Aberystwyth University

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Sauze, Colin; Neal, Mark

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A neuro-endocrine inspired approach to long term energy autonomy in sailing robots.

Colin Sauzé and Mark Neal

Abstract— There is an increasing desire to deploy autonomous robots into harsh environments where humans do not wish to go or cannot go. These robots have only infrequent contact with human operators and therefore, must be highly autonomous, both in terms of control and energy. Sailing robots represent a good example of such robots as the primary locomotive force is provided by the wind and only small amounts of electrical power are required to run the onboard electronics. An artificial neuro-endocrine controller inspired by the mammalian neural and endocrine systems offers, the ability to generate a hormone which can either inhibit or excite a neural network to reduce or increase its level of activity. Experiments using hormones linked to robot's battery level and the level of sunlight from a photovoltaic solar panel show that behaviour can be modified in a meaningful manner to manage long term power consumption.

I. INTRODUCTION

Many scientists wish to be able to obtain long term observations of remote and harsh environments by sending autonomous robots to them. Such robots are unlikely to have much (if any) contact with human operators and must therefore be sufficiently autonomous to deal with the varying conditions of their operating environment. Possible examples of such environments include outer space, polar regions, volcanoes, areas contaminated by toxins or nuclear waste and the seas. These robots will need to be energetically autonomous, either by carrying a suitably large energy source (e.g. a nuclear reactor) with them or generating energy from their environment.

One example of such a robot is a sailing robot, these are particularly capable of long term missions as they can derive their primary locomotion directly from the wind and require only small amounts of electrical energy to move actuators, run sensors, computers and communications equipment. This makes it relatively easy to achieve energy autonomy in a sailing robot in comparison to a propeller driven robot boat, a wheeled or legged land vehicle or a flying robot.

It would seem logical that drawing inspiration from biology could be a good starting point for a long term autonomous robot, given the ability of biological systems to adapt to a wide variety of conditions. Perhaps most desirable are the homeostatic abilities of biological systems which keep the system within set limits that enable life to continue. Common examples include the regulation of body temperature, blood glucose level or calcium levels. Many of

these processes are regulated through the endocrine system which operates through a series of glands which release chemical messengers known as hormones. Hormones trigger a change in a target cell by binding to receptors on that cell. They are produced by various glands which secrete them into the bloodstream allowing them to reach virtually all cells in the body. The endocrine system should not be viewed as an isolated system but as part of a larger super system involving the neural and in some cases (such as mammals) the immune system. Artificial analogues of all three systems exist in the form of Artificial Neural Networks [9], [7], Artificial Endocrine Systems [1], [8] and Artificial Immune Systems [5], [3], [13]. This work concentrates on the application of an artificial neuro-endocrine controller to long term autonomy, an Artificial Immune System was not utilised for several reasons. Firstly in biology not all species have an immune system and therefore it is not absolutely vital to maintaining homeostasis. Secondly the neural, endocrine and immune systems all deal with different timescales, the neural system with near instantaneous timescale, the endocrine system with actions lasting between a few seconds and many months and the immune system covering a timescale from minutes to years. As the target robot is typically going to operate for months not years an immune system may not be required. Finally artificial immune system algorithms are significantly more computationally complex than neural networks and artificial endocrine controllers which could cause difficulties when attempting to implement them given the limited amounts processing power found in many autonomous robots.

An artificial neuro-endocrine system operates through the combination of a traditional neural network, one or more artificial glands and hormones. The glands are responsible for producing the hormone in response to certain stimuli and may themselves be neural networks. These hormones then modulate the behaviour of the neural network by modifying its weights. The neural network has a sensitivity to each hormone, if a sensitivity is zero, that hormone will have no effect on this network. The hormone may be either excitatory or inhibitory. Excitatory hormones will increase the values of the weights inside the neural network while inhibitory hormones will reduce the weight values. Several hormones may compete with each other, with some attempting to inhibit the network and others attempting to excite it, therefore, allowing the robot to target multiple goals simultaneously.

II. METHODS

A. Sailing Robots

As discussed in the previous section, sailing robots are an ideal platform for researching long term autonomy as their primary source of locomotion is the wind and that only minimal electrical power is required to run onboard electronics and actuators. Photovoltaic solar panels and a small battery should be sufficient to run these electrical systems. However the (electrical) power budget is still going to be quite tight and intelligent power management will be required to keep the robot operational.

The concept of autonomous sailing robots has been around since at least the late 1980s [1], but has seen rapid development since 2004. In 2005 the Microtransat Challenge [2] was founded with the aim of racing autonomous sailing robots across the Atlantic ocean. Since then at least 20 groups have become involved in the development of autonomous sailing robots. These range from 50cm long modified radio control boats being used by the University of Lübeck [2] to 10m long catamaran's built by Harbor Wing Technologies [4].

There has been a tendency by some sailing robot designers, to solve power problems by over-engineering the system to create large excesses in the power budget. This can be achieved by covering every surface which receives sunlight in solar cells or the use of a fuel cell. Such an approach has been taken in sailing robots by sailing robot developers at the Swiss Federal Institute of Technology in Zurich [6] and the Austrian Association for Innovative Computer Science [12]. Although both of their robot's are capable of full energy autonomy this has been achieved at considerable financial cost (AVALON the Swiss robot cost approximately €100,000 excluding the cost of engineer time) and additional hardware complexity. For one off robot construction this approach has its merits by reducing software complexity and guaranteeing a large power budget surplus, however increasing hardware complexity of a robot also increases the probability of component failure. If large scale fleets of robots are to be mass produced the cost of each robot's hardware becomes highly critical and even small innovations in software which provide power (and therefore manufacturing cost) savings are desirable. Considerable power savings can also be achieved through good hull and sail design. An ideal sailing robot should, when the sails are set correctly be able to remain on a set course with little or no intervention from any dynamic control system. This will reduce actuator usage, as adjustments should only be required when changing course or when the wind changes direction.

Aberystwyth University has been developing sailing robots since 2004 [11], these have ranged from between 75cm and 3.5m in length and varying capabilities. The latest generation are known as the MOOPs (Miniature Ocean Observation Platforms) and have been under development since 2008. They have been used for all the experiments presented in this paper. The exact specifications of the robot are shown

[1] http://www.well.com/user/pk/ZHTAlatitude.html
[2] http://www.microtransat.org

Fig. 1. One of the MOOP sailing robots.

in table I and a photograph can be seen in figure 1. Their small size makes them easy to transport, deploy and recover, allows them to be sailed in shallow waters and means they are unlikely to cause any damage should they collide with another vessel.

For these experiments, the robots were not fully energy autonomous as they had no photovoltaic solar panels or any other means of electricity generation. The on board batteries were only sufficient for a few hours of sailing, which was sufficient for these experiments. Other variants of the MOOPs have been constructed with solar panels to allow for longer missions. All the experiments presented in this paper were undertaken on Llyn-Yr-Oerfa, a small lake approximately 12 miles east of Aberystwyth, the lake has an area of approximately 120x200 metres which are suitable for sailing on.

All sailing craft have an area (with respect to the wind direction) known as a "no go zone" where they cannot sail, this is typically quoted as being 45 degrees either side of the wind direction, for the MOOPs it was found that in anything but light winds (less than Beaufort force 2/ 4mph / 3knots) this was nearer to 75 degrees making it incredibly difficult for them to sail up wind. Therefore, for these experiments they were limited to sailing perpendicular to the wind (known as a beam reach). This is usually the most efficient course (with respect to wind direction) for a boat to sail.

B. Simulations

Producing an accurate simulation for a sailing robot is not a simple task given the complexity of the environment and the difficulties in accurately modelling the physics of the boat's interaction with water. However, given the time and effort required to test a new algorithm on a real robot,

Length	74cm
Draft	12.5cm
Beam	21cm
Weight	4kg
Sail	7cm x 30cm solid wing sail
Power	58 watt/hours NiMH batteries
Computers	Gumstix Single board computer and PIC 18F4550 Microcontroller
Sensors	SiRF III GPS, HMC6343 tilt compensated compass, AS5040 rotary encoder for wind sensor
Actuators	Radio control model servos for sail and rudder

TABLE I

THE SPECIFICATIONS OF THE MOOP SAILING ROBOT

even a simplistic simulation can be used to test and refine algorithms before running them on the real robot. We have modified an open source sailing game called tracksail [3] to allow it to be controlled via an API instead of a GUI, the API presents a similar interface to that used on the robot offering the user the ability to get the boat's heading and position, the wind direction and to set the sail and rudder positions. The modified simulator can be downloaded from [4].

C. Neuro-endocrine controllers

As previously discussed, the neuro-endocrine controller consists of a neural network and artificial endocrine controller. The neural network in this case is a 3 layer multi layer perceptron. It has 2 inputs, 8 hidden nodes and 1 output. There are two neural networks, one controls the rudder actuator and the other controls the sail actuator. In both cases one input is the current position of the actuator, the other input is either the wind direction or the heading error (difference between the current compass heading and target heading), the output is the change in the actuator position. The reason the output is the change in position instead of the absolute position is that as the hormone inhibits the network's output will tend towards 0. So if an absolute value were used, this would cause the actuator to move to one side as the hormonal inhibition increased. By giving a change in position as the hormonal inhibition increases fewer changes in actuator position occur, this in turn should reduce the frequency and magnitude of actuator movements and reduce overall power consumption at the expense of accurate course holding and sail setting. Figure 2 shows a graphical representation of this architecture. The neural network is trained using the traditional back propagation algorithm. The training data for the rudder is generated from the outputs of proportional controller, the sail data simply uses a block of 'if' statements, each which set the sail to a given position for a given range of wind directions.

Each hormone has an associated value representing its current concentration in the system. In biological systems the hormone concentration in the bloodstream naturally decays as hormones bind with receptors however, as our artificial

[3]http://tracksail.sourceforge.net/
[4]http://sourceforge.net/projects/microtransat/files/

endocrine system has no physical receptors we must artificially decay the hormone concentration over time. This is achieved with the formula:

$$h_{t+1} = h_t - (r(h_t - n - (q * h_t)))$$

where h_t represents the current hormone concentration, h_{t+1} the new hormone concentration, r is the response rate at which the hormone concentration will change. The smaller the value of r the longer the h_t will take to change. n is the normal level of the hormone which it will tend towards if no additional hormone is released. When hormone is released this may "fight" against that value if they differ. q represents the amount of hormone being released, it is normally proportional to the stimulus which triggers the hormone release and should be between -1 and 1. This value determines if the hormone is going to have an inhibitory or excitatory effect upon the neural network, negative values will inhibit and positive values will excite the network.

The neural network must be modified to take account of the hormone, the traditional rosenblatt perceptron[9] is described by the formula:

$$\sum_{i=0}^{n} w_i x_i$$

Each input x is multiplied by a weight w, the sum of these is taken and this is passed to an activation function, typically the sigmoid activation function

$$y = 1/(1 + e^{-x})$$

.

To modulate the weights in proportion to the hormone concentration the neural network formula is modified to be:

$$\sum_{i=0}^{n} w_i x_i (1 + h_k s_k)$$

Where h is the hormone concentration, s is the sensitivity of this neural network to that hormone and k represents the set of hormones.

The gland controller must release hormone in response to some form of stimulus. This could take many forms including simply releasing hormone in direct proportion to the stimuli from sensors or following more complex rules. The gland could be implemented as a neural network allowing for it too to be modulated by a hormone. This is analogous to a biological process known as a hormone cascade. In these cascades a hormone often stimulates another gland to produce a hormone which may in turn control the production of the first hormone. The possibility of an artificial hormone cascade offers the ability to reinforce an action by continuing the stimulation to the gland which keeps it running. It also introduces an additional lag into the system. This could ensure that a new behaviour runs for sufficient time to make any difference to the overall performance. As switching to a new behaviour for an insufficient amount of time may result in it failing to complete or in a constant and rapid oscillation between behaviours.
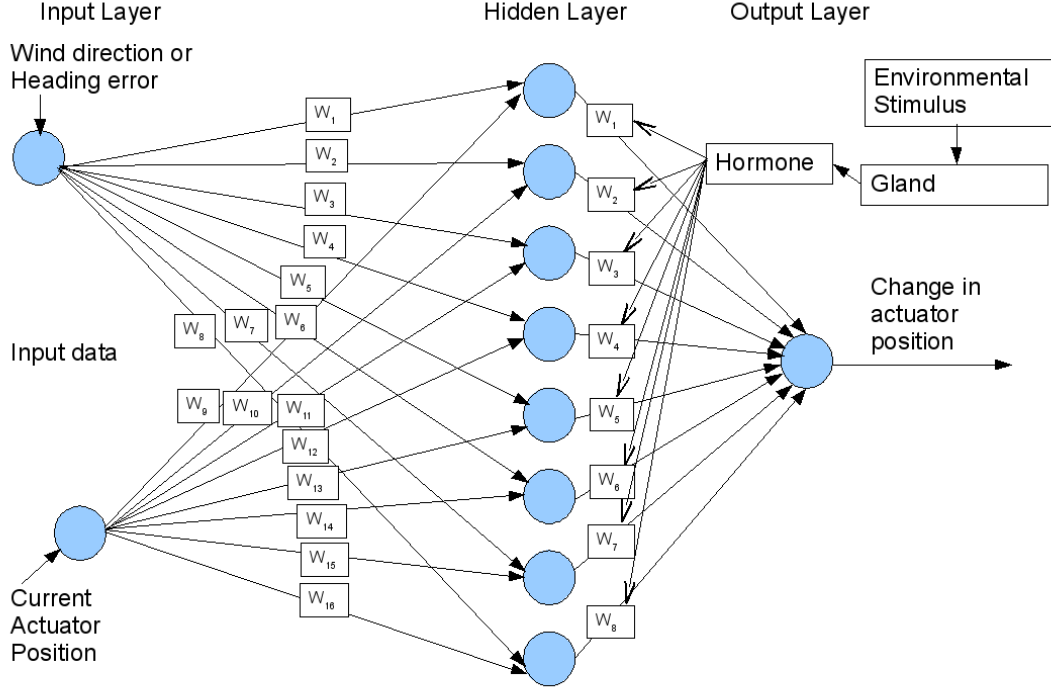
Fig. 2. The Neuro-Endocrine controller

D. Modelling Electrical Properties

Both the rudder and sail actuator have been given 11 unique positions, these are labelled as -5 to 5, with position -5 being full left, 0 being central and 5 being full right. As the MOOP lacks any hardware to measure the actual battery level, its level is derived based on the amount of actuator usage so far. Through laboratory tests an approximate value for the movement of each actuator by one position was derived, these values are 1.1192 joules for the sail actuator and 0.3814 joules for the rudder. The power consumption of the computers was not considered, because there was no facility to turn them off for a fixed duration of time. In reality, the computer actually accounts for a significant proportion of the power used (this could be solved by switching to microcontrollers as the only computers). Given this, the actual battery will run out long before the simulated one. Therefore, to produce a reasonable degree of realism the actuator power consumption figures where multiplied by 10 for robot experiments and 100 for simulations. Each actuator movement reduces the remaining battery capacity by the stated amount. Simultaneously the battery is "charged" by a (currently imaginary) photovoltaic solar panel. The charge level is proportional to the elevation of the sun which is calculated from the time of day and current GPS position. The peak solar panel output is 4.75 watts, under this system this value would only be achieved at noon on the equator.

III. EXPERIMENTS AND RESULTS

A. Fixed Hormone Levels

Initially to test the dynamics of the system an experiment was conducted with fixed levels of a hormone, using both inhibitory and excitatory hormones. The robot was given a fixed course to sail and to evaluate the size of the effect upon power savings, the amount of energy used in travelling each kilometre and for each hour of travel where compared. A range of hormone concentrations and sensitivities were used. With both negative (inhibitory) and positive (excitatory) hormone concentrations being used. For a fixed level of hormone these two numbers can be condensed into one by multiplying them together, this shall be referred to as the effective hormone concentration. Each experiment was run on both the simulator and on the actual robot to generate some idea of how dramatically the two differ and to see if the same conclusions can be drawn from both.

The results are shown in figure 3 and 4, hormone concentration has been compared with the amount of energy used for each kilometre travelled and for each hour of travel. This is because increasing the hormone concentration will result in fewer actuator movements and more suboptimal actuator positions therefore, it is possible that although power consumption per hour could be reduced this results in slower travel and could actually make power consumption per kilometre worse. Whether or not this is desirable would depend upon the exact operating requirements of the robot.

Correlation	P	n	99% significance level threshold	Accept at 99%
Energy per KM (simulator)	0.991	15	0.604	yes
Energy per hour (simulator)	0.991	15	0.604	yes
Energy per KM (robot)	0.728	23	0.497	yes
Energy per hour (robot)	0.581	23	0.497	yes

TABLE II

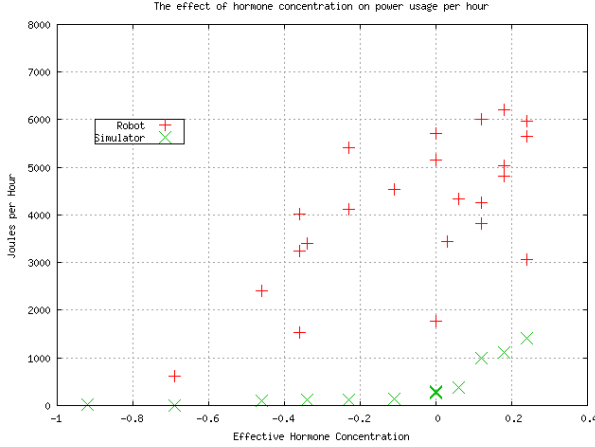CORRELATION COEFFICIENTS OF HORMONE CONCENTRATION AND POWER USAGE.

Fig. 3. Hormone concentration plotted against energy usage per hour.

Fig. 4. Hormone concentration plotted against energy usage for each kilometre travelled.

Figures 3 and 4 show that there is a strong correlation between the effective hormone concentration and power consumption. To analyse this further we ran a Spearman's rank correlation coefficient, as shown in table II there is a correlation at the 99% significance level in all cases. This shows a correlation between the power consumption and effective hormone concentration. This correlation is weaker in the robot than the simulator but is still statistically significant. This also suggests that we can alter the power consumption by modulating the neural networks controlling the robot while still managing to navigate the course. This comes at the expense of reducing both the frequency and magnitude of actuator movements which in turn can reduce sailing accuracy. At low levels of inhibition this maybe wholly beneficial as it simply helps to smooth out noise from the output of the control system. As the inhibition levels increase the robot was often observed setting the sail into positions which are clearly "wrong" for the wind direction and at this point the robot would often find itself washed up on the shore within a few minutes. Under simulation due to the lack of random changes in wind direction, the boat could end up sailing backwards indefinitely.

B. Battery Hormone

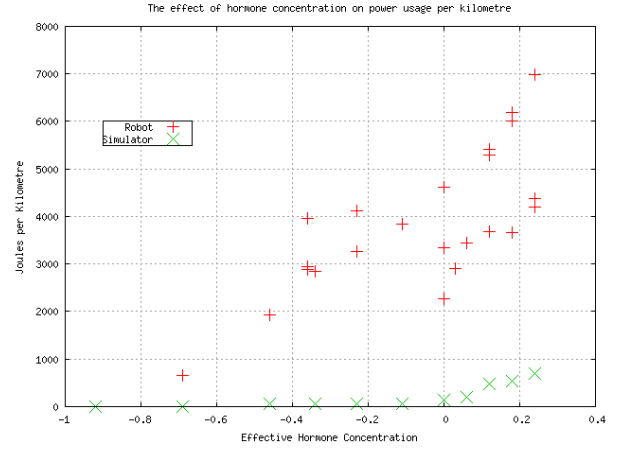Once it had been established that the a neuro-endocrine controller could manage the behaviour of the robot and simulator in a sensible fashion, the next stage was to have the hormone determined by a variable which reflected the state of the environment. The obvious simple choice was to have a hormone reflecting the battery state of the robot. This could also be viewed as a hormone to regulate the consumption of electrical power as insulin regulates the uptake of glucose in mammals. As the MOOP lacks any hardware to measure the actual battery level, its level is derived based on the amount of actuator usage, full details of how this is calculated are shown below in section II-D. The gland used the function $(b * 0.023) - 1.03$ where b is the battery remaining in watt hours, a full battery has a capacity of 55 watt hours. This causes a slightly excitatory behaviour when the battery is nearly full and an increasingly inhibitory behaviour as the battery nears empty.

1) Results: Hormone sensitivities of 0, 0.25, 0.5 and 0.75 were tested to see how the system would react to different hormone sensitivities. The experiment was run on both the simulator and the robots. A plot of the battery level and elapsed time is shown in figures 6 and 5. Summary statistics are shown in table IV and III. From these we can see that there is a dramatic change in the amount of time the boat can sail for as the hormone sensitivity increases. In the simulator the median time ranges from 565 minutes in the control (hormone sensitivity of 0.0) to 7401 minutes with a sensitivity of 0.75. The robot results show a similar but less dramatic effect, with the median rising from 119.9 minutes in the control to 198.6 minutes when the sensitivity is 0.75. Also of interest is the shape of the curve in figures 5 and 6. We had expected to see an approximately inverse exponential curve, where the battery level would initially fall very quickly and the rate of discharge would gradually reduce as the battery level dropped. This trend can be seen to some extent in the simulator results but not in the robot results. This suggests that other factors make a greater difference for the robot and effectively remove this curve. However, it still suggests that we are able to significantly reduce the robot's power consumption by introducing hormonal modulation and
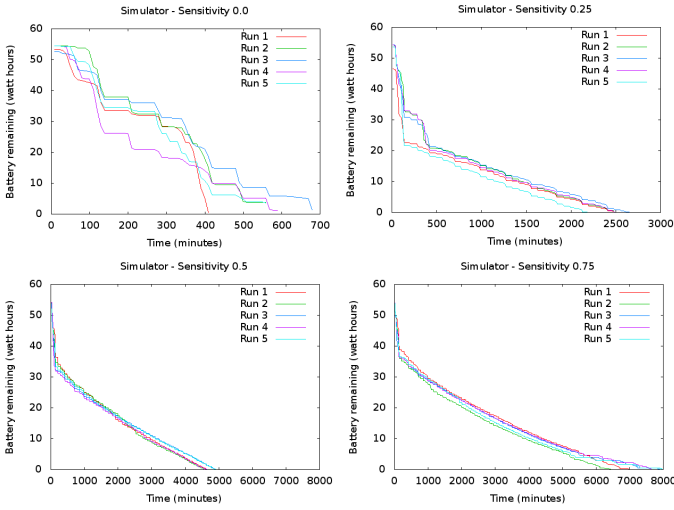
Fig. 5. Graphs showing battery level against time for different hormone sensitivities on the simulator.

Hormone Sensitiv-ity	Mean	Median	Min	Max	Lower Quar-tile	Upper Quar-tile
0.0	565.01	568.95	411.7	682.82	567.9	594.22
0.25	2490.67	2552.28	2193.53	2674.23	2477.85	2555.45
0.5	4726.41	4653.73	4552.73	4912.2	4619.92	4893.48
0.75	7401.14	7642.9	6454.8	8000.27	7000.63	7907.12

TABLE III

SUMMARY STATISTICS FOR THE SIMULATOR.

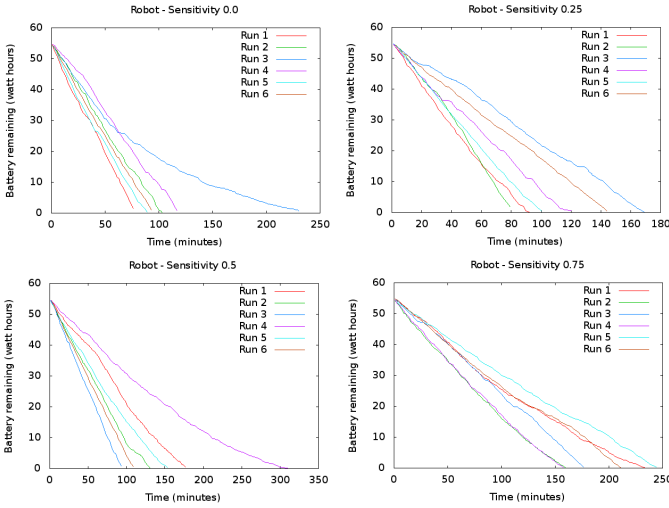| Hormone Sensitiv-ity	Mean	Median	Min	Max	Lower Quar-tile	Upper Quar-tile
0.0	119.9	99.63	78.65	231.48	91.5	115.83
0.25	118.73	111.68	81.23	169.5	94.63	139.91
0.5	164.12	143.04	95.42	313.18	116.31	172.73
0.75	198.86	195.43	159	245.35	165.37	229.88

TABLE IV

SUMMARY STATISTICS FOR THE ROBOT.

Fig. 6. Graphs showing battery level against time for different hormone sensitivities on the robot.

producing a hormone in proportion to battery level.

C. Solar Hormone

As the long term aim is to eventually power the robot from photovoltaic solar panels we have created a simple simulation to calculate the approximate power consumption and solar power input. We calculate that if the deck of a MOOP is covered in photovoltatic solar panels then it will be capable of generating a maximum of 4.75 watts. As the boat currently has no solar panels, a simple model for estimating their output has been devised by taking the power output as being proportional to the elevation of the sun. If the sun were directly overhead, as it would be on the equator at midday then the power output will be the full 4.75 watts. This assumes the solar panel is laying flat, that the sun is not obscured by cloud (this maybe somewhat optimistic for mid Wales!) and that no shadow is being cast by nearby terrain

or the robot's sail. The elevation of the sun can be calculated from the robot's current GPS position and the time.

Instead of calculating the amount of sunlight currently available, a prediction could be made for the level of sunlight in the near future. This would allow the robot to adjust its behaviour to future energy availability instead of current availability. In robots with small batteries that only last 24 hours or less, then it could be vital to consider the amount of sunlight over the next few hours when deciding which tasks the robot can undertake or the level of inhibition to apply to the control system. This could essentially allow the robot to sleep overnight in order to conserve power. In robots with larger batteries there is less need for daily behaviour changes but longer term seasonal (or location based) adjustments in behaviour could become equally important.

This leads to two possible options with regards to how to use an artificial endocrine controller to improve power usage from solar sources. The first is not to represent the level of sunlight with its own hormone and simply use the same battery level hormone used in the previous experiment. This offers no ability to act upon future sunlight levels but has the simplicity of requiring no extra hormones. The second option is to have a separate hormone which is produced in proportion to the current (or future) level of sunlight. If this hormone is also acting to inhibit the control system it should reinforce the behaviours created by the battery hormone. If dealing with a timeshifted system where the hormone is produced in proportion to future levels of sunlight, it may contradict the battery hormone. For example if its early morning and the sun is just rising, the battery is low from keeping the robot going through the night and the first signs of daylight are only providing minimal power from the solar panels. Using only the battery hormone, the behaviour would be to continue to heavily suppress the control system reducing the sailing efficiency thus reducing the ability to perform the mission. If a second hormone is present, which is taking into account the level of sun light two hours into the

future, this will cause a reduction in the level of suppression and improvement in the control of the robot.

1) Battery Hormone Only: In this experiment no extra hormones were created and the only thing to affect the behaviour was the battery charge level. Obviously as the amount of sunlight affects the battery level it will indirectly affect the behaviour of the robot. The simulation was run at 3 different times of year to reflect differing levels of sunlight and 5 times for each time of year. The dates of June 22nd, September 22nd and December 22nd were chosen to approximately equate to the summer solstice, autumnal equinox and winter solstice. The start time is midday in all cases (daylight savings time is ignored) and the latitude was set to 52 degrees North (the latitude of Aberystwyth), the hormone sensitivity s was set to 0.75. The simulation was run with a predefined course of 400 waypoints which the robot must sail back and forth between, if this course is completed or if the battery becomes totally discharged then the simulation ends. Only in the June simulations was the course completed and it appears that given the level of sunlight in June this would allow this course to be repeated indefinitely (or at least until the days get short enough to not provide enough solar power). In both the September and December simulations a flat battery was the cause of the simulation ending. The September graph shown in figure 7 shows that two of the experiments ran out of battery after only approximately 35 hours (11pm). While the other 3 have suppressed their control systems sufficiently to consume no power all night and only begin to consume any power again the next morning. This same behaviour is seen to an even greater extreme in the December graph, where two simulations end within 30 hours, another 2 manage to last 80 hours by performing no activity at night and another manages to last nearly 130 hours. While this may appear at first to be a desirable situation. It should be noted that the reason they are consuming no power during the night, is because the battery is so low that the solar hormone has totally suppressed any actuator movement and therefore the boat is just drifting. A more ideal solution would be to reduce power consumption further during the day in order to assure that there is enough battery power to keep sailing through the night.

2) Battery and Solar Hormones: To alleviate the problem of the control system consuming vast amounts of power during the day, running out of battery during the night and then totally suppressing the control system the obvious solution appears to be a second hormone which follows the level of sun light. Using an inhibitory hormone which modulates actuator movements in an inverse proportion to the level of sunlight, the level of inhibition will be at its lowest at midday and gradually increase towards sunset. A greater level of inhibition will apply in winter than in summer. The previous experiment was repeated with this second hormone being produced in inverse proportion to the elevation angle of the sun, an elevation of 90 degrees (as would be observed on the equator at midday) would trigger no hormone to be released and an angle of 0 (or less) would produce hormone at its maximum concentration. A sensitivity of 0.75 was
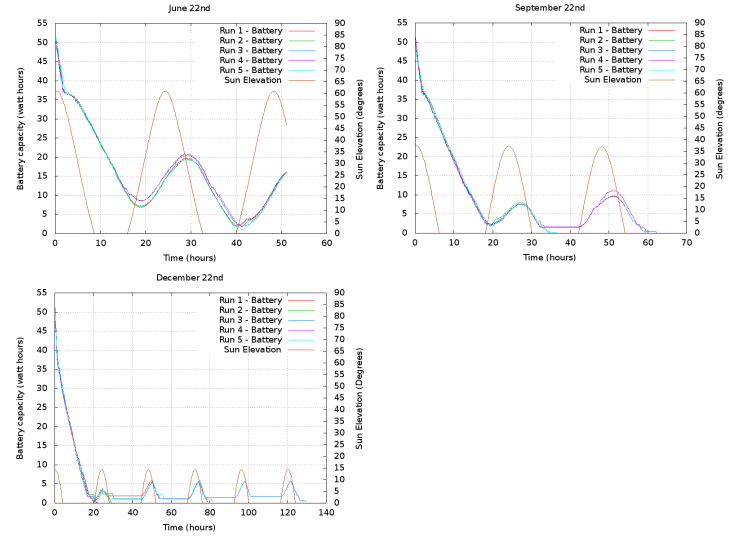

Fig. 7. Graphs showing battery level and sun elevation against time in June, September and December. The only hormonal feedback is against the battery level.
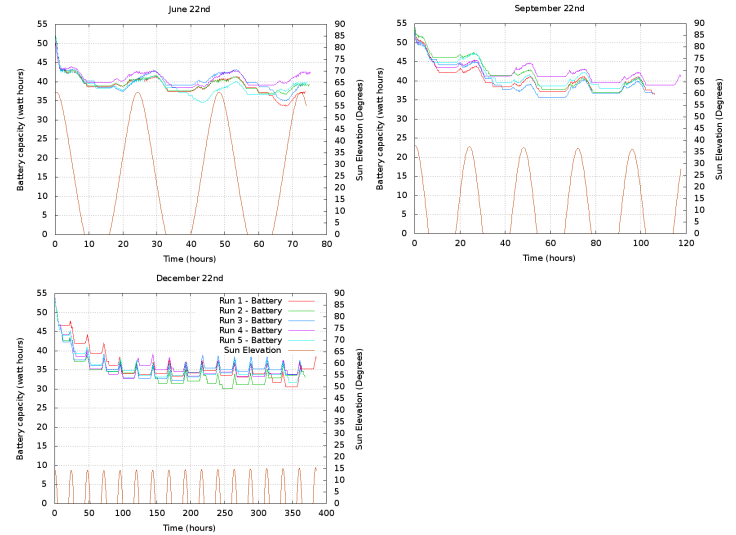

Fig. 8. Graphs showing battery level and sun elevation against time in June, September and December. A second hormone modulates behaviour against the available level of sunlight.

applied to this new hormone and the sensitivity of the battery hormone from the previous experiment was kept at 0.75.

Results can be seen in figure 8. In all cases the average battery level is kept much higher and the course is completed. However, the problem of total suppression of the control system at night is still occurring, this would suggest that the sensitivity to the solar hormone is far too high. On reflection, using a sensitivity of 0.75 for both the battery and the solar hormones is far too high, as when it is both dark and the battery is low the level of suppression will be doubled. This is vastly more than is needed to completely suppress all actuator movements. Based on the results in section III-A and III-B a sensitivity value of 0.5 or less might be appropriate.

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

This work has demonstrated the basic feasibility of an artificial neuro-endocrine controller to improve the power management of sailing robots. It shows that behaviour can be modified in a sensible manner to reduce power consumption, but that this does come at the expense of accuracy. This creates a fine grained method by which power consumption can be regulated to maintain a form of artificial homeostasis with respect to battery level, which enable us to achieve the goal of energy autonomy and thus greater general autonomy for robots operating long term without human contact. By coupling a hormone to the available levels of sun light a robot can also regulate its behaviour in accordance with the availability (both present and future) of solar power.

B. Future Work

This paper represents work which is very much still in progress. Future work will focus on running all experiments on actual robots instead of simulations, however this is no small task in comparison to running simulations. Simulations don't frequently break down, they don't require suitable weather and can be heavily parallelised at minimal expense. More effort needs to be applied to reading actual power usage and battery levels instead of estimating them as over time the difference between estimates and reality are likely to diverge.

More work still needs to be undertaken to combine multiple behaviours and to study more complex interactions between them. The hormone cascade offers many useful properties which have not yet been exploited. Another idea to be exploited is that of a stress response, which many hormones (e.g. cortisol) play a key part in. An artificial hormone could be produced in response to failing components in a robot which would trigger alternative actions to be taken to avoid that actuator. We have unsuccessfully attempted [10] this with a redundant controller for a stepper motor. Using a hormone produced in proportion to the temperature of the power transistors which enabled the control system to decide on an appropriate duty cycle for each controller. However, stepper motors proved to be a poor engineering choice and a series of electrical faults destroyed the circuit before any conclusive results could be obtained.

The small robots used here have provided a cheap, easy to use and flexible platform but are still limited by their batteries to a few hours of operation at a time. It is hoped that these experiments can be repeated on our larger sailing robot, BeagleB. This has a 3.5m long hull, 30W (peak) of photovoltaic solar panels and enough battery to last at least 7 days without any sunlight. However, it requires a large body of water to sail on, at least 2 people with a chase boat to launch and recover it and due to its size it needs to kept away from manned vessels as it has the potential to damage them.

There is no reason that neuro-endocrine controllers need to be limited to sailing robots (although their energy autonomy helps) and could potentially be applied to unmanned aerial vehicles, autonomous under water vehicles or even wheeled robots. They also do not need to be limited to robotics with other resource management problems such as operating systems, data centre management or smart grids all being obvious potential areas for the application of this technology. Current plans include the application of a neuro-endocrine controller to a fuel cell powered unmanned aerial vehicle.

V. ACKNOWLEDGMENTS

REFERENCES

[1] R. C. Arkin, "Homeostatic control for a mobile robot: Dynamic replanning in hazardous environments," *Journal of Robotic Systems*, vol. 9, pp. 197–214, 1992.

[2] R. Bruder, A. Schlaefer, and B. Stender, "Model sailboats as a testbed for artificial intelligence methods," in *In Proceedings of the 2nd International Robotic Sailing Conference*, July 2009, pp. 37–42.

[3] L. de Castro and F. J. V. Zuben, "Learning and optimization using the clonal selection principle," *IEEE Transactions on Evolutionary Computation, Special Issue on Artificial Immune Systems*, vol. 6, no. 3, pp. 239–251, 2002.

[4] G. Elkaim and C. O. Boyce, "An energy scavenging autonomous surface vehicle for littoral surveillance," in *In proceedings of ION Global Navigation Satellite Systems Conference*, 2008.

[5] S. Forrest, A. Perelson, L. Allen, and R. Cherukuri, "Self-nonself discrimination in a computer," in *Proceedings of the 1994 IEEE symposium on Research in Security and Privacy*, 1994.

[6] L. Giger, S. Wismer, S. Boehl, H. E. G. Busser, and J. Weber, P. Moser, P. Schwizer, and R. S. C. Pradalier, "Design and construction of the autonomous sailing vessel avalon," in *In proceedings of the 2nd International Robotic Sailing Conference, July 10th 2009, Matosinhos, Portugal*, 2009, pp. 17–22.

[7] M. Minsky and S. Papert, *Perceptrons*, 2nd ed. Cambridge, MA, USA: MIT Press, 1989, no. ISBN 0-262-63111-3.

[8] M. Neal and J. Timmis, "Timidity: A useful emotional mechanism for robot control?" *Informatica*, vol. 27, pp. 197–204, 2003.

[9] F. Rosenblatt, "The perceptron: A probabilistic model of information sotrage and organisation in the brain." *Pyschological Review*, vol. 65, pp. 386–408, 1958.

[10] C. Sauze and M. Neal, "A biologically inspired approach to long term autonomy and survival in sailing robots," in *in proceedings of the International Robotic Sailing Conference, May 23rd-24th 2008, Breitenbrunn, Austria*, 2008, pp. 6–11.

[11] C. Sauzé and M. J. Neal, "Design considerations for sailing robots performing long term autonomous oceanography," in *in proceedings of the International Robotic Sailing Conference, May 23rd-24th 2008, Breitenbrunn, Austria*, 2008, pp. 21–29.

[12] R. Stelzer, H. Klinck, K. Jafarmadar, and D. Mellinger, "Aas endurance: An autonomous acoustic sailboat for marine mammal research," in *In proceedings of the 2nd International Robotic Sailing Conference, July 10th 2009, Matosinhos, Portugal*, 2009, pp. 43–48. [Online]. Available: http://epic.awi.de/Publications/Kli2009a.pdf

[13] J. Timmis, M. Neal, and J. Hunt, "An artificial immune system for data analysis," *Biosystems*, vol. 55, no. 1-3, pp. 143 – 150, 2000.