Artificial Metabolism: Towards True Energetic Autonomy in Artificial Life

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Abstract. This paper reports on the proof-of-concept work to produce an energetically autonomous robot employing an artificial metabolic system using Microbial Fuel Cells. The present study compared the effects of changing a number of critical parameters, which control the fuel cell system, as a means to improve its overall performance. We demonstrate that the development of a fuel cell as an artificial metabolic system is feasible and it can provide sufficient power for a mobile robot platform to execute photo tactic 'pulsed' behaviour. The robot is code-named EcoBot I and it is the first robot in the world to be directly and entirely powered from bacterial reducing power.

1 Introduction

Autonomy comes from the Greek composite word *auto*, which means self, and *nomos*, meaning to control. Therefore, the term *autonomy* refers to and self-controlled entities that can organise and guide themselves, in a stable and reliable manner.

The term 'autonomous robot' has been ascribed to robotic systems to indicate their ability to perform tasks without human supervision. In fact, attempts to build machines that would operate without direct control date back to the ancient times. Heron of Alexandria, for example, built in 60 A.D., possibly, the first recorded example of an automaton [1]. However, the term 'autonomous' is somewhat flexible depending on the context it is used in. For example, consider the case of a robot that is released to carry out its task without external intervention but its batteries need to be charged by a human prior to its release. On completion of the task or in the event of the battery charge level getting 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 autonomous such as computational and control decisions. 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. Although that energy could come from the sun or the wind, we are interested in generating energy from chemical substrates – food. We are therefore looking into a class of robot system, which demonstrates energetic autonomy by converting natural raw chemical substrate (e.g. 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. Four 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. Finally, the substrate that will be consumed, which is directly related to the type(s) of microorganism(s) employed in the system will affect the robot's behaviour. In the case where the robot is designed to consume only a specific type of food, i.e. a '*specivore*' then its behaviour will be developed according to its needs [2]. On the other hand, in the case where the robot can consume a wide range of substrates, i.e. an '*omnivore*' then it could be given a more 'opportunistic' behaviour that will serve to its best interest [2]. In nature, animals, in the wild, often exhibit such behaviours and our work is obviously biologically inspired at the metabolic and behavioural levels. We argue that Energy Autonomy is a key element in future physical realisation systems of artificial life.

2 Fuel Cells

Fuel cells are an alternative to conventional energy plants or sources since they can offer a clean and environmentally friendly way of producing energy, for almost every kind of application. A fuel cell (Figure 1) is an electrochemical transducer that converts chemical energy to electrical energy from a fuel, without direct combustion. They comprise anode and cathode electrodes, electrolytes in liquid and/or solid form and catalysts.

The fuel cell principle of operation lies in the extraction of electrons as a result of the chemical reaction of separating a fuel, using a catalyst, in the anode half-cell. A catalyst is a substance, which speeds up the rate of a chemical reaction, however it remains unchanged at the end of the reaction. This allows the release of either positively or negatively charged ions that go to the cathode half-cell through the solid electrolyte, which also forms a physical barrier between the two half-cells. Catholyte and anolyte are the liquid electrolytes in the cathode and anode compartments, respectively that are necessary for electrolysis. Electrolysis defines the passage of electric current through a molten chemical or an aqueous solution. Hence, the anolyte is necessary for the transfer of electrons from the catalyst to the electrode and the catholyte is necessary for taking up incoming electrons from the electrode. In several fuel cells, where there is sufficient oxygen supply to the cathode, electrons recombine with cations and oxygen to form water.

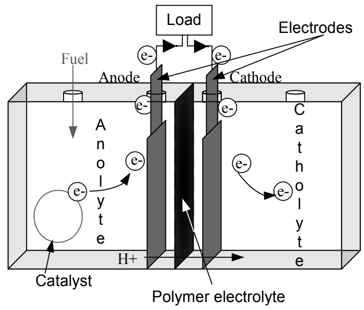

Fig.1. Schematic diagram of a general type of Fuel cell

2.1 The Microbial Fuel Cell (MFC)

Historically, MFC's date back to 1910, when Professor Michael Cresse Potter introduced the first MFC using *Escherichia coli* (*E.coli*) and platinum metal electrodes [3]. The idea of employing microorganisms to extract energy from sugars was first illustrated by Cohen at Cambridge in 1931, who revived Potter's MFC after scientists showed how enzymes in bacteria oxidise food [3].

An MFC (see Figure 2) is a *bio*-electrochemical transducer that converts *bio*-chemical energy to electrical energy, in roughly the same manner as a normal fuel cell. They fall under the Proton Exchange Membrane (PEM) fuel cell category, since that is the solid electrolyte used in the system and the fuel is *bio*catalysed by microbes. A wide range of organic substrates or nutrients of the types found in foods or food wastes can be utilised as fuel, depending on the type of microbe used.

Microorganisms metabolise the substrate, which is added to the anode half-cell, and energy (electrons) is transferred by Nicotinamide Adenine Dinucleotide (NADH) in its reduced form. This is a coenzyme, which acts as an electron carrier – a biological power source, in the metabolic pathway at the cellular level of living organisms. In its oxidised form it is symbolised as NAD^+ and as a redox couple (NAD^+/NADH) it can give electrons to almost every acceptor, since it is very negatively charged (-0.32V). For example, the difference in the standard redox potentials between the NAD^+/NADH and ½ O_2 / H_2O is actually 1.14V, and hence the change in free energy when the two interact is actually 220kJ.

The anolyte is made up of a mediator, buffer, microbial culture and sugar solution. A mediator is a substance that penetrates the microbial cell, to a certain level and extracts the electrons from the electron transfer chain. Once the mediator taps the electron, it has become reduced and the electron carrier oxidised, i.e. NAD^+. The reduced mediator diffuses outside the microbial cell and is diverted by the electrophilic attraction of the cathode electrode. As a result the electron is released onto the anode electrode to flow through the external circuit, thus oxidizing the mediator. In the meantime, NAD^+ is re-reduced to NADH by further metabolism of substrate molecules and the mediator is re-reduced by re-oxidising NADH. The buffer keeps the anolyte pH balanced as it tends to become acidic from the bacterial acid waste production. The microorganism used in our experiments is *Escherichia coli* (*E.coli* cc17 isolate culture from UWE collection) and the biochemical reaction is as follows:

$$NAD^+ + 2H^+ + 2e^- \Leftrightarrow NADH + H^+ \quad \textbf{(1)}$$

In the cathode, incoming electrons from the external circuit reduce the buffered electrolyte in order to complete the system. In the presence of dissolved oxygen, the catholyte is barely oxidised with some water (H_2O) formation. The buffer in the solution keeps the pH balanced by consuming the hydrogen cations traveling through the PEM and tending to decrease the pH. These processes in both the anode and cathode described above are known are **red**uction-**ox**idation (redox) and are schematically shown in Figure 3.

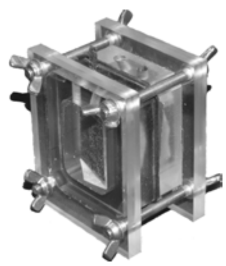

Fig. 2. Microbial Fuel Cell in its analytical form

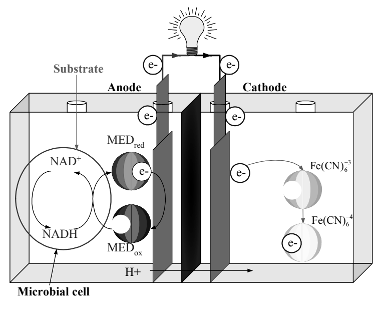

Fig. 3. Redox reactions within a Microbial Fuel Cell

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 [4]. 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 [4], 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 [5]. 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 this technique the overall efficiency should be dramatically increased. Figure 4 below is a picture of the EcoBot I prototype fully assembled.

The robot employed a bank of eight MFC's, an electronic control circuit, two photo detecting diodes and two dc geared *escap*® - 205 motors (Portescap. Switzerland). A circular piece of styrene material having a diameter of 22cm and 5cm thickness with two rectangular cuts to accommodate the MFC banks formed the main body of the robot. The overall height was 7.5cm with a total mass of 960g. The robot was balanced with the use of two caster wheels.

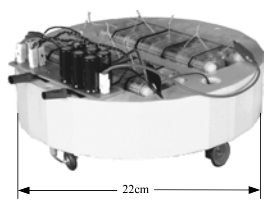

Fig. 4. UWE EcoBot I fully assembled

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 ('pulsed-behaviour'). Figure 5 below illustrates the block diagram of the robot's electronic control circuit. 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 Figure 6, and the other five were data recorded. Figure 7 illustrates the average charge/discharge cycles, in terms of average distance and time for the five trials.

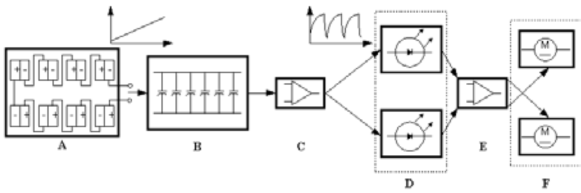

Fig. 5. Block diagram representation of the EcoBot I electronic control circuit. Block A is the MFC bank; Block B is the capacitor bank; the charge-discharge control circuit is shown as block C; block D represents the pair of photodiodes; the control circuit for differential drive is shown as block E and finally the pair of motors is shown as block F. The graph above A and B illustrates the increasing energy output from the MFCs with respect to time and the graph above C and D represents the charge-discharge cycle.

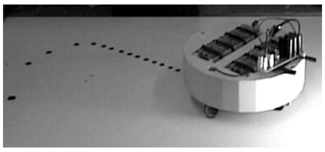

Fig. 6. EcoBot I performing photo taxis. Marks behind the robot indicate the trajectory of the photo-tactic movement and the light source is at the bottom right of the figure.

A graph of the robot's progression along a flat surface, with respect to time is shown in Figure 8. This is a graph that was produced from the recorded data of the five trials and it shows the advancements that the robot was making in burst motions. Data points show the average distance that the robot had covered for each burst motion, with the error bars indicating the maximum and minimum distance that was covered in the different trials.

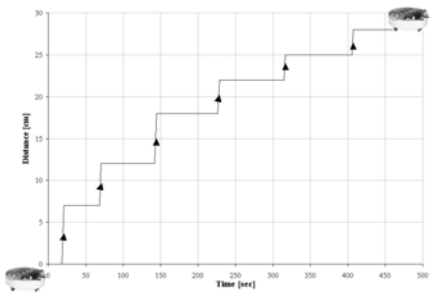

Fig. 7. Average charge/discharge cycles shown with respect to time and space

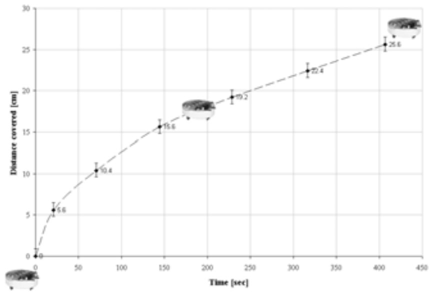

Fig. 8. Progression of EcoBot I along flat surface

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 (raw food), the electronics and mechanics involved in extracting the necessary nutrients from it will have to be highly efficient and accurate. Utilisation 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 capacity of biological systems to maintain automatic control over physio-chemical variations. 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 continuous operation. 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 energy required to execute a task is more than the readily available (onboard store).

One of the near future goals is to further improve the MFC efficiency in terms of power level and longevity, as this 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 achieve these goals and give the system 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.

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 and type of food that they will be consuming. Some robots may be designed to restrict themselves to one type of food (*specivores*) where others may exploit more than one type of food (*multivores / omnivores*). The costs and benefits of such artifacts merits further research.

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