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A Biologically Inspired Approach to Long Term Autonomy and Survival in Sailing Robots

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Abstract

Biologically inspired approaches have long been touted as a possible mechanism to improve the survival of robots operating autonomously in harsh environments. One method which has often been suggested is to mimic the endocrine system which is responsible for the modulation of a series of behaviours. The endocrine system contributes to the process of homeostasis which maintains a stable state within the body in the face of a changing external environment. An artificial endocrine system could be deployed to modulate the frequency of actuator use or sensor sampling. This could improve power management and task allocation within a sailing robot, helping it to maintain a steady state and continue operating autonomously for longer periods of time. This paper outlines the method for a simple test of this technique involving feedback of actuator temperature and a simple circadian rhythm on a small sailing robot.

1. Introduction

It is highly desirable that autonomous robots operating away from human contact for extended periods of time are able to adapt to changes in their environment. Such changes may include variations to both the external environment in which the robot is operating and the internal environment of the robot. Common examples of external changes might be a change of weather or season, moving to a new environment with different topography or even the interaction with other robots. Examples of the internal changes would include damage to the robot, available power levels, overheating actuators or even a change in the priorities of the robot's mission. One possible approach is to borrow ideas from biology, given that biological systems are able to maintain a stable internal state in the face of massively fluctuating external conditions (a process known as homeostasis). A vast amount of research has already been conducted on techniques which exploit biological ideas to enhance the survivability and efficiency of robots, however there are at present no examples of this being tested beyond laboratory conditions. This work will outline an attempt to deploy these techniques on an autonomous sailing robot intended to perform missions lasting several months.

2. Biological Inspiration

In mammals three systems are particularly key to maintaining homeostasis, these are the neural, endocrine and immune systems. The neural system connects to the rest of the body via a series of point to point links known as nerves which connect the brain to each point, these carry high speed electrical signals and are responsible for a number of short term actions such as muscle movements. The endocrine system is able to modulate a variety of behaviours throughout the body with chemical messengers known as hormones. Hormones are produced by a series of glands and secreted into the bloodstream in response to certain triggers, these can either be as a result of neural, endocrine or immune activities. Hormones secreted into the blood reach virtually all cells in the body and will upon reaching a cell bind with it, if it features a correctly shaped receptor. Upon binding the hormone will either suppress or promote a particular behaviour of that cell. The immune system is responsible for removing foreign infections from the body, it can broadly be split into two parts the innate immune system and the acquired immune system. The innate immune system is present from birth and provides a first line response to infection, the acquired immune system is built up as a form of memory which remembers how previous infections were dealt with so that the process can be performed again when needed.

These three systems do not act in isolation, rather they act more as if they are a single system which contributes towards the maintenance of homeostasis. There is a high degree of coupling between them, with each handling a different timescale. The neural system works on the smallest time scale of between a few milliseconds and a few seconds, the endocrine system operates on a scale of between a few seconds and several months and the immune system on a scale of between minutes and decades. At present biologists understanding of the neural and endocrine systems is far better than their understanding of the immune system, given this, the time frame of the immune system and the computational complexity of artificial immune system algorithms its role will not be covered by this work.

3. Previous Work

3.1 Long term autonomy in robotics

The majority of robots in operation today operate within close proximity to a human operator and for relatively short periods of time. There are few examples of real autonomous robots operating over long periods of time, currently those that do exist fall mostly into two categories, autonomous underwater vehicles and space robots. There are several examples of autonomous underwater vehicles such as ARGO floats and underwater gliders which gather ocean data autonomously over periods of several months while communicating with their operators only every few days. Space robots such as NASA's Spirit and Opportunity Mars Exploration Rovers or the long distance probes such as Cassini and Galileo operate at a considerable distance from their operators but tend to maintain regular contact with them. They display only a limited degree of autonomy, this is in part a reflection of the vast amount of time it takes to construct a space vehicle and how rapidly technology advances during this process and how conservative space roboticists are in their use of autonomy given their fear that an autonomous system will undertake incorrect decisions. As a result space robots tend to be at least partially teleoperated or when radio latency is too high, carrying out batches of previously stored instructions. None of these robots and at present virtually no operating robots make any serious attempt to make any decisions regarding their own survival, maintaining a stable state or even more than a basic attempt at power management.

3.2 Biologically inspired control systems

3.2.1 Artificial Neural Networks

Since 1940s a variety of algorithms inspired by the principles of the neural system have been devised. This began with the work of McCulloch and Pitts (McCulloch and Pitts, 1943), Hebb (Hebb, 1949) and Rosenblatt (Rosenblatt, 1958) during the 1940s and 50s. Between them they defined the basic principle of an artificial neuron (with Rosenblatt coining the term Perceptron to describe them) which contains a series of weighted inputs and a single output. Each input value (usually between 0 and 1) is multiplied by its weight, the sum of all weighted inputs is then taken and passed to an activation function which decides upon the output. The simplest activation function is simply a threshold above which the output is defined as 1 and below which it is defined as 0, more complex activation functions such as the sigmoid function can output values between 0 and 1. Later work involved placing perceptrons into three or more layers known as multi-layer perceptrons, these are able to solve quite complex pattern recognition problems and have been applied to many problems including collision avoidance and course holding systems in robots.

3.2.2 Endocrine and Behaviour Modulation Mechanisms

Despite the lack of real robots making decisions involving their survival there has been a considerable amount of work developing potential techniques. Most of this work has been biologically inspired most likely due to the goal of mimicking the way biological systems are capable of adapting to their environments. The earliest example of such work dates from William Ashby back in the 1950s (Ashby, 1960) and his book "Design for a Brain" in which he details experiments involving an analogue computer which exhibited homeostatic properties able to return a system to a steady state when an external stimulus disrupted them. Later work with digital computers was first demonstrated by Ronald Arkin in the 1990s (Arkin, 1992, Arkin, 1993), he introduced the idea of artificial hormones which act to modulate the behaviour of other systems. In his case he modulated a route planning behaviour in response to available energy levels, as the energy levels dropped the system would leave less margin for error between obstacles and the planned path. A few years later the idea was again adopted by Canamero (Caamero, 1997), Gadanho and Hallam (Gadanho and Hallam, 1998) in their work on emotional robotics. They linked emotions of the robot such as fear, happiness and boredom to motivations such as hunger, cold, danger and curiosity through a hormone inspired system. Each motivation would trigger the production of a certain hormone and the hormone with the highest concentration would dictate the behaviour of the robot at that time. This in turn would trigger corrective actions, for example finding food if hungry, which in turn would reduce the hormone concentration responsible for the current state eventually triggering a change in behaviour. A further variation of this idea was developed by Neal and Timmis (Neal and Timmis, 2003) and later Mendao (Mendao, 2007) who created an artificial endocrine system which produced hormones in response to certain stimuli, these hormones then modulated the behaviour of artificial neural networks (which were tasked with performing obstacle seeking and avoidance) by varying the weights of the network, as illustrated in Figure 1. They defined the idea of an artificial gland which produced a given hormone. Each gland produced hormone at a specified rate according to the formula:

$$g_l = \sum_k y_k . r \qquad (1)$$

and where g is the rate at which hormones are released, y is the input stimulus and r is the rate at which the hormone is produced. This model known as the "Leaky Gland" would create free hormone immediately available for use. This allowed for behaviours to be gradually suppressed or promoted as Mendao demonstrated by gradually switching between seeking black and white objects, this was in stark contrast to Canamero or Gadanho and Hallam's "winner takes all" approach. Mendao also found that his artificial endocrine system would often loose momentum and stabilise upon a stagnant state in which virtually no behavioural changes took place. His experiment involved two hormones following sine waves which switched behaviour between seeking white and seeking black objects, this highly symmetrical environment tended towards a convergence of seeking both. He identified three factors causing this: the symmetrical nature of the environment, the lack of a topology through which hormones travel and the lack of pools in which hormones build up before they are secreted. He decided to implement a system of pools that would store hormones before they were released. In this model hormones are produced when a certain stimulus occurs, but stored in the pool until a threshold value is reached, upon reaching this threshold the pool is emptied and becomes "free running hormone" and it will begin to trigger behavioural changes, this level then decays at a linear rate. He decided not to implement the idea of an artificial topology given the great complexity involved. The choice of a linear decay rate is somewhat arbitrary with little basis from biology, however in biology hormones concentrations decay as hormones bind to receptors, but without an artificial topology there is no natural decay therefore some mechanism had to be chosen.

Many hormones within the endocrine are associated with the body's own circadian rhythm, a form of biological clock. As a result our body's gradually modify their behaviour depending on what time of day they think it is, common effects of this include a slowing of the metabolic rate at night as less energy is exerted and no food is consumed for several hours while we sleep. It would seem sensible for a robot operating on its own for long periods of time to have some notion of sleeping, this would be particularly important in a solar powered robot as it is dependant on solar energy to perform its task and for its survival. Several people have already experimented with this idea including Mirolli and Parisi (Mirolli and Parisi, 2003) who added a light sensor to a robot in order to allow the robot to determine what time of day it was and then went onto to simulate a form of biological clock for the robot. Rocks and Barnes (Rocks and Barnes, 2004) took a similar approach in attempting to produce a circadian rhythm for a Mars Exploration Rover, their robot was able to take stimulus from external sources to run an internal circadian rhythm. This rhythm dictated which tasks would be executed and when they would be executed. They also allowed for this rhythm to be re-entrained by external sources so that the rover could be landed at (or later moved to) any part of the planet and re-adapt to any timezone.

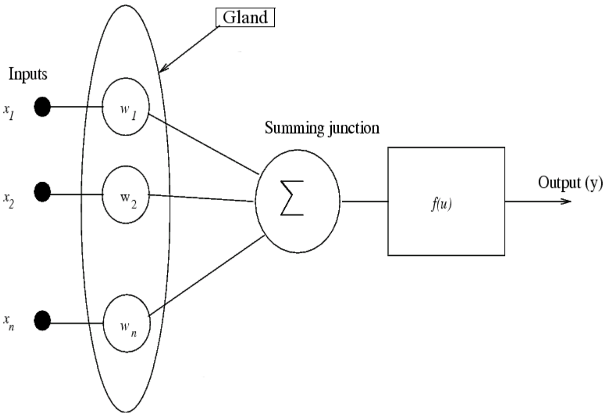

Figure 1: An endocrine modulated perceptron, as described by Neal and Timmis (Neal and Timmis, 2003). Hormones produced by the gland affect the weights of each input to the perceptron.

3.3 Alternative Approaches

Despite the vast body of work involving biologically inspired techniques as described in the previous section there is an alternative school of thought which says that robots should simply be robustly engineered. This approach is actually very popular amongst the few examples of real long term autonomous robotic missions. Few biologically inspired techniques are to be found amongst the current generation of autonomous underwater vehicles (AUVs), autonomous maritime vehicles (AMVs) or space robotics. This is usually a reflection of the engineers of these vehicles attempting to take the simplest possible designs for software and instead focusing on robust hardware and control systems. There is also a fear amongst many operators of autonomous vehicles (or those funding them) that biologically inspired control systems are unpredictable and could endanger their robot. These fears are not completely unfounded and a biologically inspired control system could very well reduce the ability to predict what course of action a robot will take and in many cases may not even leave sufficient evidence of why it performed a certain action. However the authors believe that biologically inspired techniques can enhance a robot's ability to deal with unknown and unforeseen problems, enhance the autonomy of a robot and ultimately allow for longer missions with less operator intervention. This does not mean that basic engineering issues can be ignored and a robust construction is still required, however the possibility exists that a more intelligent robot could "outwit" its less intelligent counterparts to avoid troublesome situations and therefore could be constructed in a less robust (and cheaper!) manner.

4. Design for a system

The authors envisage a sailing robot who's control system is based around neuro-endocrine controller that is responsible for keeping the robot in an operable state for as long as possible. The robot will be intended to perform ocean monitoring at either a single fixed location or a series of locations. It will contain on-board sensing systems to record its oceanographic data and a long distance communications system to transmit its findings and receive new instructions. Power will be provided by photovoltaic solar panels and internal batteries. The robot will be controlled by as few as two actuators (perhaps more for redundancy), one controlling the rudder and the other controlling the sail.

The robot will be able to sense its current battery state, its solar panel state, the temperature of its actuators and their associated controllers and it will be aware of its current position and the current time via GPS. It will be able to vary the frequency of actuator movement, satellite communications and sensor sampling, it will also be able to choose between continuing its mission, temporarily halting the mission and even returning home.

A neural network will be responsible for positioning the sail with respect to the wind direction and the rudder with respect to the current and desired headings. An artificial endocrine system will modulate behaviours, controlling the weights of the neural networks thus affecting the frequency of actuator movements. It will also control the frequency of sensor sampling and balance between the overall goal of performing the mission and preserving the robot.

4.1 Artificial Endocrine System

Several artificial hormones will be available to the system, these are stimulated by available energy levels, sunlight levels, actuator temperature and signs of danger to the robot. They will act as modulators to the neural networks and will vary the frequency and magnitude of actuator movements, they will also modulate the frequency of other systems such as the communications and navigation system. Details of each of these hormones are shown below.

1. Energy Level Hormone: Equivalent of insulin, released when electricity is available for use, for example when batteries are well charged and solar panels are active. Presence of this will increase the weights within the neural networks which control the actuators, increasing the level of actuator activity.

2. Actuator Thermoregulation Hormone: Regulates actuator and actuator controller temperatures through feedback from temperature sensors. Where redundant actuators or controllers exist there will be a hormone for each allowing gradual switching between them.

3. Danger Hormone: Equivalent of adrenaline, released when the robot is considered to be in danger, raising the weights within the steering and sailing neural networks causing them to react more dramatically. In biology adrenaline is often associated with the "fight of flee" response, in robotics this may translate to suppressing scientific data gathering and other behaviours which are not related to the immediate survival and promoting behaviours relating to avoiding danger and reaching safety. This hormone would typically be released in response to sensing dangerous conditions such as large waves, poor weather or in response to component failures.

4. Day/Night Hormone: Creates a circadian rhythm for the robot, releasing more of the hormone in the daytime. This can either be triggered through the presence of daylight or calculated from the time of year, location and time of day. Certain behaviours can be activated by this hormone depending on the time of day. A phase shifted version could also predict the amount of available solar energy later in the day, helping to schedule tasks around what will be available rather than the current availability.

5. Mission Hormone: This hormone creates a desire for the robot to perform its scientific mission and may override the requirements to save power. Ideally the

Figure 2: The ARC sailing robot.

robot operator would have some ability to configure which would have highest priority, performing the mission or preserving the robot. This decision would ultimately depend upon the operator's need to obtain data quickly and at an increased risk to the robot or whether they wished to extend the robot's lifetime in exchange for occasionally loosing data.

5. Experiment Design

A simple experiment was devised to attempt to demonstrate some of the basic concepts of an endocrine inspired controller operating in a real world scenario. For this experiment a small sailing robot known as ARC (Sauze and Neal, 2006) (shown in figure 2) was used, it is controlled through two sail actuators and one rudder actuator. These are all unipolar stepper motors and each driven by a motor controller (show in figure 3) consisting of a set of four power transistors, these are all connected to a common heatsink which in turn is connected to a temperature sensor. There are three controllers in total and each can control two motors. This configuration allows for the complete failure of one motor controller and also allows for control of a given motor to be switched to a different controller should the power transistors overheat.

For simplicity the experiment will focus only on a single actuator although the process could easily be scaled to control all three. A gland will produce hormone in response to stimulation from heat generated by one of the two motor controllers, the greater the hormone level the less the given controller is used. The glands will produce free running hormone directly and follow equation 1 to determine hormone production. The selection of which controller to use is based upon the difference between these two hormone concentrations. Additionally the greater the concentration of the hormone the less frequently an actuator will be allowed to move. This design should serve to keep the power transistors cool by flipping to the alternate set and when both overheat it will begin to reduce the frequency at which actuator is allowed to move.

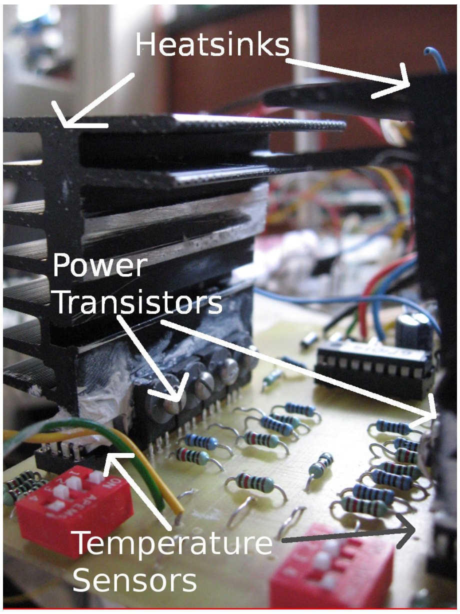

Figure 3: The ARC stepper motor controller, each set of power transistors is connected to its own heatsink.

A third hormone will represent a phase shifted circadian rhythm following the formula (note that the cosine function is assumed to be in degrees not radians):

$$y = -1 * cos((t * 15) + 15) \tag{2}$$

where y is the amount of available sunlight in one hour and t is the current time of day in hours (so 6:30am would be 6.5). The +15 term will phase shift the waveform by one hour so that the output of the formula represents the sun's elevation in one hour. This formula assumes day and night to be of equal length, in reality a more complex version of this formula which takes latitude, local solar time and season into account is required. It is perceived that this will give a clearer indication of available solar power when determining which events to schedule rather than the current level, for example if it is one hour before sunrise and the robot's batteries are running low then it might decide to start powering down systems, however as the sun will be rising soon after and begin to provide solar power this is unlikely to be a wise move. By producing a one hour phase shift this issue is avoided as is the chance that the robot will begin critical tasks shortly before sunset if the batteries are low but the solar panels are still providing a reasonable amount of power.

Another process will constantly attempt to move the actuator, although this scenario is somewhat unrealistic in a real world setting it is intended to speed up a process

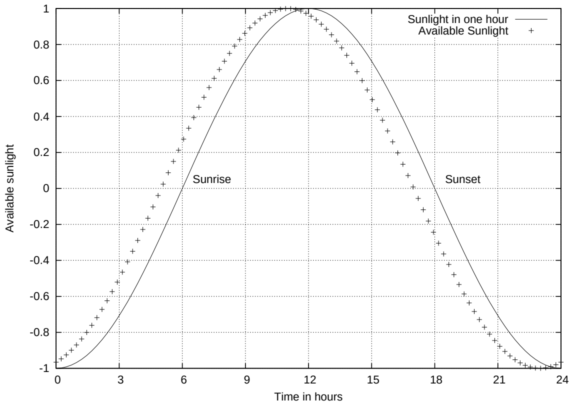

Figure 4: A graph of the circadian rhythm function shown in equation 2.

of overheating the motor controller. As the heatsinks heat up the frequency of actuator movement will drop and the temperature of the two heatsinks (or at least the temperature sensors) should remain approximately equal. In future this process will be replaced with an artificial neural network which is tasked with keeping sails correctly set or keeping the robot on course. This aspect was dropped from this experiment for simplicity and to speed up the process of overheating the power transistors.

One concept not explored by this experiment is the use of pools as described by Mendao(Mendao, 2007). Mendao suggested that without pools his algorithm tended to stagnate and converge upon a stable state in which it did not jump between behaviours and in part blamed this on the symmetry of his experiment. In this case there is symmetry between the selection of motor controller but a convergence to a situation where each is used approximately 50% of the time is desirable and the time based hormone will ensure that the entire system does show variation over time. Another design decision which needs to be taken is to decide how sensitive the system should be to each hormone, it could be that either the temperature or time hormone could be allowed to completely stop any actuator movements when they reach sufficient levels.

6. Results

Unfortunately due to a hardware fault no results have been gathered at this point. This has been due to a short circuit between the power transistors and heatsink caused by insufficient insulation, this has destroyed several of the power transistors on both controllers rendering them unusable. This requires a relatively small amount of work to replace the transistors but there was simply not enough time before the deadline of this paper.

7. Conclusions and Future Work

This work has outlined the basic architecture of an artificial neuro-endocrine controller and proposed a simple experiment involving them. This experiment will only demonstrate a small subset of the full architecture described in section 4. Further experiments will need to be designed involving a full implementation of this architecture and long term experiments at sea. As discussed in section 2. the capabilities of the immune system have not been considered, however there are a number of artificial immune system algorithms available and integrating these as part of a longer term survival strategy may well be worth consideration. This would present some problems with regards to computational complexity and in a need to provide a rich set of state information about the robot as the immune system requires far more than the handful of variables that the current architecture presents.

References

Arkin, R. (1992). Homeostatic control for a mobile robot: Dynamic replanning in hazardous environments. *Journal of Robotic Systems*, 9:197–214.

Arkin, R. (1993). *Survivable Robotic Systems: Reactive and Homeostatic Control in Robotics and remote systems for hazardous environments*, volume 1, chapter 7, pages 135–154. Prentice Hall.

Ashby, W. R. (1960). *Design for a Brain: The Origin of Adaptive Behavior.* Springer, second edition.

Caamero, D. (1997). Modeling motivations and emotions as a basis for intelligent behavior. In *Proceedings of the First International Symposium on Autonomous Agents (Agents'97)*, pages 148–155. ACM Press.

Gadanho, S. and Hallam, J. (1998). Exploring the role of emotions in autonomous robot learning. In Ca namero, D., (Ed.), *Emotional and Intelligent: The Tangled Knot of Cognition*, pages 84–89.

Hebb, D. (1949). *The organization of behavior : a neuropsychological theory.* Wiley.

McCulloch, W. S. and Pitts, W. (1943). A logical calculus of the ideas imminent in nervous activity. *Bulletin of Mathematical Biophysics*, 5:115–133.

Mendao, M. (2007). David meets goliath: A bio-inspired architecture measured against a traditional architecture. *(pending review) IEEE SMC UK&RI Journal of Applied Cybernetics.*

Mirolli, M. and Parisi, D. (2003). *Artificial Organisms That Sleep in Advances in Artificial Life*, volume 2801/2003 of *Lecture Notes in Computer Science*, pages 377–386. Springer Berlin/Heidelberg.

Neal, M. and Timmis, J. (2003). Timidity: A useful emotional mechanism for robot control? *Informatica*, 27:197–204.

Rocks, C. and Barnes, D. (2004). Entrainment as a paradigm for modelling a planetary robot's circadian rhythm. In *Proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation*, ESTEC, Noordwijk, The Netherlands.

Rosenblatt, F. (1958). The perceptron: A probabilistic model of information sotrage and organisation in the brain. *Pyschological Review*, 65:386–408.

Sauze, C. and Neal, M. (2006). An autonomous sailing robot for ocean observation. In *proceedings of TAROS 2006*, pages 190–197.