Mechanism for Actuating Seaweed Harvesting Device

by

Christopher Goul

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Signature redacted

Signature of Author: ....
Department of Mechanical Engineering

Signature redacted

Certified by: ....
Ahmed Ghoniem
[Full Title of Thesis Advisors, usually Professor of Mechanical Engineering]
Thesis Supervisor

Signature redacted

Certified by: ....
Maria Yang
Associate Professor of Mechanical Engineering
Undergraduate Officer

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ABSTRACT

Mechanical systems to automate a critical aspect of the seaweed farming process were designed and iterated to determine their feasibility as a substitute for human labor on a commercial large-scale seaweed farm. This paper explores various proposed alternatives and the advantages and disadvantages inherent to each design, with the ultimate goal of determining a single system best suited for adoption by the commercial seaweed industry. Each mechanism was designed and critiqued according to the needs of US seaweed farmers, and evaluated over criteria such as cost, complexity, speed and efficiency.

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1. Introduction

1.1 The Current State of Seaweed Farming

Seaweed production for human consumption and industrial use is a massive industry valued conservatively at ~$6 billion dollars globally[1]. 26 million tonnes of wet seaweed are harvested and processed annually, of which 94% of production occurs in 4 Asian countries[2]. Despite the enormous scale of seaweed production, the majority of labor is still performed by hand by seasonal laborers. Additionally, there is no single harvesting method employed universally- methods vary greatly depending on farm location and the type of seaweed being harvested. Large farms in China, which net around 50% of the global seaweed output, employ great numbers of laborers in wooden boats to remove seaweed by hand (typically Wakame) from lines floating in the water. In Japan the production of *Gelidium* is almost solely undertaken by female divers who, using goggles and rakes, harvest up to depths of 10m and carry up large amounts (up to 300kg) of seaweed each day[3]. Methods of collecting *Gracilaria*, from which agar is made, is similarly farmed from lines in shallow water. *Chondrus Crispus*, "Irish moss" which is the primary plant material used to make carrageenan, shares a similar method of collection with these other species[3]. Regardless of the species grown, these farms all have one thing in common; they are operated by humans. The aim of this project is to take advantage of technology to automate this already massive industry, just as the tractor was applied in the Industrial Revolution in the 20th century to agriculture. To truly take advantage of the untapped resource that is the ocean, and to achieve economies of scale, automation and the efficiency it brings is necessary.

Fig. 1: Scale of a typical seaweed farm in Fujian, China[4]

Almost universally the labor intensive processes of seaweed harvesting and planting are performed by humans. There are two methods for harvesting seaweed- the 'wild harvest', which involves collecting naturally occurring seaweeds, and 'farming', which as the name implies is the cultivation of seaweeds on artificial substrates. Of these two methods, by far the majority of production comes from farmed seaweeds, with wild seaweeds only accounting for 4.5% of global seaweed production in 2010[3]. Due to its relatively insignificant fraction of the seaweed farming industry, this thesis will primarily examine seaweed farms and technologies related to their optimization.

While methods of harvest differ, a unifying characteristic of cultivated seaweed farms across countries is that they primarily use 'long lines' and nets as growth substrates for their cultivation of seaweeds. A long line refers to a rope held underwater, by means of buoys and anchors, on which seaweed spores are planted and grown. Large farms typically have a nursery on site where they maintain seaweed seed stock- a solution of young seaweed spores- which, before the growing season, are implanted artificially onto the lines. These ropes are then placed into the water and grow throughout the growing season without any added fertilizer. After a predetermined time period which varies by species, the mature plants are harvested and lines are either trimmed or removed from the water in preparation for the next growing cycle[5]. There are two common types of long-line farm setups- the off-bottom method, which is suited for shallow protected waters, and a floating system tethered by anchors to a deeper sea floor. Figure 2 below provides a graphical representation of these systems. Net-based systems share a similar footprint to long-line designs, but use large nets oriented parallel to the sea floor instead. This method is primarily used for species of seaweed that do not grow very long, as the increase in surface area provided by the nets becomes more useful.

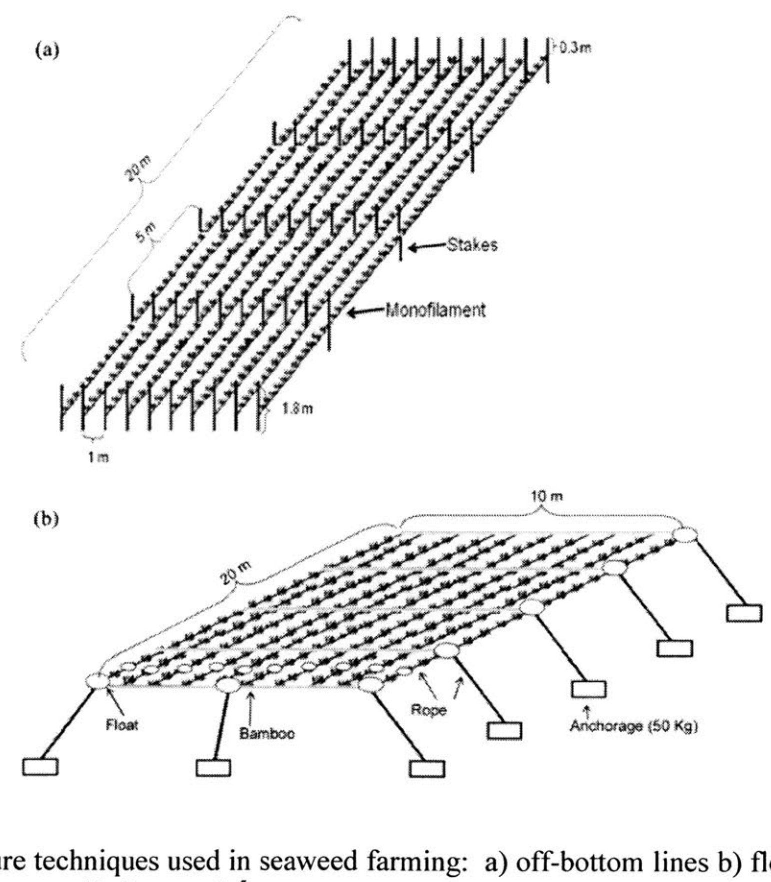

Fig. 2: Culture techniques used in seaweed farming: a) off-bottom lines b) floating lines. Dimensions vary with farm scale[5].

The design of these farm layouts reflects the two most important requirements for growing seaweed- availability of nutrients and sunlight. After other environmental requirements such as water temperature and limits on wave size are met, these two criteria have the greatest impact on seaweed farm yields. Lines must be suspended ~2-4 meters below the water surface to protect against harmful impacts of waves while permitting enough light to reach the crop. In shallow waters, this can be accomplished by using a line tethered to the sea floor, but typically this design is not suited for larger farms simply due to environmental constraints and the relative scarcity of protected shallow waters for seaweed farms to use. In deeper waters, typically ranging anywhere from 15-40m, a floating system of long lines tethered by anchors is used[6]. Shallow water farms are often operated by divers while accessing deeper farms requires the use of boats.

1.2 Types of Cultivated Seaweeds and Their Uses

Macro algae can be roughly divided into three groups; red, green, and brown seaweeds. Notable species within the brown subcategory includes species of Wakame and other Japanese kelps, which constitute the majority of species grown in China and Japan and which are primarily used for human consumption. Red seaweeds include *Euchema*, *Gracilaria*, and *Porphyra*, the first two of which are used to produce Agar and other industrial reagants while the latter is again used for human consumption. Green seaweeds constitute by far the smallest portion of this market, and typically are not farmed on a large scale[7]. The quantity of production of these kinds of seaweeds is shown in the figure below.

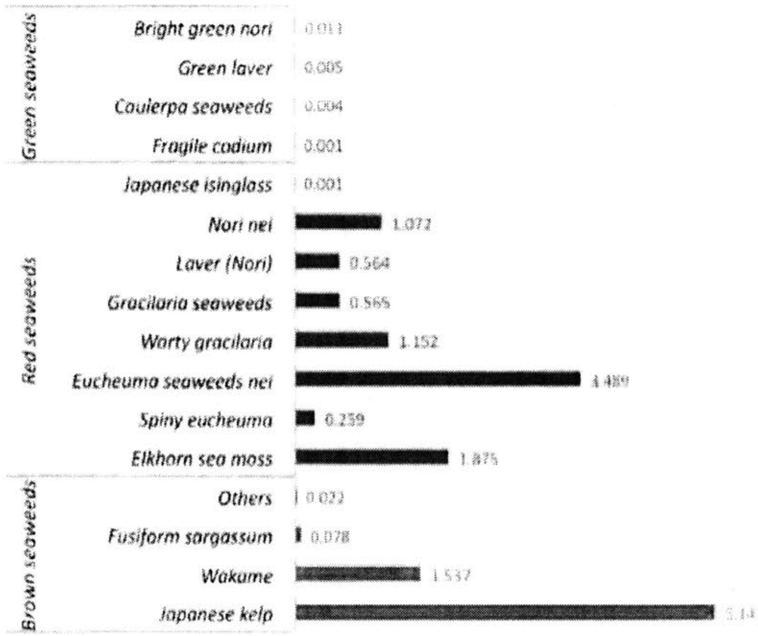

Fig. 3: 2010 Global Seaweed Production, in tons[7]

2. Design Process

In order to begin any design process, the specific problem that is being solved needs to be clearly defined. From analyzing the state of the seaweed industry globally, it became clear that some sort of automation in the farming process could reap great rewards if it could be implemented well. To apply automation to this industry, we began to look at what aspects of the farming process were most costly and/or most labor intensive. A breakdown of costs for a variety of scales of seaweed farms is reproduced below in Table 1.

Item	Indonesia	Philippines	Tanzania		India	Solomon Islands	Mexico	
	Floating	Floating	Off-bottom	Floating	Floating	Floating	Off-bottom	Floating
Production Parameters								
Total length of lines (m)	30,000	2,000	270	288	2,565	4,000	10,000	10,000
Number of cycles per year (cycles)	8	5	7	8	6		4	4
Length of a cycle (days)	45	63	45	45	45		60	60
Annual yield of dry seaweed (kg)	33,000	2,850	662	806	5,400	21,700	53,778	53,778
Annual productivity (kg/m/year)	1.10	1.43	2.45	2.80	2.11	5.43	5.38	5.38
Cycle productivity (kg/m/cycle)	0.14	0.29	0.35	0.35	0.35		1.34	1.34
Farm-gate price (USD/kg)	0.85	1.09	0.27	0.27	0.33	0.38	1.00	1.00
Gross Receipts	**28,050**	**3,107**	**179**	**218**	**1,785**	**8,246**	**53,778**	**53,778**
Variable Costs (USD)								
Propagules							13,264	13,264
Labor	4,320	759	26	28	1,041	3,556	8,853	8,853
Fuel	29	332				1,117		
Maintenance and repairs	420							
Sales and marketing	600						7,115	7,115
Total Variable Costs	**5,369**	**1,091**	**26**	**28**	**1,041**	**4,672**	**29,232**	**29,232**
Fixed Costs (USD)								
Depreciation	2,501	906	26	24	432	1,157	2,274	2,934
Administrative costs	900							
Utilities	120							
Fees for coastal land usage							3,109	3,109
Total Fixed Costs (USD)	**3,521**	**906**	**26**	**24**	**432**	**1,157**	**5,383**	**6,043**
Total Costs (USD)	**8,890**	**1,997**	**52**	**52**	**1,473**	**5,829**	**34,615**	**35,275**
Net Returns (USD)	**19,160**	**1,109**	**127**	**166**	**312**	**2,417**	**19,163**	**18,503**
Production Cost (USD/kg)	**0.27**	**0.70**	**0.08**	**0.06**	**0.27**	**0.27**	**0.64**	**0.66**

Table 1: Budgets for *Kappaphycus* farming systems in 6 developing countries[9]

It is worth noting that these farms harvest a specific species of red algae called *Kappaphycus*, which unlike Wakame or Porphyra farmed in China and Japan that have longer blades which hang underwater, is more fibrous and spherical in shape. This has practical impact on the manner of harvesting and of course the design of any device used to autonomously farm it. However when manual labor is the primary harvesting method these differences become less significant. Pre-planting nursery growth and line maintenance are other factors that do not change significantly with species of seaweed, as the sporelings behave very similarly in laboratory conditions regardless of species. Given these similarities, we figured that this table would generalize well to farms in other countries and of other species. These costs were turned into a framework through which to optimize our design. We chose to first select a series of important criteria through which to analyze various concepts, and then spend a period of time ideating and surveying the current state of the industry. The concepts we generated would then be evaluated through the developed framework, and ranked accordingly. The problem requirements for farming seaweed are listed in the table below.

Key Steps in Seaweed Farming	**Value Ranking (from Table 1 Costs)**
Harvesting	1
Seeding	2
Maintenance	3
Spore Cultivation	4
Line Removal/Installation	5

Table 2: Key parts of the seaweed farming process, ranked in terms of expense. Harvesting and seeding account for the majority of labor costs, along with some maintenance which also impacts fuel costs. Line removal and installation varies with permitting requirements and boat traffic interference.

Table 2 shows the key steps involved in seaweed farming, ranked in terms of importance by their implementation costs. Out of these 5, the most valuable step is harvesting due to the frequency with which it occurs. Other labor intensive processes, such as the seeding of lines and line maintenance, only occur at the beginning of each season or periodically throughout respectively and so are less appealing targets for automation. Phone surveys with New England farmers confirmed this analysis, although for small-scale operations these costs become more relevant due the less time-consuming harvests. After developing these requirements, we spent some time brainstorming ideas both independently and after looking at commercial farms' implementations.

	Weighting	Ski lift		Grid method				
		Island Method	Boat method	Clamp	Pulley method	Blow air method	Anchor w/spool	Cutting methods
Initial Cost	3	2	3	3	3	3	3	2
Maintenance Cost	3	4	3	3	2	2	3	3
Difficulty	3	3	3	2	2	3	3	2
Scalability	4	3	4	3	3	3	3	3
Harvesting Time	4	3	3	3	4	4	3	3
Design Time	2	3	3	3	2	3	3	2
Production Quantity	4	3	3	4	4	3	4	3
Flexibility (kelp types)	2	3	3	2	2	2	2	2
Durability	2	4	4	3	3	3	3	3
Total Score /45		28	29	26	25	26	27	23
Weighted score:		80	84	77	75	76	80	68

	Spool Line	Rigid line structure	Surface line w/clamped anchors	Non-line concepts		
				Mesh Idea	Nets	Rigid Bodies
Initial Cost	3	3	4	4	4	2
Maintenance Cost	3	2	4	3	3	2
Difficulty	3	3	3	3	3	3
Scalability	4	3	3	3	3	3
Harvesting Time	3	4	4	4	4	4
Design Time	4	2	3	2	2	2
Production Quantity	2	2	2	3	3	3
Flexibility (kelp types)	3	3	3	3	3	3
Durability	3	3	3	3	3	3
Total Score /45	28	25	29	28	28	25
Weighted score:	80	72	83	82	82	73

Tables 3 (top), 4 (bottom): Pugh chart for design evaluation. Evaluation criteria pertaining to design implementation and efficacy were selected and weighted, and then used to evaluate proposed designs for preliminary design analysis.

Design ideation began with several key factors in mind, presented above in Tables 3 and 4. The primary concerns were harvesting time and scalability, which directly pertained to the economic viability of the design. Other relevant concerns were initial and marginal costs, lifecycle, and feasibility. Flexibility, in terms of the types of harvestable seaweeds, was a significant consideration. Some species of seaweeds are typically grown on off-bottom lines, while others primarily on tethered systems. After interviewing seaweed farmers around the US and talking to researchers at Woods Hole, ultimately we learned that the key criteria for growing kelp are nutrients, sunlight, and water temperature; meet these requirements and the seaweed will grow. What does differ by species, however, is harvesting frequency and a practice called 'trimming'. East coast farmers growing *Saccharina Latissima* perform maintenance and small harvests on their lines frequently by trimming only a few inches off the ends of the growing plants. This allows them more control over their harvest, and makes it easier to meet changes in demand as the plants they trim will eventually grow back during the rest of the growing season. Other important considerations were cost and durability, although without extensive experience working in the sea these were trickier to incorporate into the first design.

The results of this preliminary analysis were taken with a grain of salt, as many designs were closely ranked and this very approximate analysis could not possibly have enough resolution to justify a purely numerically based design selection. The 13 designs included in the table represented our best efforts to produce a variety of unique, independent designs. The 'ski lift' designs, which will be shown later in this section, were reminiscent of a ski lift underwater with a rotating line with which to bring seaweed to a harvesting platform. The 'grid method' designs involved a large frame tethered via anchors to the sea bottom, and could be raised to the surface for a more facile harvest. Other concepts involved modifications of current farm long-line systems, with anchors that could detach from the growth substrate for easy removal or a line that could be reeled in to a boat. The idea of using a rope as a substrate was also challenged, but these variants ultimately were not selected due to technical difficulty and uncertainty.

In the remainder of this section, the harvester designs and their iteration will be presented chronologically to provide an overall sense of the trajectory of this project. Deeper analysis of the systems and their advantages and disadvantages can be found in the Results section. A render of the first iteration as well as the prototype built from the 'V1' design are provided below.

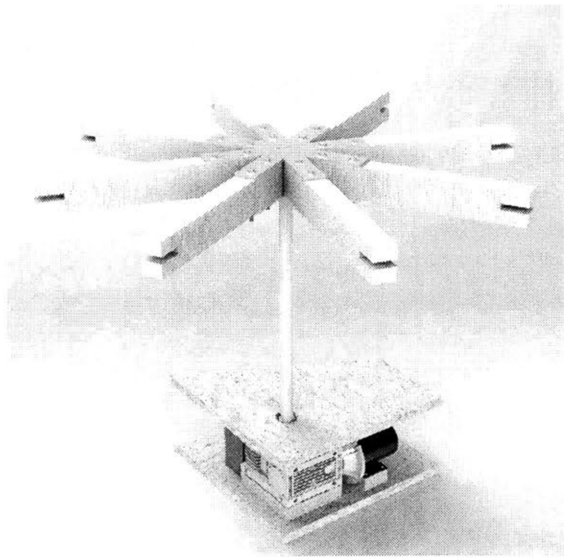

Fig. 4a: Core Module for the V1 Harvester

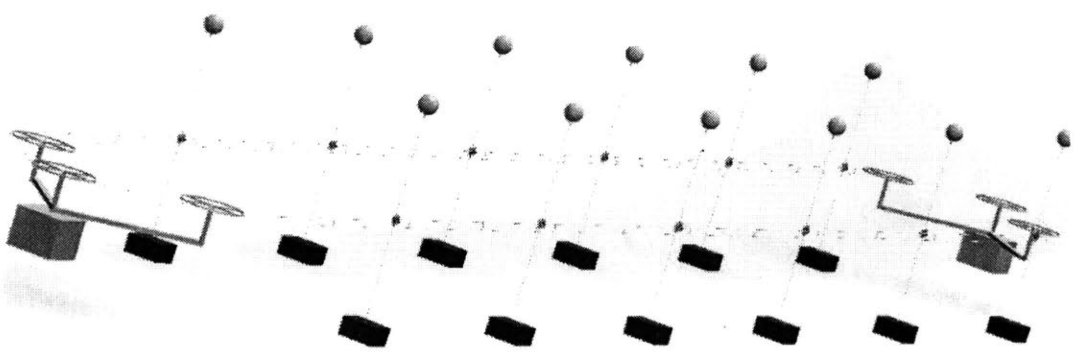

Fig. 4b: Abstracted system model for V1. Orange block and wheel systems at each end are placeholders for the device in 4a).

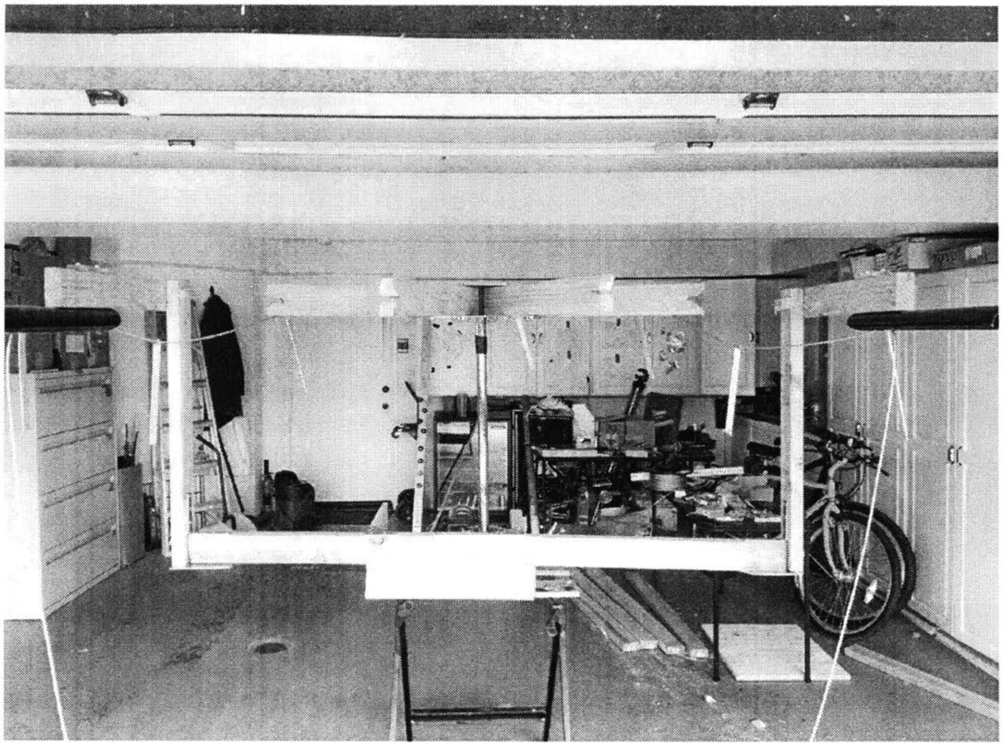

Fig. 4c: Prototype of the V1 Harvester

The idea behind the V1 design was to mount this mechanism on the back of a boat, and rotate an elliptical line of seaweed so it can all be harvested at a single point. In theory, its operation was meant to resemble that of a ski lift. Given that this concept has such a present, tested real-world analog it seemed that its implementation would be relatively straightforward. Model 'towers' underwater, pictured in Fig. 4b), contained a series of pulleys designed to allow the lines to pass through during the harvester's operation. After building and testing this system, we quickly came to realize that the complexity of the design and its reliance on tension to keep the lines attached were critical flaws. In an ocean environment susceptible to unpredictable motions caused by waves and currents, this system would have a difficult time reliably operating.

The big takeaway from this initial design was the problems caused by complexity. For the second iteration, we chose to pivot towards a simpler system that maintained much of the flexibility inherent to the first design. The engineering model as well as its physical manifestation are presented in the figures below.

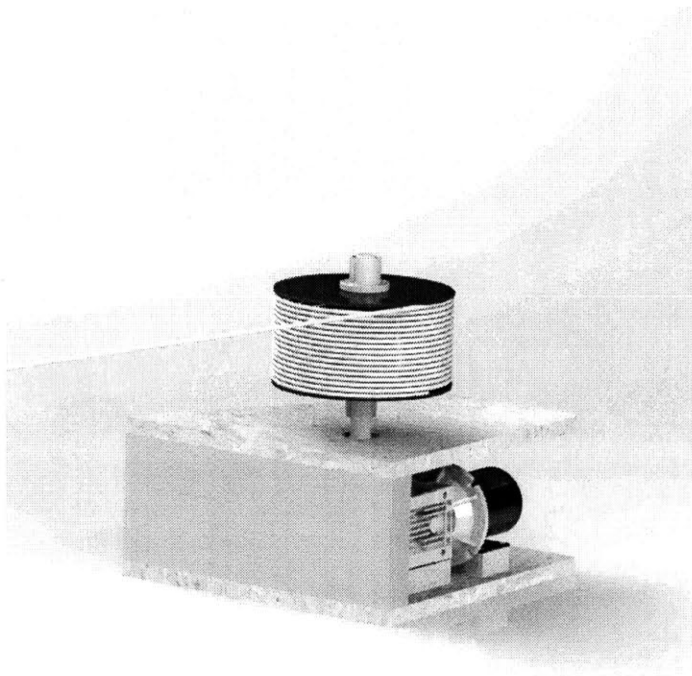

Fig. 5a: Core module for the V2 harvester

Fig. 5b: Implementation and testing of the V2 design

In testing V2 outperformed the first design, and we were able to harvest at rates of ~0.5 m/s. This system was powered by an electric motor with rechargeable batteries, which was heavily geared via worm gearbox to allow for high torque and self-locking of the lines. It was a large step forwards in terms of simplicity, although it brought with it a new host of design considerations as to its implementation and scalability on a large farm.

The goal of the next iteration was to test if the simplicity of the harvester could be improved further. Instead of having a farm line pulled to a boat at which it is harvested, why not instead bring the boat along the line, much like the current practice in commercial seaweed farms. Only, instead of having a human pull up the line with seaweed by hand, cut it off and place it in a net, have a machine do it instead. This variation was another closely-ranked idea we had evaluated with the Pugh chart. We took a survey of all the different harvesting methods currently used in seaweed farming around the world, and settled upon an interesting manner of harvesting currently only used in small Japanese farms for a rare species called *Ogonori*. The farmers took advantage of the unique fibrous structure of the plant and used a suction pump as a vacuum to suck the seaweed from off-bottom lines. If this system were able to be applied to other species of seaweeds, either directly or after cutting the plants into smaller pieces, the harvesting rate could be greatly improved using this method. We set out to test this mechanism for our 'V3' system.

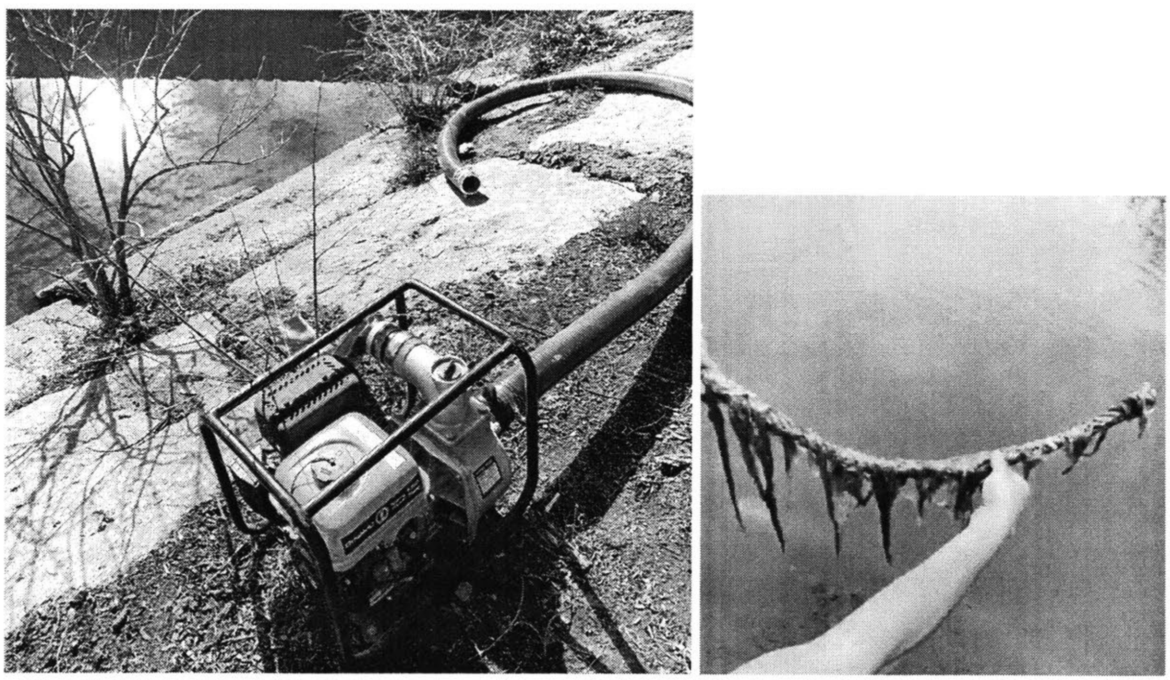

Fig. 6 a, b: a) (left) Modified trash pump used to provide suction b) (right) Sugar kelp line from Massachusetts farmers

Unfortunately, the testing from this method proved inconclusive due to sealing issues encountered when using the trash pump. Restoring the pump to operational capacity and repeating this test falls into the future work of this project. . One potential concern with this method is the affect pump blades could have on the output product. In our testing, we hoped to test both the standard metal pump impeller as well as a rubber impeller, and see the effect that the switch might have on the output. Given a greater budget, the use of a peristaltic pump (which would have negligible physical interaction with the pumped seaweed) would be quite useful to test as well. Unfortunately, due to temporal and monetary constraints these did not happen.

While most of this work pertains to automating seaweed harvesting, that is not the only step of the process that was considered. Seeding of the lines, and several mechanisms to speed up the process, were also designed and tested. Typically, seaweed spores are grown in a nursery and implanted onto a cylinder wrapped with twine, which is then wrapped around a thicker rope in the sea from which the seaweed will grow. The first implementation of a simple mechanical seeding system using a conventional spool of seeded line is presented below.

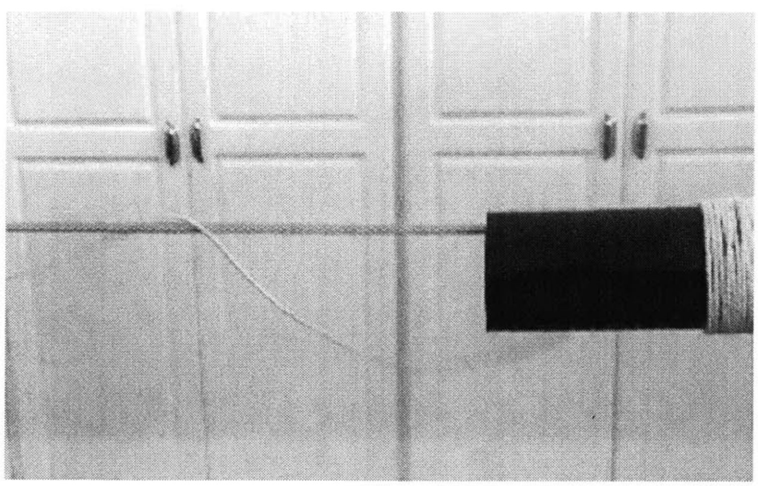

Fig. 7- First iteration of a seeding mechanism to be used with an autonomous harvester

The black PVC pipe in the above figure wrapped in twine represents line seeded with seaweed spores produced by a typical seaweed nursery. As the line moves relative to the black pipe, the rolled twine unravels and wraps itself securely around the line. This simple mechanism allows for quick seeding once the cylinder with seeded twine is placed around the grow line. However, this testing highlighted a big issue with the system- how do you place this cylinder around the line? Especially on a large scale, where conceivably you would have multiple spools of seeded twine to lay out on a single rope, the setup of this system could become a tricky issue. This concern gave rise to a subsequent iteration on this design, which does not require the grow line to be threaded through the spool of seeded twine.

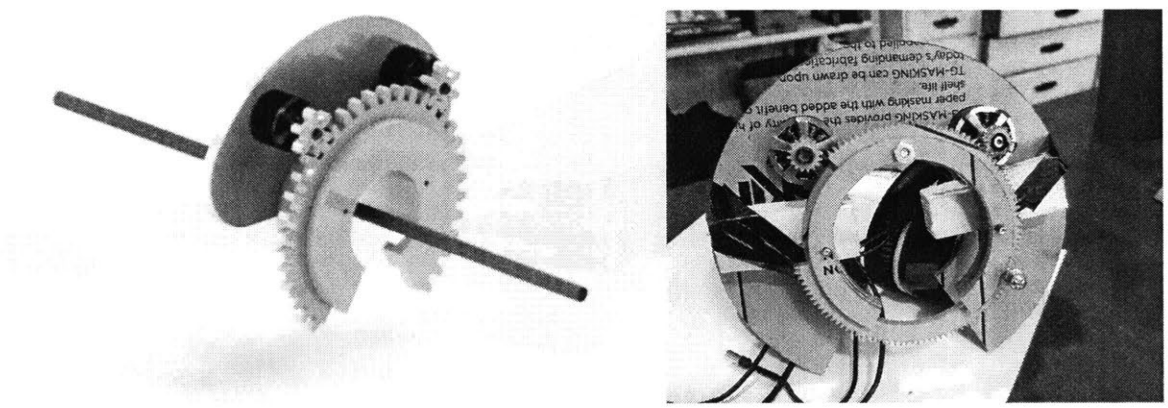

Fig. 8- Render of revised seeding mechanism, first physical implementation.

Figure 9 shows a mechanism designed to wrap seeded twine around a cylindrical rope. The gap at the bottom permits this device to be mounted vertically onto the grow line, greatly simplifying the attachment process. The rotating gear would have one end of seeded line tied onto it, so when the motors are given power the device wraps it around the long line. When the spool runs out of line, removal is an easy process as the whole system can simply be lifted off. The physical testing demonstrated the viability of this cutout-gear system as it was able to rotate smoothly when connected to power. However, this device's feasibility underwater as well as position control to manage the opening at the bottom of the device have yet to be implemented.

3. Design Analysis

The development of these prototypes presented a host of interesting engineering challenges that have not been tackled as of yet due to the novelty of this endeavor. The design of V1, which required an elliptical line carrying the seaweed to be dragged through the water and onto a boat, would require a robust power source capable of meeting the torque demands of a largely unmeasured source of friction: wet farmed seaweed. Due to its availability, variety, and ease of operation, an electric motor was quickly chosen as the optimal power source for the rotation of the line. The primary forces of the relevant system arise from inertia, drag caused by the motion of the seaweed, friction caused by currents, and a variety of other smaller effects caused by non-uniform towing motions, gravity, and buoyancy[8]. Fortunately, some aspects of this system-specifically, drag forces on wild beds of *Macrocystis Pyrifera*, have already been monitored and proved very useful in these calculations.

To size the motor, a power requirement was the primary consideration. Given design constraints imposed by existing seaweed farms, we selected a maximum harvesting speed of 1 m/s of a 50m long elliptical line. Line length is a typical value based on the farm setups of surveyed East Coast seaweed farmers. A drag coefficient of ~0.3 in typical conditions was obtained from literature, as well as buoyancy estimates of mature plants[8]. Approximating the line of seaweed as a plate (given the small cross sectional area of a blade of seaweed) drag due to the frontal area as well as skin friction were calculated to give a net required force to be output by the motor. Given a required pulling force and distance, the power requirements of the motor were calculated and then scaled by a safety factor of 2. There were many unknowns in this scenario that had the potential to affect the power requirements, but given our general lack of experience growing seaweed we decided to approximate the value and apply a large safety factor to potentially account for the unknowns. In testing, we found that the chosen motor and gearbox were more than powerful enough to pull the test line (albeit much shorter than the proposed 50m) through water. We were able to implement this power system in the first and second iterations (V1 and V2) with no problems on the motor output. Artificial loads were simulated to strain the miniature system to predicted levels, and forces typically unaccounted for in the simple model used to select the motor were applied as well (e.g. jostling, excessive weight on the line, and additional friction).

3.1 Economic Feasibility

From these tests we obtained preliminary information on the operating characteristics of our system. But how do these numbers compare to existing farms, and is the value added by this automation enough to justify the overhead cost of our system? A survey of farm costs, not only of East Coast farmers but also farms of several Asian countries was taken and used for comparison.

Table 1 presents operational costs and returns for a variety of different farm sizes in enterprises around the world. Labor costs ranged from ~38-80% of the total costs in these farms, a ratio generally increasing with farm size[9]. In order for the harvesting device to be cost effective, it must be extremely scalable. Data from each harvest cycle of the sample Indonesian farm, the largest provided, places harvesting at a rate of ~667 meters per day, with an equivalent labor cost of 12$ per day[9]. Given Indonesian minimum monthly wage costs, this works out to ~3 workers on the farm assuming conservative wages. Over the series of 8 harvesting cycles a year this seemingly insignificant value adds up, but does provide a representative target for the harvester to meet. In terms of harvesting rate, the 667 m/day works out to 1.5 m/minute of 8 hour working days, a value 1/20th that of the second iteration of our prototype. For comparison purposes, a typical commercial farm in Korea using a more efficient pulley system can achieve

~0.1 m/s. However, the added harvesting speed of our device does come at a higher overhead cost. Additionally, the incorporation of this harvesting system into a larger farm design must be considered as well. Given the prototype development cost of ~$400, which is able to rotate ~100m of line, the cost appears somewhat concerning. However, the key part of this design is that cost doesn't scale linearly- a single such mechanism mounted on a boat could theoretically be used on multiple sets of lines set up on a farm.

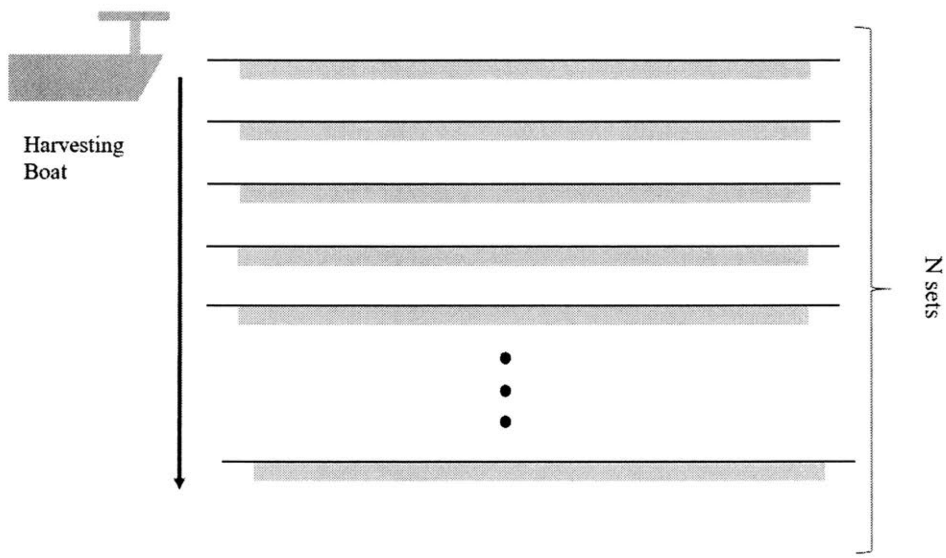

Fig. 9: Potential farm design for V2 demonstrating scalability of a single harvesting mechanism. Green blocks represent seaweed, and the long lines are shown in black.

Using a farm setup similar to the one depicted in Figure 9, which uses the V2 iteration, a single harvesting mechanism can be applied to larger farm areas, reducing the overall cost of implementing this technology. When considering the economics of these various iterations, the key factors that most significantly affect cost are harvesting rate and scalability. The proposed solutions must not only be able to outperform human laborers in terms of harvesting speed but also in terms of harvesting cost at a large scale. The appeal of these automated mechanisms is that they already outperform manual laborers both on slower Indonesian farms as well as more state-of-the-art Korean farms (~0.1m/s) by a significant margin. Although V1 and V3 experienced testing issues that prevented us from getting a good estimate of their effective harvesting rate, V2 was very promising even though it was only run at 0.5m/s (as opposed to the desired 1m/s). With subsequent iteration and improvements on the design we are confident that this rate can be further improved.

The cost of prototype development is another relevant concern, as 400$ for the actuator of a harvester portends a relatively large net cost compared to the cheap labor prevalent on developing countries' seaweed farms. The labor cost on these farms of 12$/day is a shocking number, especially when that covers the cost of operating such a large seaweed farm with multiple paid laborers. However, due to the already vast gap in harvesting rate between our device and manual labor, at a factor of 20x in the initial prototype, the benefits of switching to an automated mechanical harvesting system are still clear.

Finally, it is worth noting that the majority of data used for commercial farm analysis comes from farms growing *Kappaphycus*. For farms in Japan and China, which have very large seaweed production and consumption, data pertaining to their associated costs and yields was difficult to find. It was not suggested by what documentation was available on their harvesting methods and farm designs that their manual laborers outperform those in the sample farms discussed in this paper. Farmers in boats cutting seaweed by hand have an advantage in terms of their cheap labor cost, but remain unable to compete with a mechanical system. Additionally, given the similarity of the farming and harvesting procedures, the designs documented in this paper should perform similarly when implemented with the majority of commonly farmed species.

4. Conclusion

The state of the commercial seaweed industry and its reliance on manual labor inhibit growth and pose unnecessary costs to companies and individuals operating the farms. Furthermore, heavy reliance on nearby manual labor prevents true scalability and limits farms to near-coast waters. An analysis of the economics behind the current seaweed farming industry reveals the relatively high cost of labor in running these farms. Automating the harvesting process, via iteration on the discussed mechanisms, appears to offer a clear advantage to current farmers over traditional manual labor-intensive methods.

Significant work on this technology remains, however. Integration of the individual harvesting system into the overall farm design must be accomplished relatively seamlessly, and extensive testing on durability and the many unknowns posed by working in the ocean also remain. Seeding technologies and their coordination with an automated harvesting system have the potential to further reduce labor costs associated with seaweed farming. However, the returns from the development of seeding automation are significantly lower than that of harvesting simply due to the low frequency with which seeding operations are carried out. Overall, the potential for improvement is great, and further testing on the V3 suction mechanism could reduce costs even more and provide a simpler, more straightforward path to integrate the harvesting mechanism into existing farms.

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