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Imitating Metabolism: Energy Autonomy in Biologically Inspired Robots

Ioannis Ieropoulos[1]
[1]IAS Lab, CEMS Faculty
UWE, Coldharbour Lane, Frenchay, Bristol, BS16 1QY, UK
Ioannis2.Ieropoulos@uwe.ac.u

John Greenman[2]
[2]Faculty of Applied Sciences
UWE, Coldharbour Lane, Frenchay, Bristol, BS16 1QY, UK
John.Greenman@uwe.ac.uk

Chris Melhuish[1]
[1]IAS Lab, CEMS Faculty
UWE, Coldharbour Lane, Frenchay, Bristol, BS16 1QY, UK
Chris.Melhuish@uwe.ac.uk

Abstract

This paper reports on the initial work to produce an artificial metabolic system for an energetically autonomous robot using a Microbial Fuel Cell (MFC). We describe the fuel cell developed in our laboratory and demonstrate that it is feasible to provide sufficient power for a mobile robot platform to execute photo tactic 'pulsed' behaviour.

1 Introduction

The term 'autonomous robot' has been ascribed to robotic systems to indicate their ability to perform tasks without human supervision. In fact, from the ancient times, people have attempted to build machines, which could operate without direct control. For example, in 60 A.D. Heron of Alexandria built, possibly, the first recorded example of an automaton [1]. This was a self-moving cart, driven by a counter-weight that was attached to the wheeled base axles through ropes. However, the term 'autonomous' is somewhat flexible in that it covers degrees of autonomy. For example, consider the case of a robot whose batteries are charged by a human and then released to carry out its task without further external intervention. On completion of the task or in the event of the battery charge becoming critically low the robot returns to a base for recharging and/or new instructions. On one hand certain aspects of the robot's behaviour may be considered as autonomous; computational and control decisions are made without human supervision. On the other hand, without a human in the loop, the robot would not be able to replenish its energy to accomplish the task. With this in mind our long-term goal is the creation of a robot, which can generate energy for itself from its own environment. That energy could, for example, come from solar energy or even wind energy. Our interest however, is in generating energy from chemical substrate – food. We are therefore interested in a class of robot system, which demonstrates energetic autonomy by converting natural raw chemical substrate (such as carrots or apples) into power for essential elements of behaviour including motion, sensing and computation. This requires an artificial digestion system and concomitant artificial metabolism.

Adopting such a strategy may have an impact on the manner in which researchers and engineers incorporate their autonomous mission requirements. Three key issues are; firstly, useful energy will not (for the foreseeable future) be able to be instantly converted from raw substrate and secondly, there will be tasks (particularly those involving effectors or motion) which could not be powered continuously. The net effect is that this class of robot may have to include a 'waiting' behaviour in its repertoire in order to accumulate sufficient energy to carry out a task or sub-task. We refer to this form of behaviour as 'pulsed behaviour'. Thirdly, a robot may need to solve multi-goal action selection problems. In particular, it may be required to exhibit 'opportunistic' behaviour in terms of breaking off from its mission to forage or take advantage of energy resources such as a fallen apple. In nature, animals, in the wild, often exhibit such behaviours and our work is obviously biologically inspired at the metabolic and behavioural levels.

2 Microbial Fuel Cell

The idea of employing microbes to extract energy from sugars has been known for many years [2]. Raw substrate can be converted to sugars and then used in a Microbial Fuel Cell (MFC); a *bio*-electrochemical transducer that converts *bio*-chemical energy to electrical energy. The MFC, shown in Figure 1, comprises anode and cathode electrodes and a culture of live microorganisms as a biocatalyst. Metabolising bacteria produce energy (electrons), which are tapped by the mediator found in the anolyte. The reduced mediator is able to diffuse outside the microbial cell and is diverted by the electrophillic attraction of the cathode electrode to become oxidised at the anode electrode. Released electrons then flow through the external circuit, which is connected to the two electrodes, and hence an electric current is produced. Further metabolism produces more energy, which in turn produces more electrical power. These redox reactions can be described by $NAD^+ + 2H^+ + 2e^- \Leftrightarrow NADH + H^+$ where NAD^+ is the Nicotinamide Adenine Dinucleotide electron carrier coenzyme in its oxidised form.

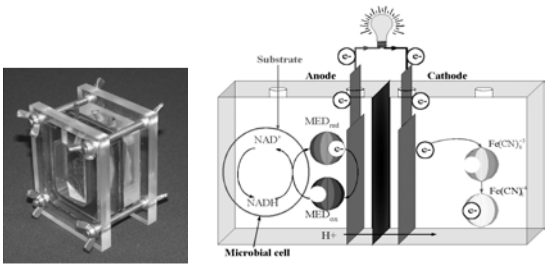

Figure 1: (left) MFC in its analytical form, (right) Redox reactions within the MFC

3 EcoBot: An MFC powered robot

Using the above-mentioned technology as the sole power source, a proof-of-concept robot was built which performs photo-tactic behaviour. It was code-named EcoBot I and it was the first robot in the world to be directly and entirely powered from bacterial reducing power and the second to be running on sugar [3]. It involved no other form of conventional power source such as secondary batteries or solar panels and furthermore it was more efficient and more compact in size than Gastronome [3], which was the first such artifact to have been constructed. Inexpensive and in most cases sub-optimal substances and materials have been exploited to the maximum of their performance to give energy outputs in the range of 37.2J and achieve efficiencies of the order of 1.56%. Even though this figure is low, it is consistent with the current MFC technology. Further experiments conducted recently in our laboratory, have shown improved performance, which matches and in some cases outperforms microbial fuel cells incorporating immobilised electrodes [4]. The MFC's currently employed are of a batch (closed system / non-continuous) nature where there is no refreshment of the nutrients and vital substances. These first results imply that the longevity of such a system could be increased by a factor of 10. In nature, all living organisms operate in a continuous mode (open system) and by adopting that technique the overall efficiency should be dramatically increased. Figure 2 below is a picture of the EcoBot I prototype fully assembled.

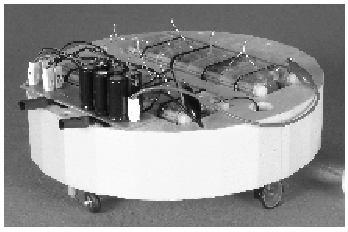

Figure 2: EcoBot I

The robot employed a bank of eight MFC's, an electronic control circuit, two photo detecting diodes and two motors. Energy produced by the MFC's was accumulated in a bank of six capacitors and on reaching a certain threshold, was released to fire the motors according to the photodiodes' indication. A differential drive was employed so that the robot would follow the light and when a second threshold was reached the robot would become 'idle' until enough energy was accumulated to fire the motors again. This gave the prototype a form of burst motion photo-tactic behaviour. The robot experiment, moving from a start point to a light source, was repeated seven times. Two of these trials were video recorded, a snapshot of one of which is shown in the picture of Figure 3, and the other five were data recorded. Figure 4 is a graph illustrating the average charge / discharge cycles, in terms of average distance and time for the five trials.

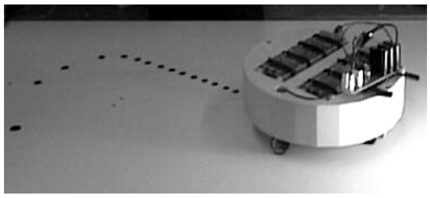

Figure 3: EcoBot I performing photo taxis. Marks behind the robot indicate the trajectory of the photo-tactic movement and the light source is on the bottom right of the figure.

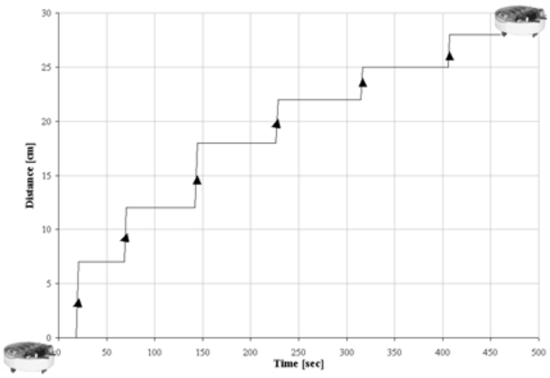

Figure 4: Average charge/discharge cycles

As was mentioned earlier, EcoBot I was only the first step of many to produce the final envisaged system and there are a number of implications that need to be considered for any further development. These can be divided into two main categories;- the hardware and the behavioural issues of the system.

In a system where continuous chemical fluid flow is employed, there will have to be a number of micro-pumps and filters to keep the system operating. Parameters such as temperature, pH and liquid level will have to be continuously monitored and controlled. As the robot will be looking for its energy source, which will be in the form of raw food and extracting the rich nutrients from it, the electronics and mechanics involved will have to be highly efficient and accurate. Of course, an important secondary effect is that the employment of such devices will have an associated energy requirement, which in turn leads to the behavioural implications.

Simple “low battery” warning indications will just not be enough. The energy accumulated may be in the form of electrical charge, however this will be derived from a bio-electrochemical device. This implies that both internal sensors to provide feedback for more accurate control and external sensors to enable the agent to perform its task will have to be used. Negative feedback will be a key element in the system since in biological systems this is the basis for normal operation. It is through feedback that homeostasis is achieved at all levels of organisation in living systems – from the molecular to the social. Homeostasis means, “staying the same” and it refers to the unique capacity of biological systems to maintain automatic control over physio-chemical variations, by means of negative feedback. Imitating this critical parameter will form a significant challenge.

4 Discussion

MFC technology is still in its infancy and the levels of power achieved are very low. It is quite clear that the power source will, for most applications, not be in a position to provide enough power for the robot to operate in a continuous mode. Therefore, the energy, as with the EcoBot I prototype, will first have to be accumulated before it is used, thus resulting in the “pulsed” behaviour. Managing a variable energy resource is not a trivial task and therefore energy reserves must be employed to account for situations where the distance between the agent and the food is greater than normal and would take more than the readily available energy to be covered.

One of the near future goals is to further improve the MFC efficiency in terms of power level and longevity. The more it is achieved in this area, the less complicated the rest of the system will be as the MFC’s will form the ‘live engine’ around which the rest of the robot will be built. Re-design and soft engineering of the MFC system is of highest priority, to increase efficiency, decrease weight and give it an appropriate design configuration, in this way imitating the gut. Gas diffusion electrodes will be tested as these have the advantage of using free oxygen from the air to act as electrolytes and take up electrons.

Real autonomy, in the context of artificial intelligence is not only a matter of executing a task with minimum or no exogenous intervention, while having to rely on the human factor for energy requirements. Natural metabolic systems solve this problem by employing redox energy to do work. We seek to imitate nature in this respect and EcoBot I demonstrates that such an approach is feasible.

In the future, such robots could be classified according to the range of food that they will be consuming. *Specivores* would be a name for such robots that may restrict themselves to one type of food or perhaps by using an ecology of microorganisms (mixed culture) they could digest most of natural food sources which would classify them as *omnivores*.

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