DIVEBOT: A diving robot with a whale-like buoyancy mechanism.

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Abstract

In this paper we describe a prototype underwater robot capable of altering its density by heating oil. It is designed to gather information in the ocean, as a member of a flock of such robots. We also describe the forces acting on the robot, and suggest a preliminary control model.

1. Introduction

Sperm whales feed primarily on squid and often have to find their food at depths between 1000 and 2000 meters. To do this they require sophisticated buoyancy regulation. It has been known for some time that they achieve long-term buoyancy regulation by altering the temperature of their spermaceti organ, located in the enlarged snout. In a large male this organ may contain four tons of spermaceti oil. The temperature regulation is achieved by alterations in blood flow through the organ.

Typically the whale dives, using muscular power, at a speed of about 4 knots and resurfaces at about the same rate. On this basis a dive of 1000m would take about 15 minutes for the round trip. Whales often spend an extra 30 min feeding at depth, and during this period they must maintain neutral buoyancy. Spermaceti oil varies in density according to its temperature. At depth the whale cools the oil by drawing cold water into the nasal passage, which lies just below the spermaceti organ. It warms the oil by pumping arterial blood through the organ. In this way the whale can regulate the temperature of the spermaceti oil, and achieve neutral buoyancy at the depth at which it is feeding. See Clark[1] for more details.

A robot buoyancy mechanism, based upon the whale principle, would have the advantage that, being entirely liquid-filled, it would be incompressible and have the potential to descend to great depths. This is the principle behind the DIVEBOT described in this paper. The current technology on making probes to dive is primarily based on mechanical instruments and pistons to change the density of the probe[2,3,4]. Our robot has the potential capability of diving to deep water, and since it has a simpler design it is cheaper to manufacture. This means that it can be disposable.

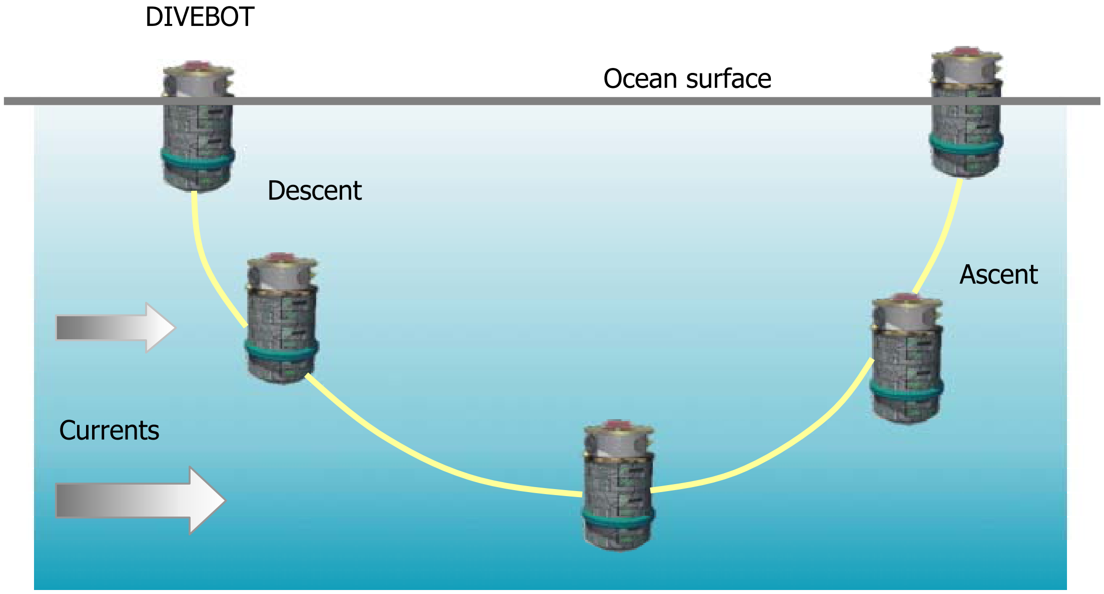

Figure 1. Trajectory of DIVEBOT.

2. The DIVEBOT

It is important at this point to mention that there is a distinction between the final design of the robot and the design presented in this paper as the prototype. The final design is deployed from sea or air. These DIVEBOTS are intended to be deployed as a flock, thus enabling the ocean currents to be mapped by the technique of flock distortion[5].

The deployment of the DIVEBOT is depicted in Figure 1. The robot descends slowly, due to its slight negative buoyancy, while controlling its buoyancy. At a certain depth, the heaters are turned on, and the robot ascends due to its now positive buoyancy, resulting from its reduced density. During this process, the robot is carried along by the currents. Throughout the whole operation, the robot is monitoring the ocean environment, and storing the information in its on-board computer. When the robot resurfaces, it can communicate the data to satellite.

The most important component of the robot is an oil-filled chamber, which is contained within an insulated cylinder. Heaters and batteries are placed inside the oil-filled chamber. An expansion tube connects the oil-filled chamber to the outer environment (seawater). Within this tube is an oil-water interface. When the oil is heated, it expands, pushing water out of the expansion tube, and decreasing the density of the robot as a whole. The rest of the components, including electronics, are placed in oil so that the robot can operate in very deep water. The basic principle of the robot is illustrated in Figure 2.

3. The prototype robot

The prototype robot is designed to demonstrate the concept of DIVEBOT. The robot (Figure 3) has the following features as shown in Figure 4 - a large *main oil chamber* leads to an *expansion chamber* connected by an *expansion tube* and *sea water vent* to the ocean. All this part of the robot is insulated with *wax filler*. The robot has a removable *end cap* and oil is initially introduced via the expansion chamber, through a hole which is then stopped by the *oil filler plug*.

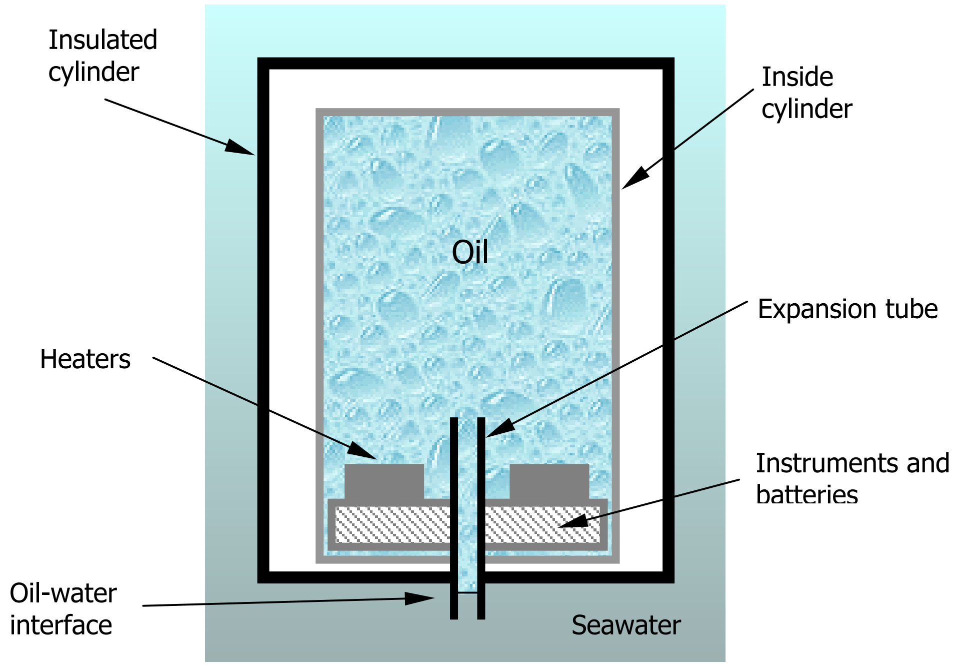

Figure 2. Principle of operation of the DIVEBOT.

Batteries are housed in the *end cap*, and these supply *heaters* that warm *heater plates* in the *oil chamber*. The end plate also contains *trimming chambers* accessible from the outside.

The electronics and the transducers are housed at the other end of the robot, with the exception of the *oil temperature transducer*, which protrudes into the *oil chamber* through the *heater plate*. This transducer makes it possible for the robot to control its own internal temperature. The other transducers are housed in the *transducer cap* at the other end of the robot. The electronics housing has a small *air expansion chamber* for safety reasons. Details of all these components are given below.

Figure 3. DIVEBOT. (Length: 38 cm, Diameter: 16.8 cm, Weight: 8.4 Kg).

3.1 Main oil chamber & heater assembly

The main oil chamber contains 1330ml of olive oil, which is approx. 16% of the total robot volume. It is a double skinned vessel with a stainless steel indirectly heated (electrically isolated) heater plate securely mounted to take the pressure of an experimental test dive (up to 50m). The whole chamber is surrounded and insulated with wax except for the area between the heater plate and the battery, which is an air space. In the final deep-water version this space will be filled with oil, as will the electronics housing which is also

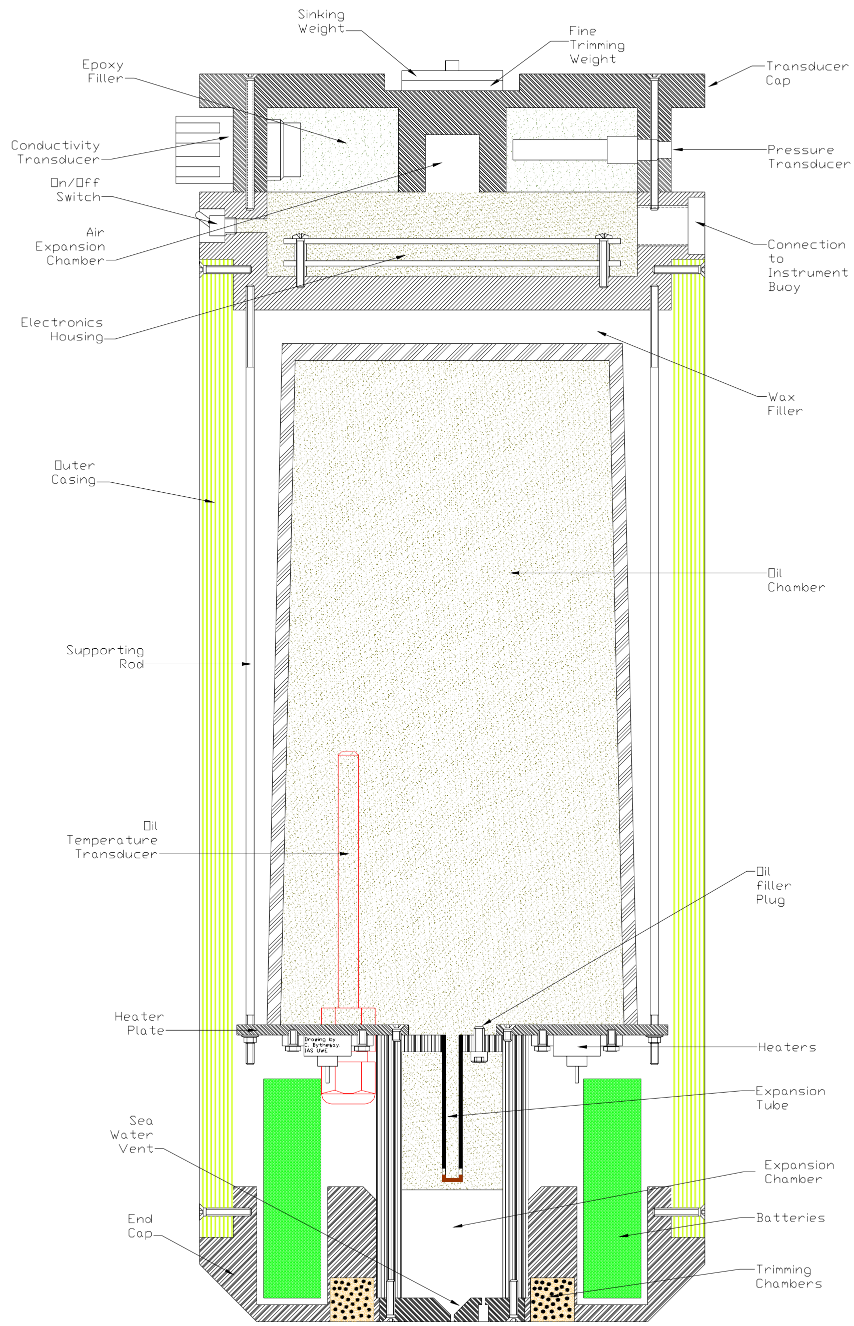

Figure 4. Internal layout of DIVEBOT.

an air space at present. There is also a temperature sensor, which senses the oil temperature in the centre of the main chamber.

3.2 Buoyancy trimming

The buoyancy of a complete robot when sealed has to be as close as possible to neutral, but must err on the side of being too light. This allows a small amount of extra weight to be added to achieve neutral buoyancy before the experiment starts. For course trimming, that is to get within 5 – 10 gm of neutral buoyancy, approx. 40gm of lead shot can be waxed in to the 4 small chambers in the *end cap*. This is called the *trimming weight*. The top of the robot has a thread to connect weights for fine trimming. These are in two categories: *fine trimming weight,* which is added to make the robot neutral, and a *sinking weight,* which is the weight added to make the robot sink once it is neutral.

3.3 Power supply

The power supply comprises two connected batteries. One of 7.2 Volts and the other of 6V, they share a common ground. The cells are of the venting type for safety reasons. The batteries are Nickel Metal Hydride giving a good energy density, high current capacity, relatively low weight and constant output voltage. Better and larger batteries could be used and would offer an improvement in performance.

3.4 Expansion chamber

After several experiments with the earlier prototypes it was discovered that an expansion chamber is required to solve a certain number of problems as follows:

- To contain the expanded volume of oil.
- The main oil chamber should be kept free from contaminates such as air, water and sand, which can affect the repeatability and accuracy of tests. The main oil chamber is hard to access as its totally sealed and insulated.
- Before a run the expansion chamber contains up to 15 cl of air as a result of cooling and contracting after the previous test run, which is unacceptable as the mass of the robot has to be within 3 or 4 grams each time it is used. The air has to be vented before testing can begin, so seawater can replace the air in the robot.
- To allow easy replacement of the oil in the main chamber.
- To allow the main oil chamber to be moved away from the outer surface of the robot to improve the insulation of the oil chamber.

The *expansion chamber* addresses these problems by means of the oil chamber expansion tube, which has two side orifices at its tip which are exactly half way down the expansion chamber. The dimensions and volumes have been chosen to ensure that the expansion tube orifices are always immersed in oil no matter how the robot is positioned and therefore contraction of oil in the main chamber always draws in oil and no contaminates. The sequence of events before the robot is set up for a run is illustrated in Figure 5.

3.5 Seawater vents

The seawater vents have been designed so that when the robot is being primed at the start of an experiment the air can be expelled without loosing any oil. As the oil is heated up, it expands and pushes the seawater out. This has been achieved by designing orifices where the shape and

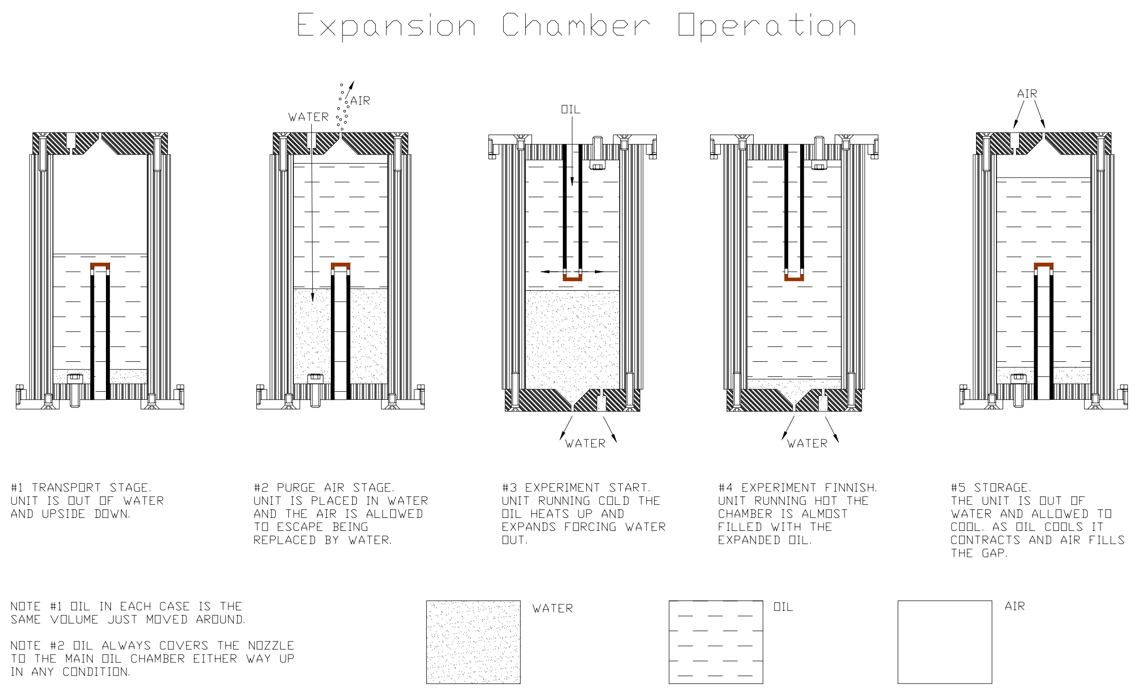

Figure 5. DIVEBOT expansion chamber.

diameter are critical. It works due to bubble size and the different surface tensions of the liquids involved.

3.6 Electronics

The electronics chamber is 11.5cm in diameter and 3cm deep and houses two electronics boards. One is the analogue/instrumentation board, which has amplification, signal conditioning and the line drivers for transmitting the transducer signal as well as interfacing to the digital board. The other is the digital/control board, which uses a microcontroller to control the operation of the robot and also to provide future data logging capabilities. See Figure 6 for a block diagram of the electronics.

Hardware is included to control the functioning and power management of the robot. The transducer block houses all the transducers except for the oil chamber temperature sensor. It forms the lid to the electronics chamber.

3.7 Safety devices

There are several different safety devices built in. These are necessary because the robot is a sealed pressure vessel with a sizeable power source.

- There are two self-resetting fuses one for each of the batteries.
- There is an air expansion chamber, needed if the batteries should vent due to abnormal loading.
- There is a temperature cut-out on the heater plate set to 85 deg C.
- There is the ability for the microprocessor to isolate the heater circuit or the instrument power or both, should it detect abnormal operating conditions.

- Since charging is a problem in the enclosed space due to excessive heat generation, there is a modification under way to include a temperature measurement of the battery pack.

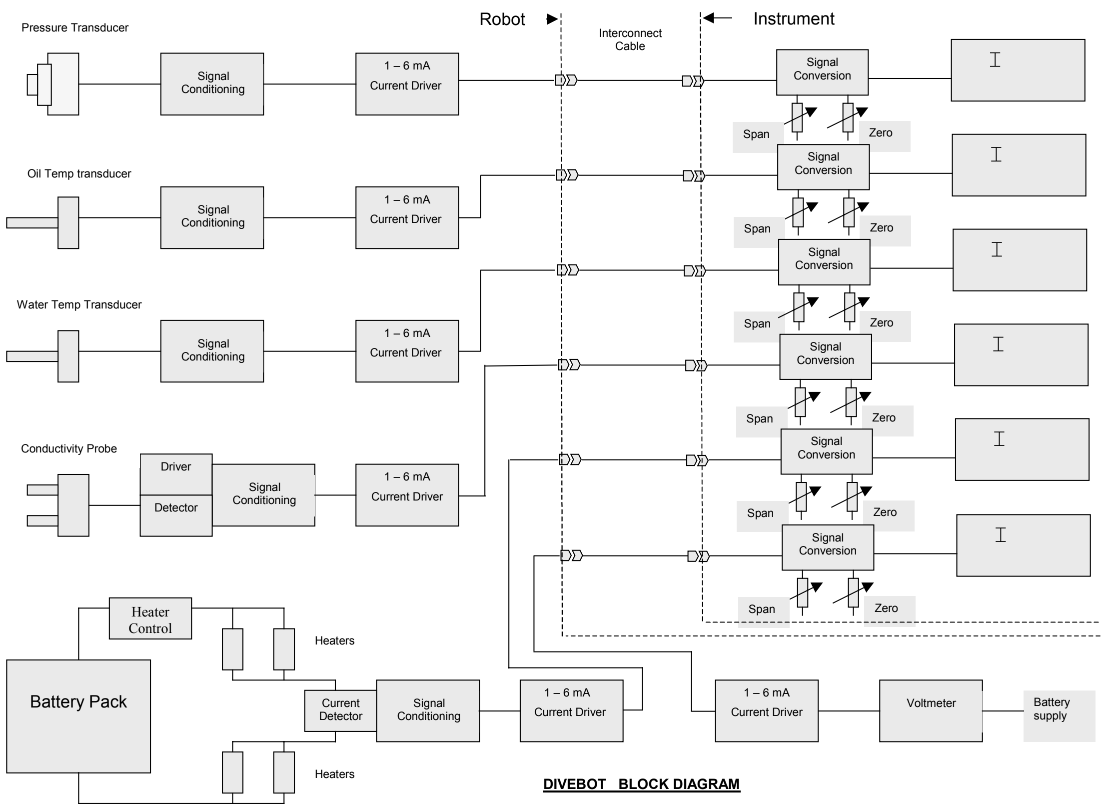

Figure 6. Block diagram of DIVEBOT electronics.

4. Shallow water sea trials

Sea trials were conducted at Playa Flamingo, playa Blanca, Lanzerote. This is a gently sloping sandy beach, protected by two large break-waters. The robot can be easily observed in the clear water.

The basic procedure is to trim the robot to neutral buoyancy (*fine trimming weight*), then attach a known weight onto the robot (*sinking weight*). The robot at this point starts to sink. Sometime later the heaters are turned on. As the oil heats up, it expands in the expansion chamber pushing out seawater through the vent. This decreases the robots mass, hence decreasing its density. Over a period of time the density reduces until at some point it becomes less than that of the water around it and at this point the robot will start its accent to the surface. Meanwhile all the sensor values are logged until the robot resurfaces.

The robot was attached by an umbilical cable to an instrument buoy (Figure 7) which floats close to the robot. The instrument buoy displays to the operator the output of the robot sensors, water temperature, robot depth, oil temperature, conductivity (salinity), heater current, battery voltage, and time. In addition it contains the line driver circuitry, sensor calibration facilities and provides the power for data transmission from the robot.

The umbilical cable has been designed to have as little effect on the buoyancy of the robot as possible. To achieve this nine very fine single strand copper conductors have been used without any common sheathing so that the cable has maximum flexibility and very little weight. To provide some protection to these fine wires a nylon filament is also added.

Figure 7. The instrument buoy.

The tests where carried out in less than 1 metre of water as it was only necessary to determine when the buoyancy has changed sufficiently to overcome the *sinking weight* that was added. The ascent to the surface at this point is achieved quite rapidly, in approx. 10 – 20 seconds. Shallow testing is advantageous since it is possible to observe the robot's behaviour and spot any problems. One such problem was the effect of air bubbles collecting under the robot, which was enough to significantly change its buoyancy. The air bubbles where released from the sand. This resulted in redesigning the shape of the robot.

The robot must be allowed to stabilise for at least 20 minutes in the water before final buoyancy trimming takes place. This allows the temperatures to equalise and the expansion/contraction of all parts of the robot to be in a state of equilibrium. Failure to do this would introduce an error of up to several grams. When the robot has stabilised in the water the process of final trimming can take place, which is to adjust the *fine trimming weight* until the robot is neutral. With care the buoyancy can be adjusted to within 1 gram, that is the addition of a 1 gm weight will start to sink a floating neutral robot. Once the robot is neutral, an appropriate known *sinking weight* is added which is in the range of 5 to 15 grams.

After several runs with differing weight arrangements, it was discovered that for every gram of *sinking weight* it took approximately an extra 8 minutes for the robot to rise from the moment that the heaters were turned on. Logging the various measurements starts when the heaters are turned on and finishes when the robot breaks the surface. On some occasions the robot will overshoot and sink again slightly. This is perhaps because of tide currents, air bubbles attached to the robot or energy lost trough overshooting. In this case the time ends when the robot breaks the surface twice. Measurements are taken and logged every 2 minutes and the experiments last between 40 minutes and 1.5 hours.

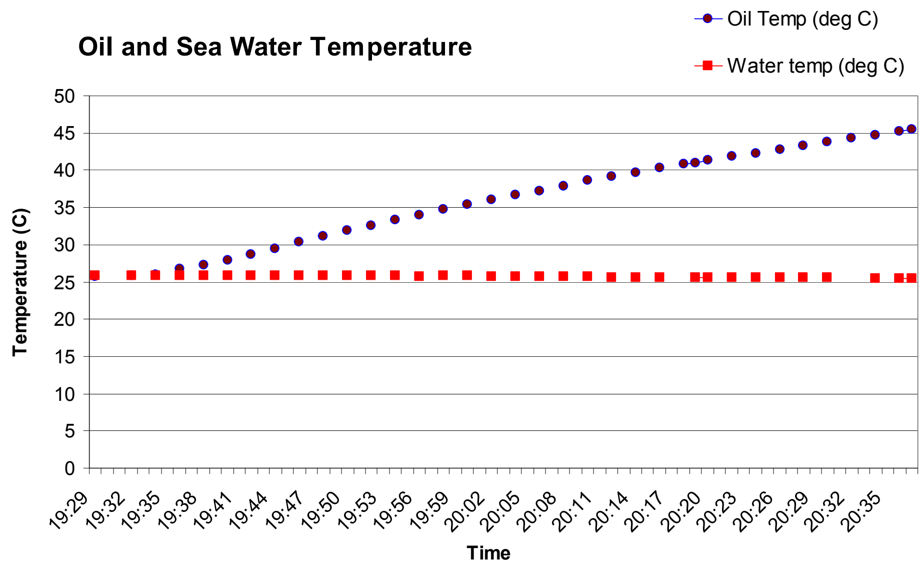

Figure 8. The oil and seawater temperature results from experiment.

5. The results from one typical experiment

Below is a brief list of recorded measurements from a typical experiment. Start of run is when the heater is turned on and the end of run is when the robot resurfaces.

- Sea temperature was 27.9°C in the start of the run and fell by 1.5°C.
- The oil temperature rose by 19.8°C.
- Total energy used during the run was 28.8 Watt.Hours.
- It took the robot 68 minutes to rise.
- Salinity of seawater remained constant.

The recorded seawater and oil temperature over the course of run is shown in Figure 8. The graph is exponential and so only as a rough guide it is possible to say that a 2.4°C rise in oil temperature in comparison with sea temperature lifts 1 gram. It also takes 1.5 Watt.Hours of energy to raise the oil temperature by 1°C.

The depth of the robot over time is shown in Figure 9. In the beginning, the depth varies a few centimeters due to the fluctuations caused by the tide and the robot touching the seabed. After a certain amount of time the robot starts to rise. Unfortunately the resolution of rise time was poor due to lack of equipment. This will be improved in the future.

6. Physics of DIVEBOT

When the DIVEBOT is underwater, there are a few forces applied to it at any given time as illustrated in Figure 10. By considering these forces and using conventional physical laws and modeling, it is possible to approximately calculate the behaviour of the DIVEBOT.

Modeling the DIVEBOT is important since it can be used to predict what the robot will do and certain changes can be made to the design of DIVEBOT to make it work as we want. The next

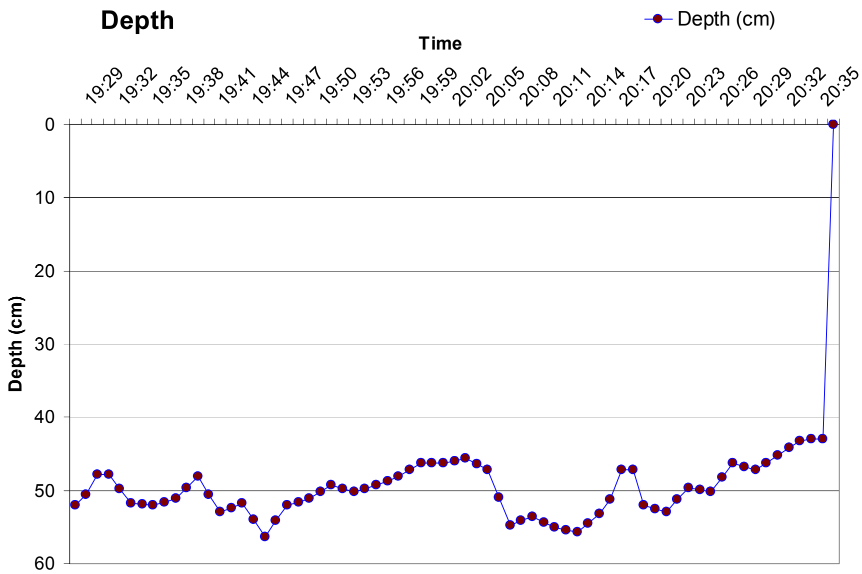

Figure 9. The depth of the robot over time. The heater is turned on in the left hand part of the graph and after a while the robot starts to rise. Depth 0 is the ocean surface.

section will cover a preliminary mathematical model based on the thermodynamics and physics of DIVEBOT. Later the results taken from the experiment explained above will be compared to the results obtained from this model.

Using the model, it is also possible to answer certain important questions. An important question is perhaps this: How deep can the robot go, such that it would be able to come to surface without running out of power? Or what is the optimum weight and volume of the robot, so minimum amount of energy is spent during runs?

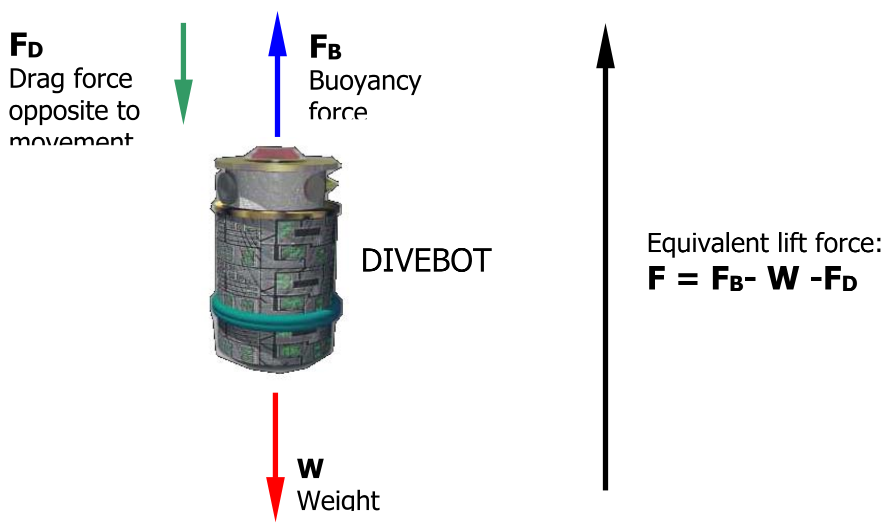

Figure 10. The forces applied to the robot when it is underwater and the DIVEBOT is about to come up.

7. An abstract model

For a simple abstract model we can assume that the sea temperature stays constant at all times for the entire depth. Also sea density is assumed to be uniform. First, we look at the heat flow. Once the heater is turned on, the heat flows from the heater to the oil in the *main oil chamber*. The oil starts expanding. However the heat in the oil can leak out through the insulator to the sea and as a conductive leak from oil to seawater in the *expansion chamber*. To simplify this, both are combined and considered as a linear leak according to the following equation

$$Q(t) = L(\theta_{OIL} - \theta_0) + C\frac{d\theta_{OIL}}{dt}$$

where Q is the battery input in Watts, L is leak factor in W/ºC, θ_{OIL} is the oil temperature and θ_0 is the original oil temperature which is the same as sea water temperature. Also t is time in minutes and C is the heat capacity of oil in W.Min/ºC.

It is also assumed that the seawater does not affect the oil temperature. For example if the DIVEBOT has been in deep cold water and is rising, it might enter a warm current. This means that the sea temperature can be more than oil temperature and this will violate the above equation since there won't be any leak from oil to the heat source, which is the seawater. This assumption will be updated in future, as it is an important factor, especially when the sea and oil temperature are very close This model is made for ascent only, as descent should consider the effect of sea temperature more accurately. The abstract model with these approximations is shown in Figure 11.

To find out the depth of the robot over time from the model, the physics of DIVEBOT are considered. As shown in Figure 10 the following equation holds

$$F = F_B - W - F_D \tag{1}$$

where F is the lift force, F_B is the buoyancy force, W is the weight of DIVEBOT and F_D is the drag force against the rise. And

$$F_B = \rho_{oc} V_r g$$
$$W = (M_r + m_T + \Delta m)g$$
$$F_D = C_D A \rho_{oc} \frac{v^2}{2} = k\rho_{oc} v^2$$

Here ρ_{oc} is the density of ocean, V_r is the volume of DIVEBOT, g is earth's gravity, M_r is the mass of robot, m_t is the mass of virtual trim, Δm is the mass of *sinking weight*, C_D is a drag constant, A is area of cross section of DIVEBOT and v is the velocity.

Sinking weight is the trim that was added to the robot to make it sink. But this is done after neutralizing the robot in water. This means that in the beginning $W = F_B$. Since this equation requires an accurate estimation of all the parameters, any inaccuracy will violate this equation, which affect the calculations. Therefore a virtual trim is also added to balance the equation accordingly to compensate for the inaccuracies of the measurements. This value is selected to

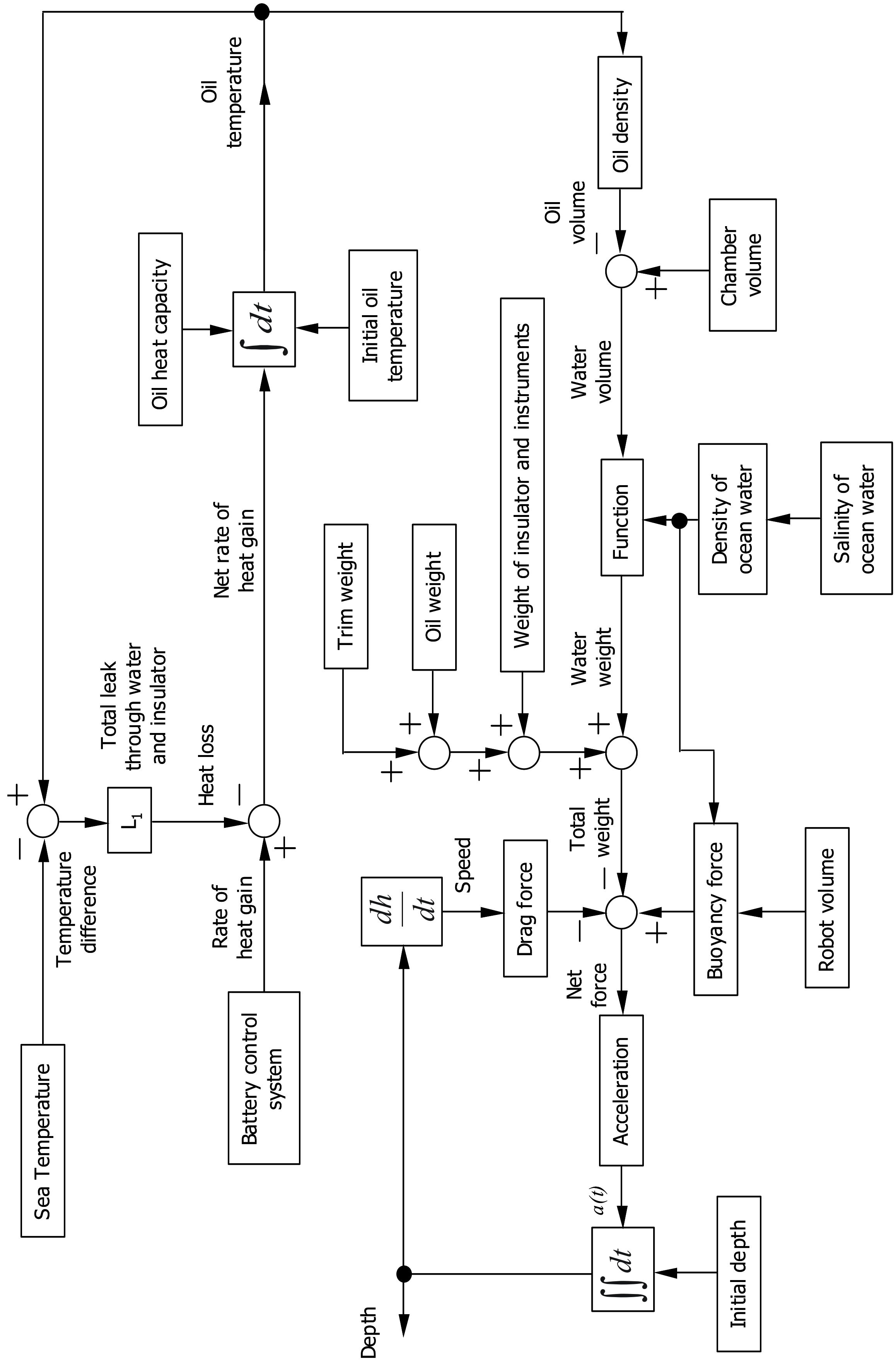

Figure 11. The abstract model to calculate the depth of DIVEBOT using the robot parameters. Many parameters are assumed to be constant, hence this model is only a starting point.

satisfy $W + W_T = F_B$ where $W_T = m_T g$.

Drag force is calculated using the standard equation for the cylinder approximating the shape of the robot. In the future the robot will be designed with a different shape so this equation should be updated to reflect that.

Now assume that the robot is on the bed of the ocean or at a predefined depth with the *sinking weight* on top and the heater is turned on. The idea is to know the depth over time. Assume that h is the depth of robot where $h = 0$ is the original depth of the robot and that as the robot rises this value is increased all the way up to the surface. According to Newton's second law

$$F = (M_r + m_T + \Delta m)a$$

where a is the acceleration of robot upwards. Since $h = 0$ in the beginning, therefore

$$a = \frac{d^2h}{dt^2}$$

If all these are inserted into equation (1) then

$$\rho_{oc}V_r g - (M_r + m_T + \Delta m)g - k\rho_{oc}v^2 = (M_r + m_T + \Delta m)\frac{d^2h}{dt^2}$$

and rearranging to

$$\frac{\rho_{oc}V_r g}{(M_r + m_T + \Delta m)} - g - \frac{k\rho_{oc}}{(M_r + m_T + \Delta m)}\left(\frac{dh}{dt}\right)^2 = \frac{d^2h}{dt^2}$$

Mass of the robot changes over time due to the expansion of the heated oil. As oil expands it pushes the seawater out of the robot, which makes the robot lighter and hence easier to rise. The mass of the oil is therefore constant and the only change is the seawater inside the robot. This means

$$M_r = M_{INS} + M_{OIL} + M_{WATER} = M_{INS} + M_{OIL} + \rho_{oc}(V_c - V_{OIL})$$

where V_c is the volume of the entire chamber (main and expansion chamber together), M_{OIL} is the mass of oil, M_{WATER} is the mass of seawater inside the *expansion chamber* and M_{INS} is the mass of the insulator and the rest of the robot. Mass of the oil and the robot (with no seawater inside) can be measured independently and is constant. The only term changing in the above equation is V_{OIL} and is calculated as

$$V_{OIL} = V_i + \beta(\theta_{OIL} - \theta_0)$$

This is assuming that the oil expands linearly in the temperature region under consideration. V_i

and β are obtained using experiments performed on the type of oil that is used in the robot. Putting the variable volume in the differential equation and also considering the heat flow equation discussed earlier, the depth can be calculated using the differential equation system

$$\begin{cases} Q(t) = L(\theta_{OIL} - \theta_0) + C\dfrac{d\theta_{OIL}}{dt} \\ \dfrac{\rho_{oc} V_r g - k\rho_{oc}(\frac{dh}{dt})^2}{(M_{INS} + M_{OIL}) + \rho_{oc}(V_c - (V_i + \beta(\theta_{OIL} - \theta_0)) + m_T + \Delta m} - g = \dfrac{d^2 h}{dt^2} \end{cases}$$

This can be solved numerically to obtain results for θ_{OIL} and h over time.

8. Comparison of model and experimental results

To compare the results obtained from experiment with the mathematical solution, numerical values of most parameters should be calculated. These values, such as heat capacity of oil, insulator constant, amount of energy pumped into heater, mass of robot, etc., are derived from the experiment. Therefore the model is based on these data. In the future two sets of experiments should be done, one to calculate various parameters, and another to compare the results with.

Figure 12 shows the comparison between the temperature of oil taken from data and the results calculated from the abstract model. There is some difference in the beginning of the graph. This is the direct result of one of the assumptions. The model only considers the heat flow of oil and

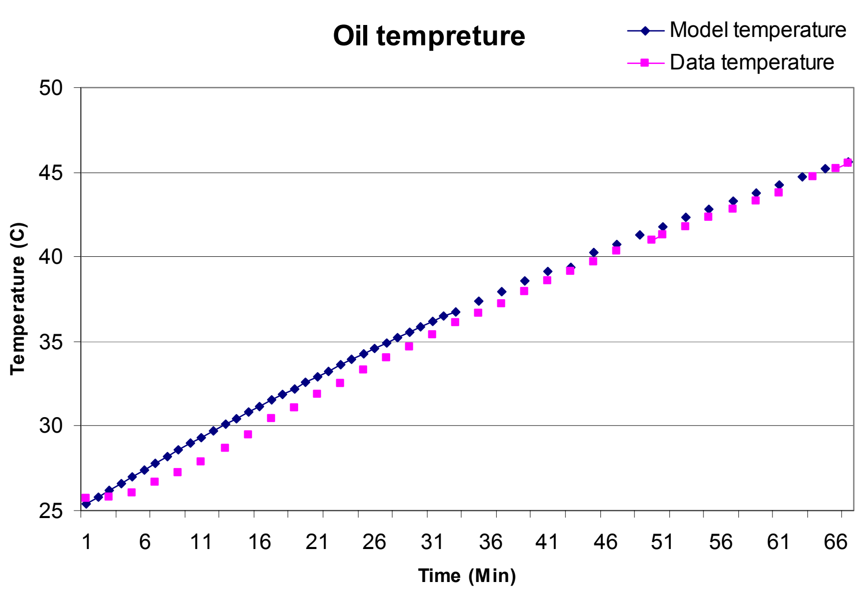

Figure 12. Oil temperature is compared using the measured data and the prediction derived from the abstract model.

the heater itself is not modeled. When the heater is turned on, it takes sometime for the heater to warm up and this is why the recorded temperature has some delay in the beginning.

The result for depth of the robot using the model is shown in Figure 13. When the oil starts expanding, the robot becomes lighter until the added trim weight is counteracted. Then as the robot continues to become even lighter, it starts to rise with a variable acceleration. As it rises faster, the drag force is also increased which reduces the acceleration until the net effect of all forces on the robot becomes zero. At this point there is no more acceleration and the robot continues with a constant velocity, called terminal velocity.

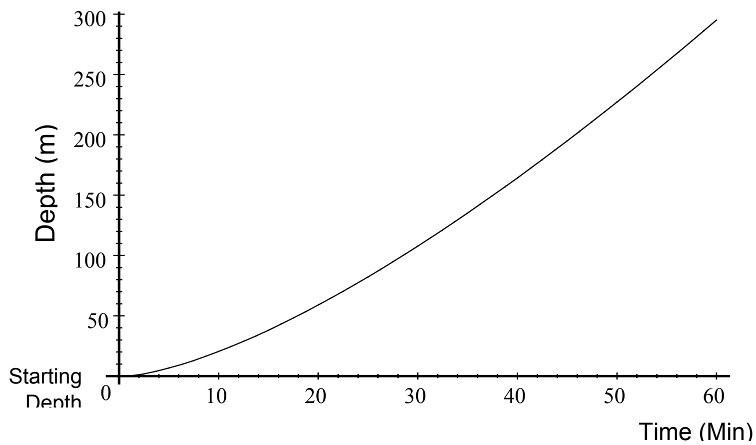

Figure 13. Depth of robot calculated using the differential equation system and the parameters from experiment. Depth 0 is when the robot is underwater, and as this value is increased the robot rises to surface.

9. An enhanced model

To have a more realistic understanding of the robot's behavior, an enhanced model of the DIVEBOT was developed. This model includes the effect of most of environmental variables in a more realistic way. These variables change over time and interact with each other during sampling. The enhanced model is shown in Figure 14.

The dashed parts in the enhanced model are the new components added to the abstract model. Sea temperature is no longer constant. The effect of sea temperature on oil and the complete feedback loops for different environmental variables are also added. The most important is the battery system, which determines the rate of heat generation.

To know how deep can the robot go, it is important to know the precise characteristics of the batteries in all possible conditions. For start, lets imagine that the batteries produce a constant amount of energy over time, so the heater is heating the oil continuously. Considering a very simple battery model as shown in Figure 15, it is possible to calculate the rise time of the DIVEBOT using the differential equations outlined earlier. The battery model simply assumes that the total capacity of the battery does not change under any circumstances, even by varying the amount of battery current taken. The result is shown in Figure 16 for various battery current

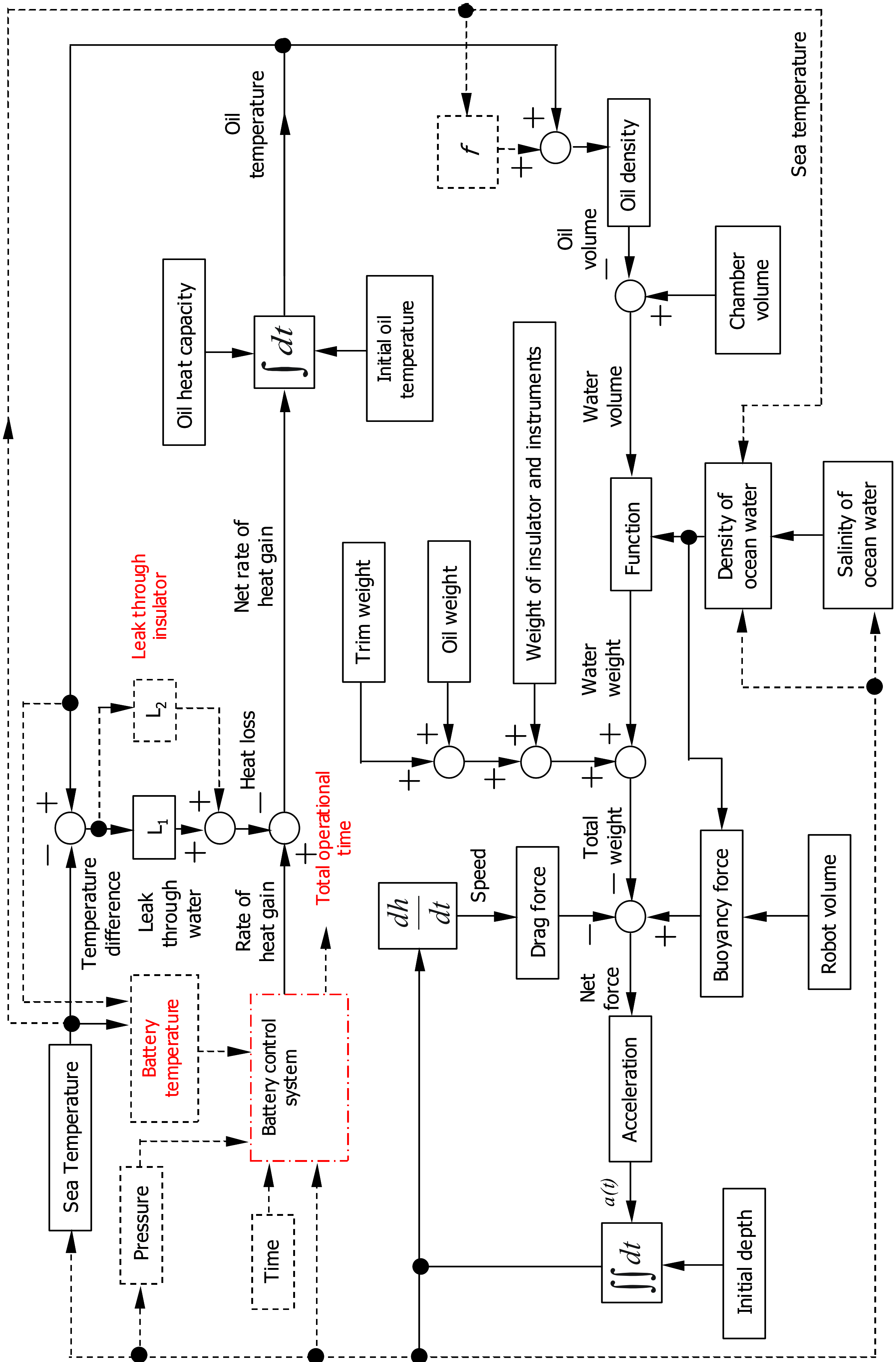

Figure 14 Enhanced model of DIVEBOT. The dashed parts are added to the abstract model shown in Figure 11.

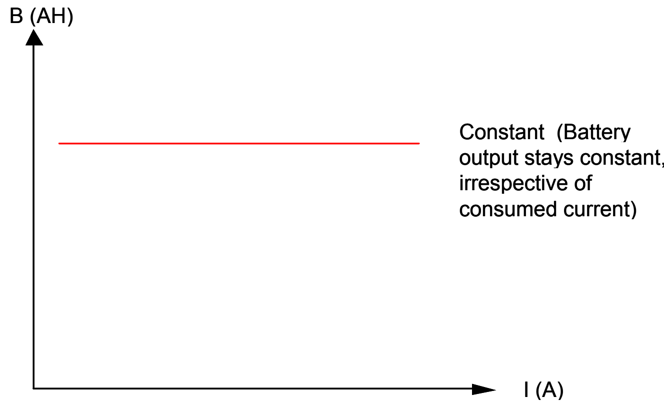

Figure 15. A simple model of batteries. The capacity of batteries stays constant at all times.

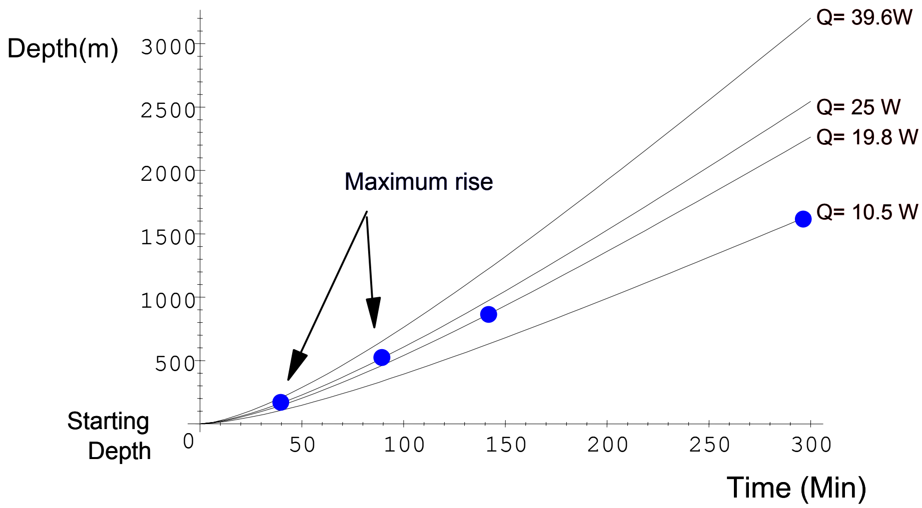

Figure 16. Each graph is the rate of rise of DIVEBOT for each heater rate. Maximum points are calculated according to total time that batteries last at that rate.

settings (Q). Each graph represents the depth of robot over time. Since the rate of battery current taken and the total capacity is known, it is possible to calculate how long the batteries last. This will give a maximum ceiling for each graph (circular points).

The maximum of these points is the optimum settings for the robot, since it will be the maximum of maximum depth of the robot (Notice that this calculation ignores the decent of the robot for simplicity)

However since the capacity is assumed to be constant, it seems that the less current taken out of batteries, the longer it lasts and hence the deeper it can go. This is in fact unrealistic, and it simply shows how important it is to have a very accurate model of the batteries and the DIVEBOT to make conclusions.

As a result, an extended model of batteries is created. This is shown in Figure 17. The idea is to consider all of the important environmental variables and include their effect on the model. Important variables are battery temperature, pressure, time, and various battery characteristics such as nominal capacity and cycles of charge and discharge. Most of the blocks in the block diagram represent graphs for input/output variables. Some of these graphs can be obtained from

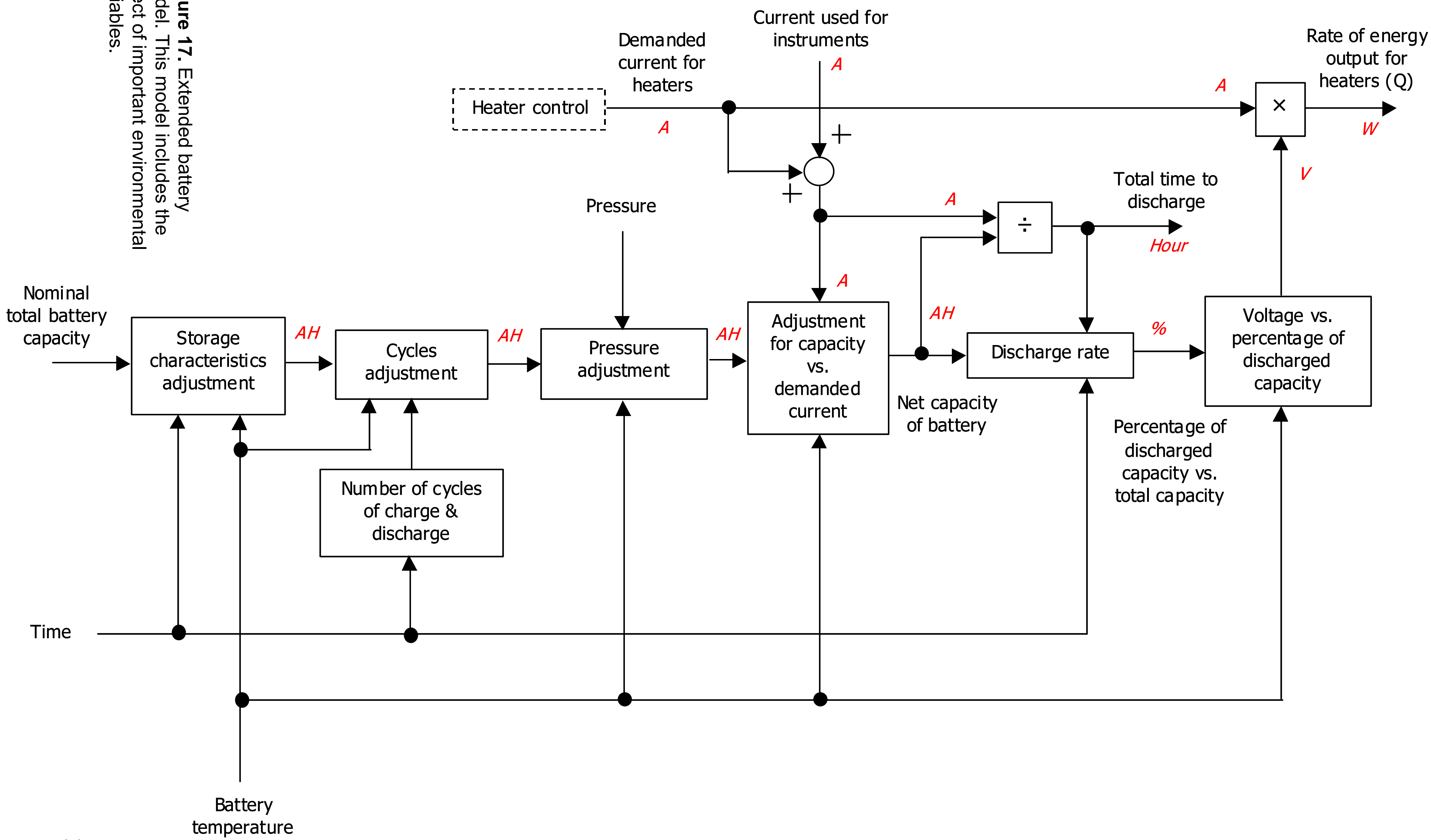

Figure 17. Extended battery model. This model includes the effect of important environmental variables.

manufacturers of batteries, but most of them should be found by experiment especially for the range that the DIVEBOT is operating at. Calculating the battery model accurately is the subject of current research. However to demonstrate the challenges ahead a conceptual reasoning is given below.

The graph shown in Figure 18 is perhaps the right shape for the battery model. The important difference is that the capacity of the batteries changes according to the amount of current taken. Other environmental variables are ignored for simplicity at this point, however eventually there would a family of graphs representing the battery as the environmental variables change. As the graph shows, after a certain threshold, as more current is taken out of batteries it will reduce their capacity. Also if a very small current is taken from the batteries, the capacity drops too, and hence the bell shaped curve. The next step is to use this graph with previous calculations to find out the maximum depth of the robot. The conceptual result is shown in Figure 19. This time, since the battery capacity drops as less current is taken out of it, the graph of maximum points does not rise steadily as before. There is now an optimum point for the connected maximum points. Using this point and its corresponding settings it is possible to set up the DIVEBOT to achieve the maximum depth.

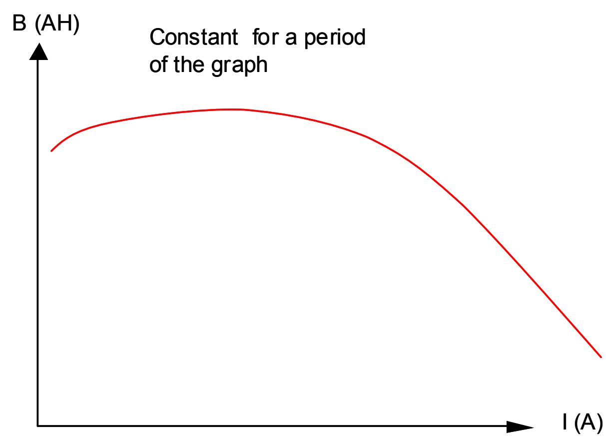

Figure 18. A better model for batteries based on guesswork.

10. Conclusion

In this paper it was demonstrated that the concept behind DIVEBOT is practical and although there are many challenges to overcome, the DIVEBOT offers many advantages that is difficult to find elsewhere. DIVEBOT combined with the flock distortion technique offers a reasonably practical method of sampling oceans for the benefit of science.

Future research will focus on various enhancements of DIVEBOT, and on setting up more experiments for analysis of the model. As explained above it is very important to consider as many environmental variables as possible in the model and the experiments as the influence of each parameter is quite drastic.

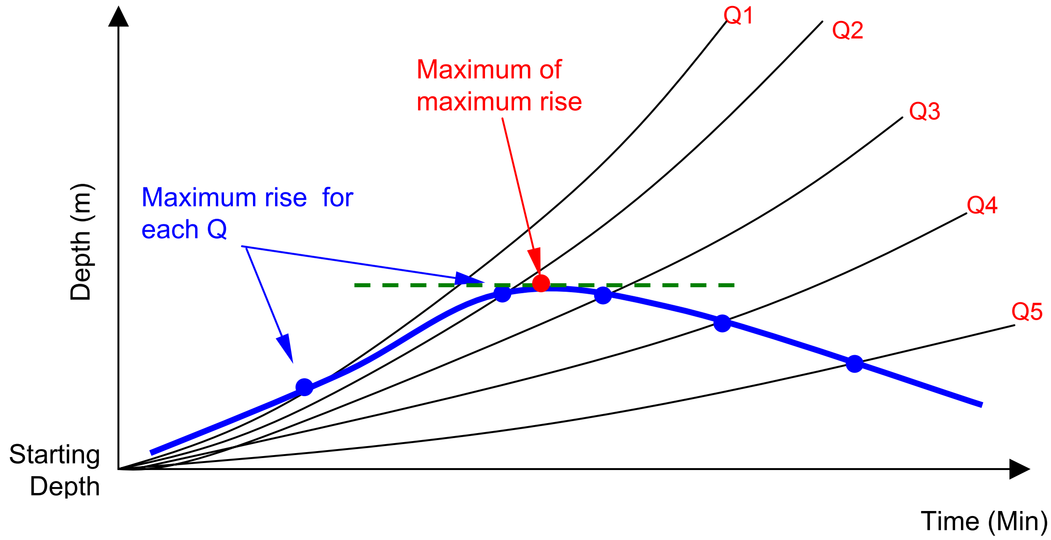

Figure 19. Using the battery model, a series of maximum points are calculated and are then connected. The maximum of these is the optimal point.

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