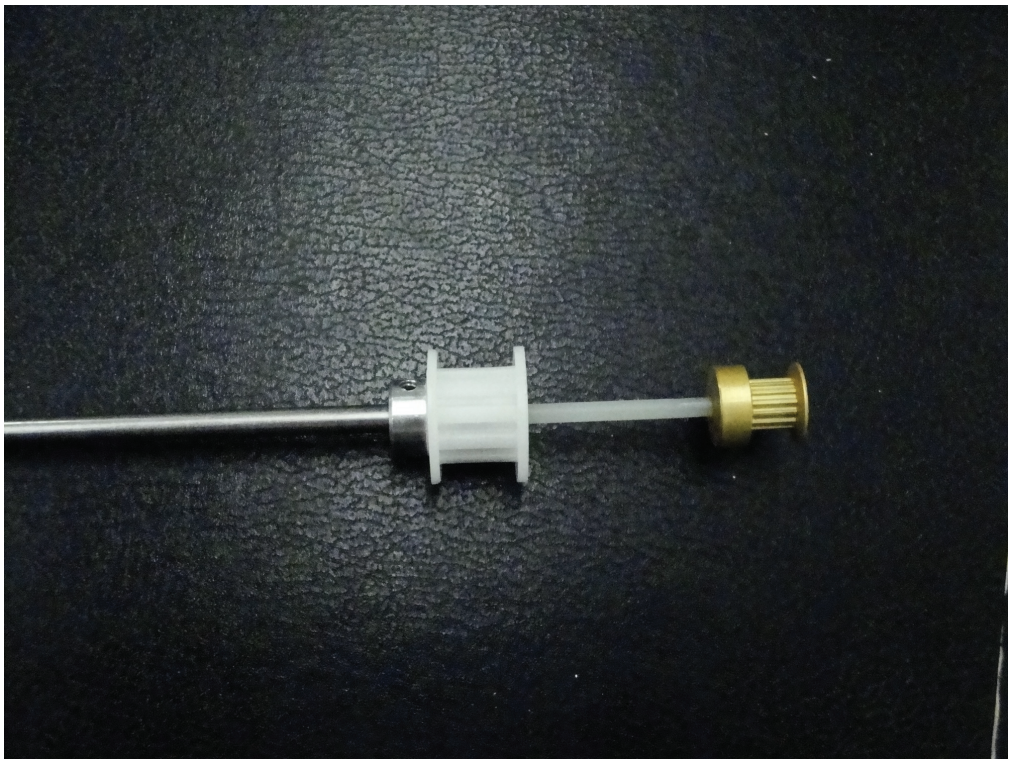


Figure 8: Nested shafts, intended to rotate in opposite directions

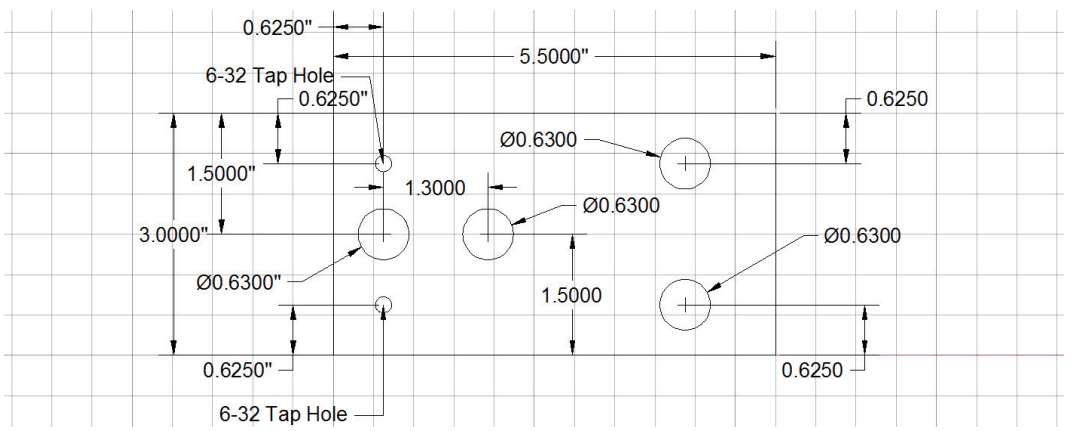


Figure 9: Autocad Drawings of the top plate that hold the gearing system. The plate is $\frac{1}{2}$ inch thick.

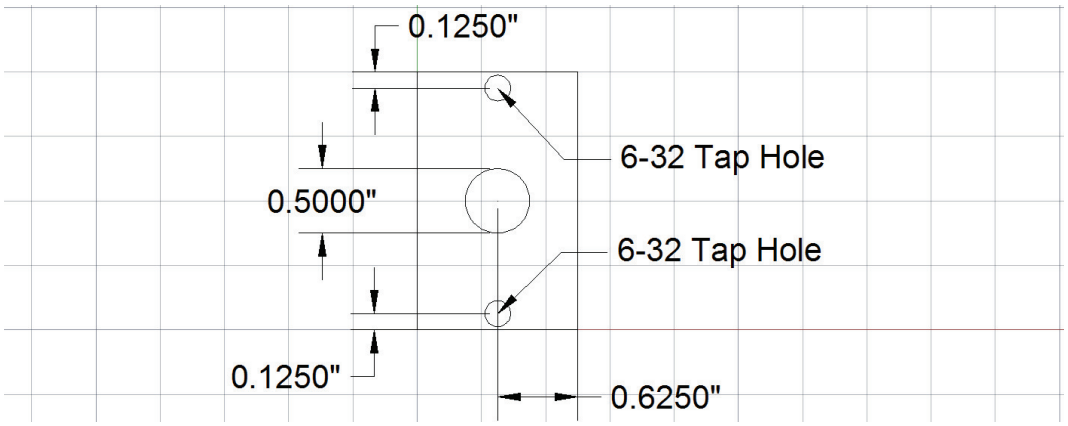


Figure 10: Autocad Drawings of the bottom plate that hold the bottom of the shaft in place. The plate is $\frac{1}{2}$ inch thick.

4.2.1 Drag Force concern

The same drag equation discussed earlier does apply to this design, and because there will be a total of 4 blades (two symmetric sets) a factor of 4 is needed in the equation for power (eq. 9). The power requirement can be much lower for this design because the filament is cut by the two blades meeting, and not by the speed of the impact. This allows it to use very low angular velocities, resulting in much smaller drag.

Assuming again that $C_D = 1$, with four 10mm thick blades with a 4 inch (˜10cm) radius rotating at 100rpm I calculate a torque caused by drag that is about $70mNm$. This can be overcome with a power output of of $.70W$. It could easily be powered by the motor of a cordless drill. This could be verified experimentally by measuring the current drawn by the motor powering the device, and calculating the power used.

4.2.2 Shaft Stability Concerns

Due to the length of the shaft, and the thinness of the plate the it is mounted in, I found that it bends and twists very easily. This bending and twisting is in part do to the tension on the belts in the gearing system,and partially due to anything the shaft might bump into. To stabilize the shaft, I connected a piece of U-channel aluminum to the mounting block, and another piece of plate at the bottom of the channel. By drilling holes into the plate, and running the shaft down though bearings, the shaft can be mounted into a plate at both ends. In this way, it is stabilized at the top and bottom of the shaft (See Figure 11).

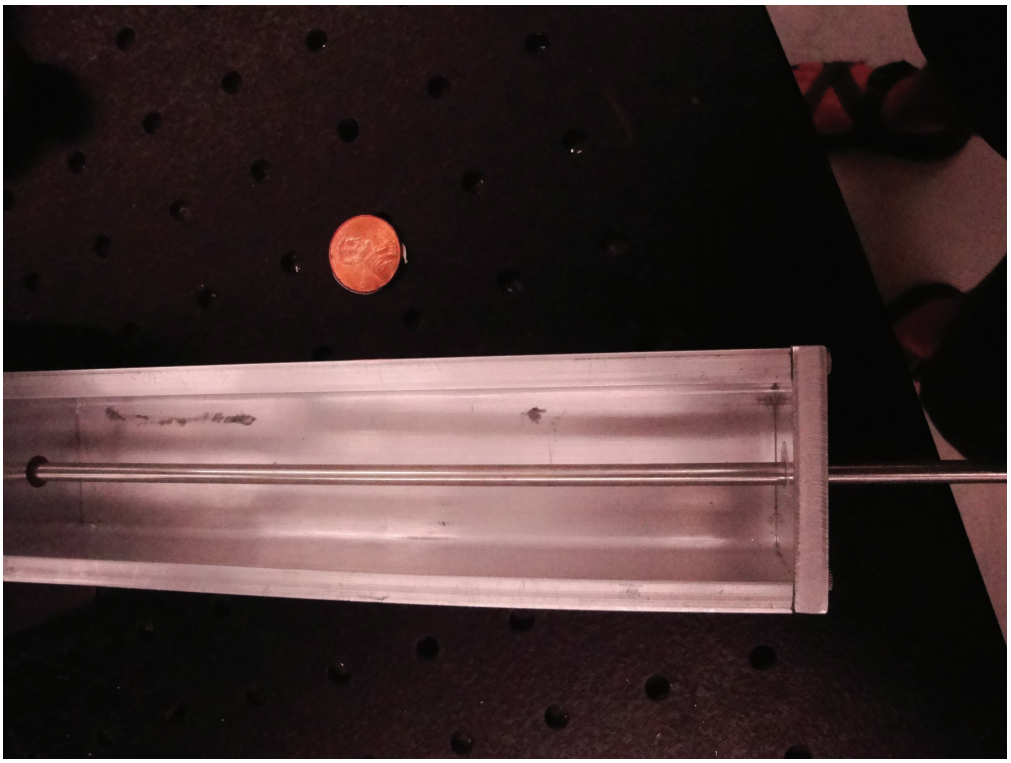


Figure 11: Edge on picture of the prototype showing the channel used to stabilized the length of the cutting shafts.

4.2.3 Material Concerns

Since this device will be working in water, it is important that the materials be corrosion resistant. Most of the materials and parts used have been ordered through McMaster-Car. All metal parts were either Type 303 Stainless Steel, or Type 6061 Aluminum. Specifically, the hollow outer tube of the nested shaft, and the gear shafts are stainless steel. The inner shaft is made of Teflon PTFE resin so as not to cause metal on metal friction. The timing belt pulleys are made of either nylon or anodized aluminum, and the timing belts are made of urethane. In current small scale proof of concept models, the shafts are set into holes drilled into aluminum plates.

4.2.4 Blade Design

Due to time constraints we were not able to complete the blades. The blade could be machined from stainless steel, but could also have been made from a plastic. A 3D printed blade would would likely be easier to make than trying to machine one due to the concave curvature. A specific equation to describe this curvature has not been selected, but the upper or lower half of an ellipse (above or below the semi-major) axis would suffice. The important detail in this design is that it allows the tips of the blades to come together before the rest of the cutting edge. This keeps the algae trapped within the blades as it is cut, instead of potentially being pushed out from between the blade.

5 Future work, testing, and model Problems

5.1 Problems

The existing model works as a proof of concept for the nested counter rotating shafts, but is incomplete without blades. Since the majority of the external drag force will be due to the blades, the power requirements could not be tested. Additionally, it is difficult to estimate the internal friction of the device. The moving parts are all run through bearings to reduce friction, but as you will notice in figure 7, the belt connecting the gears is rather tight. The McMaster-Carr recommended allowing an extra 10% for belt stretching. Upon examining the 14" belt, it was clear that it would not stretch an additional inch, so the design only allowed for an additional 1% stretch,and even this seems to have been too much. As such, the internal friction of the existing model is very high due to an overly tight belt.

5.2 Future Work

To actually be tested, the model needs to have the blades completed and attached. As mentioned above, I believe the easiest way to create the blades would be 3D printing. The plastic compound used by these printers would not degrade in water, and although it would not have the strength of metal, should be more than sufficient to cut through the algae stalks. They could be attached to the shafts using set screws for the purposes of this test model.

The other immediate problem is the internal friction from the over-tightened belt. The simple solution to this problem is to put one of the idler pulleys (Far right side of figure 7b) on some sort of set screw in a slot that allows it to be moved up and back to tighten and loosen the belt, but the time I realized that it was a problem, there was not time to design and implement this solution.

5.3 Testing

If the blades for this model were to be completed were to be completed and the existing problems addressed, it would need to be tested. There are at least three tests that should be undertaken. First, the model should be run at speed both in and out of the water and the power output of the motor measure. This would hopefully confirm the estimates the external drag and provide a way of measuring the internal friction. Second, he model should be used to harvest a patch of algae. This would test if it actually serves it's intended purpose and if the speed it is run at is sufficient to effectively cut the algae without binding, or missing sections. Finally, two patches of algae should be harvested, one with the model I have created, and one using the current scraping method. Then, after a period of time, both of these patches should be harvested using the scraping method (to ensure all the regrowth is recovered) and the amount of regrowth should be measured. This would show whether or not this harvester actually produces a more efficient regrowth process.

6 Acknowledgments

I would like to thank my advisor, Professor Bill Cooke, for helping me get this project off the ground, and offering ideas when I was unsure how to proceed. I would also like to add a special thanks to Will Henninger in the machine shop. Without his help, this model would likely have never come together.

7 References and Photo Credits

7.1 References

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7.2 Photo Credits

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