Generating Power for Remote Applications in Extreme Environments

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Abstract

This paper describes the design of a self-powered underwater robot. The robot takes power from passing currents and harnesses them using a turbine mounted on top. The robot is designed to withstand the harsh underwater conditions, such as the high pressure, low temperature and high salinity water. This being the case the robot is to be made out of plastic for the exterior to combat rust and filled with oil to combat compression from the pressure. This paper also shows the testing of the generator that could be used and a single phase equivalent circuit is derived. Actions to be completed are choosing a power converter and construction; however the construction must occur before the choice of power converter. It is also found that using batteries to store power will greatly aid the robot.

1. INTRODUCTION

Around the world there are many extreme environments in which conventional battery power is not suitable for powering devices due to the fact that the battery has to be replaced when it runs out and the environment does not easily allow for this. Getting rid of conventional battery power essentially means creating a self-powered device.

Extreme environments can have temperatures ranging from -30 to 2000°C with extremely high or low pressures. The challenge of this project is to design a device that can generate power for some application and withstand the environment. Of benefit is the environment itself as high temperatures and pressures can be used to generate power because there is an abundance of it in the extreme environment, this excess of supply also means efficiency is not a large problem.

In this project the extreme environment chosen is the undersea environment. Under the sea the temperature can range from 3 to 21°C (1) and the pressure increases one atmosphere per ten metres of depth under water (2). Thus the solution must be able to handle these temperatures and pressures while being able to generate power.

The specific tasks of this project are to investigate an extreme environment, find a suitable way to power a device and then to design a solution. The goal upon completion is to have a well thought out design that could be built and used in the real world.

As an example of the possible applications of such a device, a small robot that crawls along the ocean floor either videoing what it finds or testing ocean floor sediments shall be the focus of this solution.

2. CHOOSING AN APPLICATION

The sea covers approximately three quarters of the earth's surface (3) however its depths remain largely unexplored and unknown. One of the reasons for this is the harsh and inhospitable conditions that exist undersea. There is no oxygen to breathe underwater, the pressure increases one atmosphere for every ten metres (2) and the temperature drops considerably as the depth increases. Due to these harsh conditions it is preferable to send a robot instead of a man, the problem however is that robots require a reliable power source. One solution to this would be use a battery powered robot, however batteries require recharging and constant maintenance. A better solution then would be to have a self powered robot that could stay underwater for indefinite periods. The robot to be designed in this paper is thus an underwater self-powered robot.

3. CHOICE OF POWER GENERATION

Given that the extreme environment was the undersea environment the first task was to choose a method of power generation. Four different possible ways of generating power in the sea were considered and the following information was found.

3.1 Pressure

High pressure is one of the extreme environmental elements of the sea for which this project was chosen. Thus it makes sense to try exploit this characteristic as there is virtually no limit to its supply. However in exploiting it the environmental impacts should also be considered.

From the research done it was found that to create energy from pressure a differential must be obtained. In the sea environment there is high pressure but there is not a differential. There were two ways that were thought of to obtain a differential; the first was by having two devices with one much deeper than the other, as it is known that the pressure increases the deeper an object is. Thus the two devices have different pressures and a differential is found. The disadvantage to this though is that the whole solution would have to be rather large and would therefore not be very helpful for moving devices and would be prone to damage from sea creatures. The second way that was thought of to create a differential was to use the undersea currents which would press against a plate creating a differential. This technology is in fact already been in use in the form of hydrophones (4) and uses piezoelectric technology.

3.2 Temperature

A low temperature is the other environmental extreme of the sea and so it makes sense to try exploit this. However as with pressure a differential in temperature is needed. The only way hypothesized to create such a differential was to once again have two devices at different depths so that different temperatures are found. However since this is the same solution as for pressure it has the same disadvantages.

3.3 Chemical

It was briefly considered that the chemicals in the ocean could be used in a chemical reaction to create power for the application (for a table of the chemicals found in the sea see appendix 1); however it was quickly found that this thought was naïve. The reason it was naïve is that the chemicals in the seawater are in a post-reacted state meaning that they will not react in any way for the project. If any chemical pair was not yet reacted they would react of their own accord in the seawater. The only way to force a chemical reaction then would be to bring another chemical to react with something in the seawater; however this option is actually a battery in an elementary sense and thus does not meet the design requirement.

3.4 Kinetic

The solution of using the pressure of currents to create a pressure differential was the best solution found thus far however the problem was that the current would push the device off course when contacting the plate. Another solution that solves this problem is actually a lot simpler than the piezoelectric technology although not as exciting; a turbine. Using a turbine would allow water to flow through the device, allowing it to generate power while stopping the current from pushing the device off course. The currents found in the deep sea environment are known to be up to 5 knots but more commonly around 3 knots ($1.54ms^{-1}$) (5).

3

3.5 Decision

Given the options above, the method of power generation was decided to be kinetic utilizing a turbine to harness the power of undersea currents.

4. SPECIFICATION

The final design must create a robot that can handle the environment around it. This means the robot must be resistive to corrosion, especially rust given that it is in salt water. The robot must also be able to handle the temperature which is believed to be anywhere between 3 to 21°C(1). In addition there is also a pressure element that the robot must handle and will increase by one atmosphere for every ten metres of the depth underwater the robot is submerged in (2). The said conditions are the specific conditions that the robot must deal with underwater. In addition to these are the more usual ones that the robot must be extremely reliable with its own power source and be able to move under that power.

However in order to create a robot design in the space of time given it was decided to make simplifications to the robot design that could be rectified in the future once the initial design was proven. For example the robot design given gives no ability to turn or maneuvre around difficult obstacles. The robot also has no remote control feature; that is the robot simply moves forward when given power and is idle otherwise. Having no remote control also means that at this point the robot cannot incorporate batteries to store power. Furthermore the robot does not have the features that would make it useful such as sediment testing facilities or an onboard video camera, these features are intended to be added once the robot has proven the ability to harvest and put to use the power from passing currents.

5. THEORY OF OPERATION

5.1 Overview

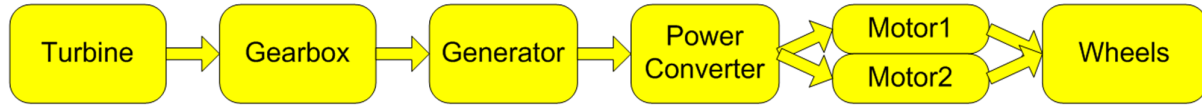A relatively simple design has been produced and a block diagram of it is shown in Figure 1.

Figure 1. System Block Diagram

5.2 Turbine

In order to harness the power of the passing currents a turbine is attached to the top of a small robot. As a starting point this turbine will be in a fixed position, that is, it will not be able to turn into the current in order to maximize the power. The size of the turbine is governed by the amount of power required. The output motors chosen to power the wheels of the robot require 5V and 1A each when running and there shall be two motors; one powering the back wheels and one powering the front wheels. This means that a total of 10W of power will be required at the output not including any extra features the robot might incorporate. Assuming other features might need up to 10W, the total output power becomes 20W; finally assuming the power converter to be about 80% efficient the input power will need to be at least 25W.

Using the following equation for power from a water turbine (6):

$$P_{elec} = \frac{\eta \rho A V^3}{2}$$

The efficiency of the turbine is assumed to be = 0.3 given the Betz Limit of 0.6 and the density of water to be 1024kg/m^3 (7).

$$25 = \frac{0.3 \times 1024 \times \pi \times \left(\frac{d}{2}\right)^2 \times V^3}{2}$$

V is velocity, about 3 knots = 1.54 m/s^{-1} (8)

$$25 = \frac{0.3 \times 1024 \times \pi \times \left(\frac{d}{2}\right)^2 \times 1.54^3}{2}$$

$$d = 0.238$$

Therefore the diameter of the turbine needs to be at least 23.8 cm.

5.3 Gearbox

Since the required revolutions per minute (rpm) for the 25W of power is 2400, as found after testing, a gearbox will be required to ramp up the turbine speed from that which the current turns it at. As to the speed of the turbine in this application, there seems to be very little information available in literature to help estimate this. As a starting estimate, the turbine would be assumed to

5

spin at the same speed as the current, approximately 1.54ms^{-1} (5). This means that the rpm will be $1.54*60/(0.238\pi) = 124$ rpm; this means to get to 2400 rpm a gearbox ratio of 19:1 will be required. It should be noted that if more torque is required, then more blades will need to be added however this will reduce the speed (9); at this point a three bladed turbine is considered adequate.

5.4 Generator

The generator chosen was the Scorpion S-4025-16, which is a 3 phase delta wound permanent magnet motor (10). Working as a motor it was said to run at 17.5V phase to phase and peak to peak and have a continuous output of 2 kW; however when tested as a generator these figures were found to be around 5V with a continuous output of only 70W as shown in the testing section of this report. However as only 25W is needed the generator is to be spun at approximately 2400 rpm. This generator was chosen not for optimization of design but for optimization of cost as the generator was already in the department and hence could be used free of charge.

5.5 Power Converter

The power converter takes the power from the generator and transforms it into an output suitable for the wheel motors. The power converter must convert the 4.7V, 5.4A three phase AC wave (as found after testing) into a 5V, 2A single phase DC waveform. Many power converter solutions are available so it is important to look at characteristics that will narrow the selection. As the only outputs are the two motors no isolation is required, and thus a three phase rectifier bridge consisting primarily of six diodes is used to transform the three phase AC to single phase DC. A small amount of DC bus capacitance is then required to filter and stabilize the waveform. After that a buck-boost DC-DC converter will be used to regulate and step up or down the voltage depending on the voltage at the time.

Figure 2. Power Converter Block Diagram

5.6 Output Motors

The output motors aim to take the power from the power converter and use it to power the wheels which give the robot the ability to move. The motor chosen, like the generator, was chosen as it was available on hand. It is the RE-540 made by Como Drills and it has 4.5 - 15V and 1A running characteristics (11). The internal resistance of the motor is found to be $0.73\,\Omega$ using the equation $R_{int} = \dfrac{V}{I_{stall}} = \dfrac{6}{8.24}$ (12). In order to give the robot traction in all situations the robots shall be four wheel drive and hence two identical output motors shall be put in parallel, one for the front wheels and one for the back. Having the motors in parallel will also decrease the resistance seen by the generator which will increase the power output as seen in the testing section of this report.
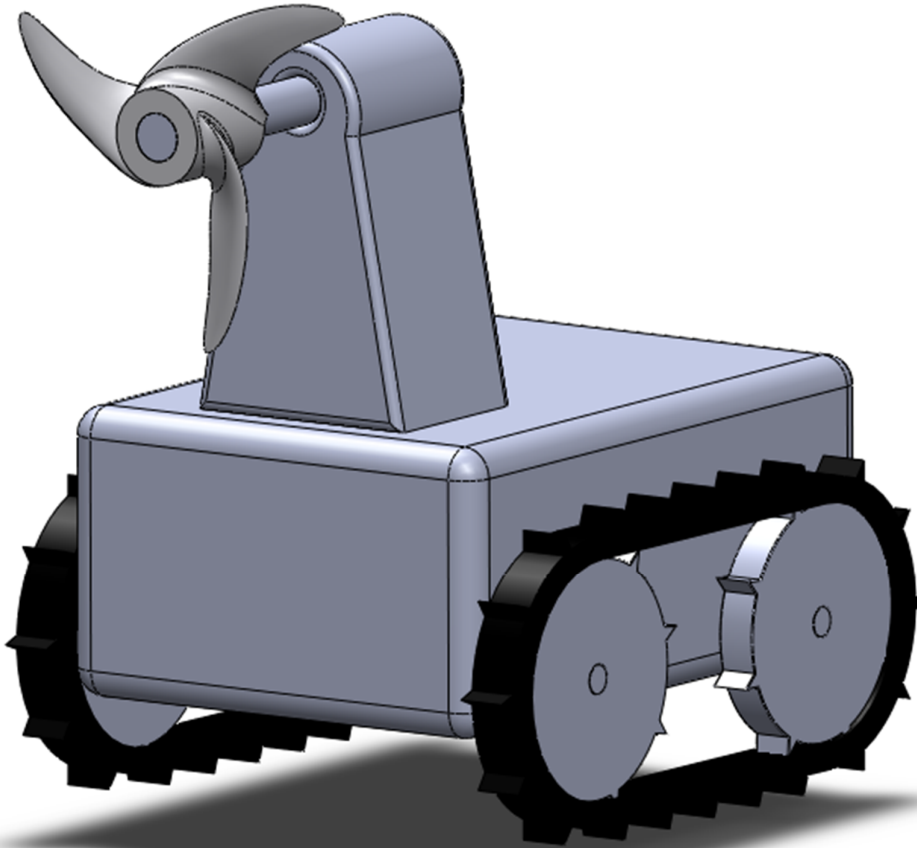
5.7 Wheels

In order to get traction in the soft undersea sediment, large spiked wheels with attached tank tracks have been chosen. The use of tank tracks will distribute the weight of the robot over a large area to reduce the chances of sinking.

6

5.8 Undersea Challenges

Given that water conducts electricity it is imperative that no water can get into the electronics of the robot. This means that the robot must be completely water tight. However at depth undersea the atmospheric pressure has increased one atmosphere for every ten metres underwater (2). This means that if the robot is filled with air it is likely to be crushed as air compresses under pressure. For this reason the robot will be filled with an incompressible liquid that is also non-conducting. Oil is a perfect choice as it fulfills both these requirements and is relatively easy to obtain. In terms of the build stage, this means that the robot should be submerged in an oil bath as the casing is sealed. In this way the robot can be sure to have no air in it.

To avoid rust, the robot will be made of plastic wherever possible. That is the enclosure, turbine, wheels and tank tracks will all be plastic. This leaves the only the generator, the motors, and the power converter to be metal; however these components will be enclosed in oil and as such should not be at risk of rust.

5.9 Design Concept

Figure 3. Artist's view of completed robot

6. COST

Item	Cost
Generator	$180 (10)
Motor (x2)	$51 (13)
Turbine	$25 (14)
Power Converter	$15 [estimated]
Tank tracks and wheels	$50 [estimated]
Enclosure	$50 [estimated]
Oil	$10 [estimated]
Total	$381

7. TESTING

Before building electrical devices, the testing of key components must occur. In this case the key component is the generator as the characteristics of it will determine the specifics of the gearbox and power converter part of the design. To determine the characteristics of the generator, the generator was set up with a variable resistive load attached to each phase and the voltage was measured through one phase. The generator was then spun using a mechanically attached dynamometer as shown in Figure 4. The resistive load was to model the load on the generator developed by the power converter and motor, while the dynamometer was to mimic the turbine (see appendix 2 for a diagram of this). The following measurements were taken and then graphed in Figure 5.
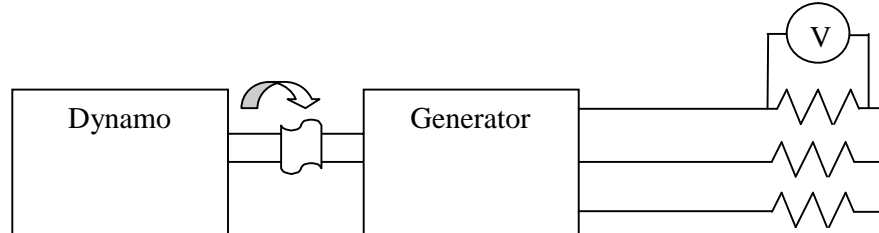
Figure 4. Loaded circuit test setup

Table 1. Voltage and Current Testing of the Generator at $5\,\Omega$ per phase

Per Phase Resistance $5\,\Omega$		
Speed	Voltage (Vrms)	Power (Wrms)$[=V^2/R]$
0	0.000	0.000
200	0.311	0.019
400	0.520	0.054
600	0.752	0.113
800	0.991	0.196
1000	1.256	0.316
1200	1.486	0.442
1400	1.726	0.596
1600	1.970	0.776
1800	2.209	0.976

2000	2.462	1.212
2200	2.698	1.456
2400	2.929	1.716
2600	3.167	2.006
2800	3.408	2.323
3000	3.636	2.644
3200	3.856	2.974
3400	4.105	3.370
3600	4.334	3.757
3800	4.540	4.122
4000	4.764	4.539

Table 2. Voltage and Current Testing of the Generator at 1Ω per phase

Per Phase Resistance 1Ω		
Speed	Voltage (Vrms)	Power (Wrms)[=V^2/R]
0	0.000	0.000
200	0.293	0.086
400	0.501	0.251
600	0.734	0.539
800	0.963	0.927
1000	1.200	1.440
1200	1.439	2.071
1400	1.660	2.756
1600	1.903	3.621
1800	2.139	4.575
2000	2.375	5.641
2200	2.609	6.807
2400	2.850	8.123
2600	3.100	9.610
2800	3.339	11.149
3000	3.560	12.674
3200	3.817	14.569
3400	4.044	16.354
3600	4.307	18.550
3800	4.542	20.630
4000	4.763	22.686

Table 3. Voltage and Current Testing of the Generator at 0.5 Ω per phase

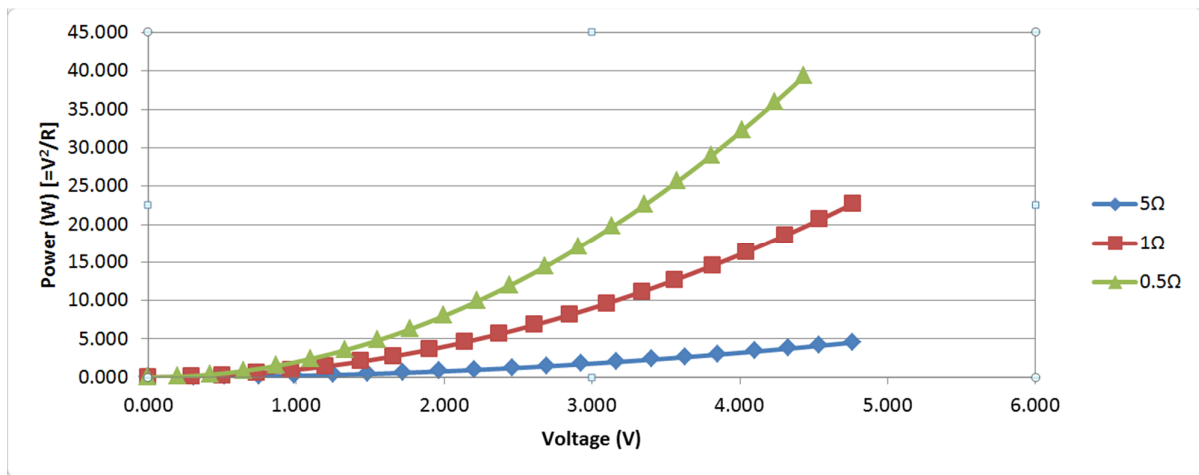| Per Phase Resistance 0.5 Ω		
Speed	Voltage (Vrms)	Power (Wrms)[=V^2/R]
0	0.000	0.000
200	0.200	0.080
400	0.423	0.358
600	0.645	0.832
800	0.869	1.510
1000	1.098	2.411
1200	1.333	3.554
1400	1.551	4.811
1600	1.771	6.273
1800	2.002	8.016
2000	2.226	9.910
2200	2.448	11.985
2400	2.688	14.451
2600	2.912	16.959
2800	3.140	19.719
3000	3.360	22.579
3200	3.580	25.633
3400	3.808	29.002
3600	4.018	32.289
3800	4.240	35.955
4000	4.438	39.392

Figure 5. Plot depicting the relationship between the total power and voltage for the generator depending upon the resistance per phase.

Following this a single phase equivalent circuit of the generator was modeled by taking the open and short circuit tests. The short circuit tests in particular had to be taken quickly to stop the generator from overheating and the wires from melting from the high currents generated.
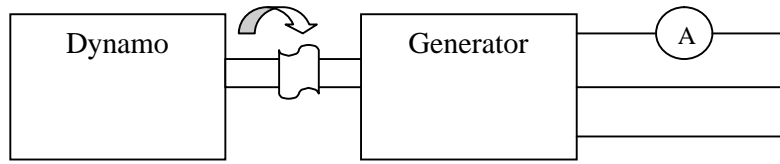

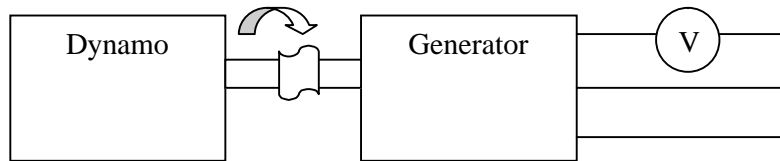*Figure 6. Short circuit test setup.*

Figure 7. Open circuit test setup.

The inductance, L, of the equivalent circuit can be worked out from the open circuit voltage and short circuit current as shown in the derivation below, where Z = impedance, R = Resistance, ω = Angular Frequency and n = Speed in revolutions per minute:

$$Z = \frac{V_{OC}}{I_{SC}}$$

And $Z^2 = \sqrt{\omega^2 L^2 + R^3}$

$$\therefore L = \sqrt{\frac{Z^2 - R^2}{\omega^2}}$$

$$L = \frac{\sqrt{\left(\frac{V_{OC}}{I_{SC}}\right)^2 - R^2}}{2\pi\left(\frac{n}{60}\right)}$$

Where the resistance, R, is given by the Scorpion datasheet as $0.034\,\Omega$ (10).

Table 4. Short and open circuit test results

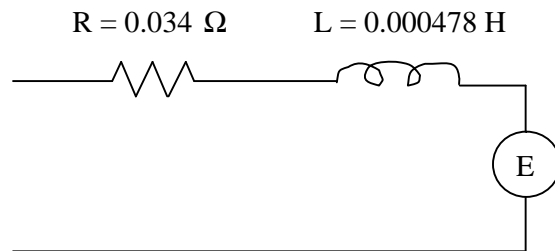| Short and Open Circuit tests				
Speed	Isc, rms	Voc, rms	Voc/Isc	L
0	0	0.000	0	-
500	20	1.176	0.101823	0.000863
1000	36.1	2.564	0.123009	0.000575
1500	43.6	3.801	0.15099	0.000501
2000	53.0	5.144	0.168105	0.000427
2500	62.0	6.450	0.180198	0.000371
3000	63.4	7.757	0.211909	0.000371
3500	66.3	9.226	0.241035	0.000366
4000	69.0	10.533	0.264396	0.000353
Average				0.000478

$R = 0.034\ \Omega$ $L = 0.000478\ H$

Figure 8. Single phase equivalent circuit of generator

8. DISCUSSION

8.1 Generator Results

From Figure 5 it is clear that the generator produces more power for a smaller resistance. This means it is a much better idea to parallel the two output motors rather than have them in series as it will decrease the overall resistance and hence increase the power.

Given the results of the generator it can be seen that the output power ranges from 0 to 40W per phase for resistances of 0.5 - 5 Ω and speeds of 0 – 4000rpm. The total power available would then be $P_T = 40*\sqrt{3} = 70W$. This is well above the required 25W, and hence the generator need only spin at around 2400rpm for a resistance per phase of 0.5 Ω. At 2400rpm and 0.5 Ω per phase the three phase voltage is $2.7*\sqrt{3} = 4.7V$ and the current is 2.7/0.5 = 5.4A, these numbers are used throughout the report previously.

8.2 Design Results

It is unfortunate that the design must include a gearbox as they are known to be very inefficient. However a gearbox is required because of the type of generator used; the permanent magnet generator used has a voltage dependent on the speed of rotation, thus a slow speed of rotation will get a low voltage and hence a low power. The only way to speed up the turbine, aside from getting a stronger current, is to decrease the amount of blades, however this will decrease the torque (9) and then the turbine would be unlikely to be able to turn the generator.

8.3 Future Steps

Following the work done in this report the next step in the design process would be to build the robot itself. This would mean at the very least having the bottom part of the robot complete, that is everything except the turbine and generator mounted on top.

From this a motor could be tested using a variable wall supply to find exactly what voltages and currents would be needed to create movement from the tank tracks.

Once these characteristics were confirmed the power converter could be chosen and purchased. The next step would be to test the power converter using a wall supply to simulate the expected output from the generator, which would confirm that the correct output characteristics were being given to the output motor. The output motors would then be connected and the tank tracks would run. Once this part of the system was seen to work properly the turbine and generator would be mounted. The robot would then be tested using the dynamometer to turn the generator and a success would be indicated by the tank tracks turning. The final step then would be purchase a turbine and gearbox that would spin the generator and the correct speed.

Finally testing would occur underwater checking that the device was indeed watertight and last of all a water tunnel would need to be constructed to simulate a current passing through.

8.4 Possible Improvements

The single biggest improvement would be the addition of batteries to the robot so that it could store the energy it generates, in this way if the robot was not in a current it could still continue to move for some period of time, and also if the robot wanted to move against a current batteries could give

it the extra power needed to do so. Furthermore the weight of the batteries would hold the robot to the ocean floor in strong currents.

Other improvements mostly relate to getting rid of the other simplifications, for example, a rotating mechanism for the turbine would be very helpful so that the robot could catch side on currents. A further example would be adding a video camera so that the robot could video what it finds. Finally in terms of using the robot a controller module would need to be added.

9. CONCLUSIONS

This paper has outlined a design for an undersea, current-turbine powered, robot. Testing has been done on the given generator to ascertain its characteristics so that a suitable output motor and power converter can be chosen. The exterior materials of the robot are to be made entirely from plastic to resist the corrosion and rust that would occur in metal. The enclosed componentry shall be filled with oil, to counteract any compression from the increased pressure undersea. All components are chosen so that they are able to withstand temperatures ranging from 3 – 21 ºC. The generator tested may be better substituted for a lower speed one that could give out a better power curve for the robot. The approach taken in this project has been well thought out and an excellent amount and quality of work has resulted.

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11. APPENDICES

11.1   Appendix 1

Detailed composition of seawater at 3.5% salinity					
Element	At.weight	ppm	Element	At.weight	ppm
Hydrogen H2O	1.00797	110,000	Molybdenum Mo	0.09594	0.01
Oxygen H2O	15.9994	883,000	Ruthenium Ru	101.07	0.0000007
Sodium NaCl	22.9898	10,800	Rhodium Rh	102.905	.
Chlorine NaCl	35.453	19,400	Palladium Pd	106.4	.
Magnesium Mg	24.312	1,290	Argentum (silver) Ag	107.870	0.00028
Sulfur S	32.064	904	Cadmium Cd	112.4	0.00011
Potassium K	39.102	392	Indium In	114.82	.
Calcium Ca	40.08	411	Stannum (tin) Sn	118.69	0.00081
Bromine Br	79.909	67.3	Antimony Sb	121.75	0.00033
Helium He	4.0026	0.0000072	Tellurium Te	127.6	.
Lithium Li	6.939	0.170	Iodine I	166.904	0.064
Beryllium Be	9.0133	0.0000006	Xenon Xe	131.30	0.000047
Boron B	10.811	4.450	Cesium Cs	132.905	0.0003
Carbon C	12.011	28.0	Barium Ba	137.34	0.021
Nitrogen ion	14.007	15.5	Lanthanum La	138.91	0.0000029
Fluorine F	18.998	13	Cerium Ce	140.12	0.0000012
Neon Ne	20.183	0.00012	Praesodymium Pr	140.907	0.00000064
Aluminium Al	26.982	0.001	Neodymium Nd	144.24	0.0000028
Silicon Si	28.086	2.9	Samarium Sm	150.35	0.00000045
Phosphorus P	30.974	0.088	Europium Eu	151.96	0.0000013
Argon Ar	39.948	0.450	Gadolinium Gd	157.25	0.0000007
Scandium Sc	44.956	<0.000004	Terbium Tb	158.924	0.00000014
Titanium Ti	47.90	0.001	Dysprosium Dy	162.50	0.00000091
Vanadium V	50.942	0.0019	Holmium Ho	164.930	0.00000022
Chromium Cr	51.996	0.0002	Erbium Er	167.26	0.00000087
Manganese Mn	54.938	0.0004	Thulium Tm	168.934	0.00000017
Ferrum (Iron) Fe	55.847	0.0034	Ytterbium Yb	173.04	0.00000082
Cobalt Co	58.933	0.00039	Lutetium Lu	174.97	0.00000015
Nickel Ni	58.71	0.0066	Hafnium Hf	178.49	<0.000008
Copper Cu	63.54	0.0009	Tantalum Ta	180.948	<0.0000025
Zinc Zn	65.37	0.005	Tungsten W	183.85	<0.000001
Gallium Ga	69.72	0.00003	Rhenium Re	186.2	0.0000084
Germanium Ge	72.59	0.00006	Osmium Os	190.2	.
Arsenic As	74.922	0.0026	Iridium Ir	192.2	.
Selenium Se	78.96	0.0009	Platinum Pt	195.09	.
Krypton Kr	83.80	0.00021	Aurum (gold) Au	196.967	0.000011
Rubidium Rb	85.47	0.120	Mercury Hg	200.59	0.00015
Strontium Sr	87.62	8.1	Thallium Tl	204.37	.
Yttrium Y	88.905	0.000013	Lead Pb	207.19	0.00003
Zirconium Zr	91.22	0.000026	Bismuth Bi	208.980	0.00002
Niobium Nb	92.906	0.000015	Thorium Th	232.04	0.0000004
			Uranium U	238.03	0.0033
			Plutonimu Pu	(244)	.
Note! ppm= parts per million = mg/litre = 0.001g/kg.					

16

Circuit Diagram

Expected   Voltage = 0 – 5V
Current = 0 -10A Per Phase

Dynamo

Generator

V

0.5Ω

Generator

Power Converter

Motor

0.5Ω