Energetically Autonomous Robots

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Abstract. EcoBot I is a robot developed in the IAS Lab that uses Microbial Fuel Cells (MFC) as the 'live engine' and glucose as the fuel. This prototype robot employs no other form of conventional power supply and it proves the concept of autonomy whilst at the same time performing photo-taxis. Recent experiments conducted in our lab, employing two different techniques, have suggested that the power output from these devices can be increased by one or even two orders of magnitude. We classify these techniques into three generations, namely Gen-I, Gen-II and Gen-III, which display different characteristics exploitable by energetically autonomous robots. This paper reports on the work to improve the performance of the EcoBot I onboard power source.

Introduction

The term 'autonomous robot' has been ascribed to robotic systems to function without human supervision. In fact, from the ancient times, people have attempted to build systems, 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]. However, the term 'autonomy' is somewhat flexible in that it covers different 'modes of autonomy' leading to inconsistencies in its use. Two major modes are: *computational autonomy* and *energetic autonomy* [2]. Computational autonomy can be defined as the ability to determine and carry out actions, independently, which may or may not be related to the obtainment of energy [2]. Energetic autonomy refers to the ability of the agent, to maintain itself in a viable state for long periods of time. Its behaviour must be stable in order not to yield to an irrecoverable debt in any vital resource, i.e. it must not cross any of its lethal limits [2,3]. Until recently, autonomy has mostly been addressed from the perspective of computation. For example, consider the case of a battery-operated robot that is released to carry out its task without external intervention. On completion of the task or when the battery charge becomes 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 e.g. 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 development of a robot, which can generate energy for itself coming from its own environment. In this respect our definition of an autonomous agent is more akin to that of Stuart Kauffman's but without the burden of self-reproduction [4].

We are therefore interested in 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 that can be achieved through the use of Microbial Fuel Cells (MFCs).

Adopting such a strategy may have an impact on the manner in which researchers and engineers in the robotics community incorporate their 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 cannot 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 'interrupting' its mission to forage or take advantage of energy resources such as a fallen apple. We therefore envision autonomous robots capable of exhibiting homeostasis, i.e., maintaining a state(s) of internal equilibrium, which is however different from its external surroundings through the automatic control over physio-chemical variations, by means of internal feedback and external 'behavioural' mechanisms.

This paper describes three generations of MFCs developed in our lab, which are not only historically distinguished; they are also distinguished in the way they function. Gen-I MFCs require exogenous mediators such as Methylene Blue (MB) or Neutral Red (NR) that need replenishing and can be environmentally toxic. This type of MFCs refers to the initial work that has been used to power a small robot to perform photo-taxis. Gen-II MFCs are also mediator-depended only in this case the mediator is an electroactive metabolite of the microbes employed. The metabolite is produced from replenishable sulphate that is used as their end electron acceptor. Gen-III MFCs are true *mediator-less* systems since the microbes used are *anodophiles*, which means that they use the anode electrode as their end electron acceptor.

Generations II and III refer to the subsequent work to improve the system's performance by exploiting the metabolic activity of microbes that feed on different substrates (sulphate, acetate, glucose). These substrates can be considered as a 'half-way-house' and in this respect we consider the MFC as the 'live engine' in our robot. Our longer-term goal is to link the MFC to a microbial digester that produces the glucose/acetate fuel, from raw organic substrate. In this way a robot will be able to extract its energy from natural 'foodstuffs' in the environment.

1. EcoBot I – The first truly bacterial powered robot

Details of EcoBot I and its energetics have been previously reported and we refer the interested reader to previous papers [5,6,7]. As a prototype it successfully proved that MFCs could be used as onboard self-sustained power sources for autonomous agents. EcoBot I was the second robot to employ an MFC [8] but the first not to include additional power in the form of batteries – i.e. to derive its energy purely from the sugar 'fuel'.

2. Three Generations of Microbial Fuel Cells (MFCs)

2.1 MFCs

MFCs are bioelectrochemical transducers that convert biochemical energy to electrical energy. This technology began in the 19th century when scientists had demonstrated that electricity could be produced from bacteria [9]. Ever since, MFCs have been extensively investigated to understand the kinetics, thermodynamics and bio-electrochemical reactions involved. Bennetto was the first who developed the 'analytical' form of the MFC (see Fig. 1a), which is still used as the basis in MFC research [10]. Habermann and Pommer

developed an MFC using sulphate-reducing bacteria, which generated continuous power for 5 years [11]. In 1994 Caccavo *et al*. discovered a microbial species that belonged to the *Geobacter* family and they named *Geobacter sulfurreducens* [12]. It can utilise glucose and other sugars as well as acetate and has been shown to produce a considerable amount of power [13]. Recently it has been reported that *Rhodoferax ferrireducens* is an other anodophile that can produce power from sugars without the use of any mediators [14].

Our approach to energetically autonomous agents is to exploit the reducing power of such microbes as *Geobacter sulfurreducens* to provide self-sustained autonomous behaviour in robots. Extracting nutrients from chemical substrates, such as raw food or sewage sludge to be used in MFCs, offers the potential of true energetic autonomy. The robot can be given a behavioural repertoire and microbial 'ecology' to best suit the type of raw material it will utilise. Autonomous robots are likely to be employed in remote and/or inhospitable places. For example, it could be used to navigate, to monitor and take samples for experimental analysis from a dangerous toxically polluted location.

2.2 First generation (Gen-I)

Power output from these devices depends, among other factors, on the size and volume of the fuel cell as well as the surface area and material of the electrodes. The average open-circuit voltage from these devices is 0.7V and the average current density is approximately 0.15mA/cm^2. Gen-I MFCs (as do Gen-II) employ mediator molecules, which shuttle between the microbial cell and the anode electrode. They 'enter' the cell in the oxidised form and become reduced, i.e., they gain an electron. The reduced form then makes its way to the anode electrode where it releases the electron (oxidised) and continues the cycle. Mediators are chemicals, which have to be manually prepared and added to the fuel cell, as the bacteria in the case of Gen-I MFCs cannot produce these. There is also a point in time, normally after 3-4 weeks in a batch (closed) system, when these mediators degrade and have to be replenished. The interception between the mediator molecule and the electron occurs either at NADH, which is short for Nicotinamide Adenine Dinucleotide, or at a lower stage i.e. cytochrome *c*. NADH (reduced form) is an electron carrier, in the bacterium's catabolic cycle and acts as a biological power source. Direct contact between bacterium cells and electrode surface is also of great importance since the shorter the distance between the two the less the ohmic resistance for electron transfer. A wide range of mediators have been tested by many researchers in the world on which some MFCs heavily depend, even though direct electron transfer without the use of mediators has been previously reported [15]. The performance of those MFCs was, however, generally inferior to all other mediator MFCs found in literature.

2.3 Second generation (Gen-II)

In Gen-II MFCs the mediator (sulphide - H_2S) is produced by the reduction of sulphate (SO_4) by the microorganism. This results in a completely different and far more efficient chemical mechanism even though SO_4 still needs to be replenished. The basic principle of operation is more or less the same as with Gen-I, except that in this case the mediator is an electroactive metabolite of the microorganisms. This means that this is a more favourable system to be integrated with an autonomous agent, since there is no need for manual replacement of any chemical, apart from the energy source which could be a rich in SO_4 substrate, the finding and consumption of which will form part of the robot's behaviour.

For many years a number of microorganisms have been known for their sulphate reducing abilities. One such microorganism is *Desulfovibrio desulfuricans*, a marine

anaerobe. This was actually the microbe used in the fuel cells of Habermann and Pommer, in combination with a number of other microbes [10]. *D. desulfuricans* has the ability to use sulphate as its end terminal acceptor and in doing so reduce sulphate to sulphide (H_2S). H_2S is electroactive, which means it gives off its electrons to the oxidant with the most positive redox potential. In the absence of oxygen, the next most positive oxidant is the anode electrode. Hence the sulphide offers the mediating means for the electrons to flow and is cycled between the bacterium cell and the electrode surface. The redox reactions taking place within the Gen-II MFC are shown in Figure 1 (b) below.

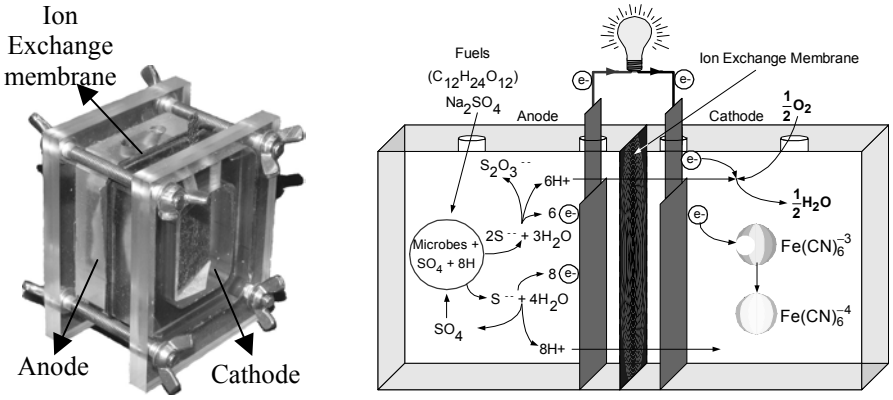


Figure 1. (a) MFC fully assembled and (b) redox reactions within the sulphide producing MFC

In their work, Habermann and Pommer employed a mixed culture of microbes for a more efficient operation. *D. desulfuricans*, which is the dominant bacterium of the microbial consortium is strictly anaerobic that needs lactate to metabolise and produce sulphide. Therefore, lactate (lactic acid) producing microorganisms such as *E. coli* and *Proteus vulgaris* were added in the anolyte to produce the chemical metabolite that is necessary for *D. desulfuricans* to survive and to consume any oxygen (O_2) molecules. With these microbes in the same compartment, there would definitely be a built-up of waste products and in particular of acetate. *Pseudomonas aeruginosa* and *P. fluorescens* efficiently utilise acetate and were added in the consortium for the utilisation of this waste product and of O_2. In this way, the only major by-products from such a fuel cell are CO_2, H_2O and Thiosulphate (S_2O_3) (Fig. 1b), which can also be reduced to sulphide.

2.4 Third generation (Gen-III)

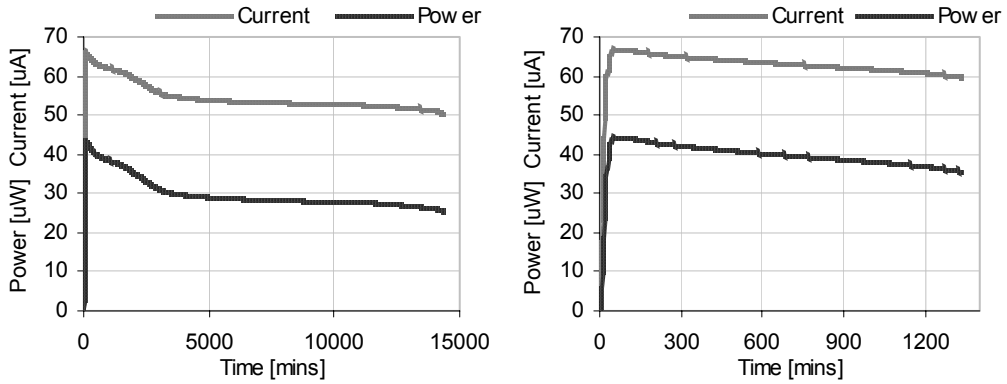
Third generation (Gen-III) MFCs employ the anaerobic microbe *Geobacter sulfurreducens* that readily gives off its electrons to the electrode surface [11]. These microorganisms have the ability to attach themselves onto the electrode surface forming a monolayer (single layer biofilm). All the other cells in the vicinity will not attach until they find an oxidising surface. Once the monolayer is formed, the electrode then becomes their natural oxidant to which the microbes readily release electrons. Importantly, this system works without the use of artificial or natural mediators. It requires no replenishment of mediator or its 'synthesis' by the microbe thus making this form of MFC attractive to autonomous applications. Furthermore Gen-III MFCs have two other significant advantages. Firstly, the direct physical and biochemical contact between the microbes and the electrode surface when the single layer biofilm is formed means that the ohmic resistance of the electron flow is minimum, hence the efficiency is increased. Secondly, this bacterium can utilise metabolic waste such as acetate produced by other microorganisms e.g. the mixed culture of the Gen-II sulphide producing MFC. This suggests two things:

either the two generations can be combined as one MFC provided that all species can survive together, or that the waste from one level of Gen-II MFCs can be directly fed to another level of Gen-III MFCs in the multi-level system of the autonomous robot.

3. Methods and Results

3.1 The First Generation MFCs

The MFC shown in Figure 1 was used in all experiments and Gen-I was used as the control for all subsequent experiments. Sterile solutions were added aseptically prior to *E. coli* inoculation, which were left to grow for ~24hrs at 37°C. The bacteria were fed once at the beginning of the experiment and the load was connected continuously until the end. Hence the recorded voltage from which the current and power were calculated was a continuous function of time that indicated the bacterial reducing power. The load was a 10kΩ resistor that was connected between the anode and cathode electrodes in parallel with the data capture equipment. Figure 2 (b) below shows the current and power output from a single 50mL MFC for 1 day. Based on these data, the EcoBot I was constructed and tested.



(a) (b)

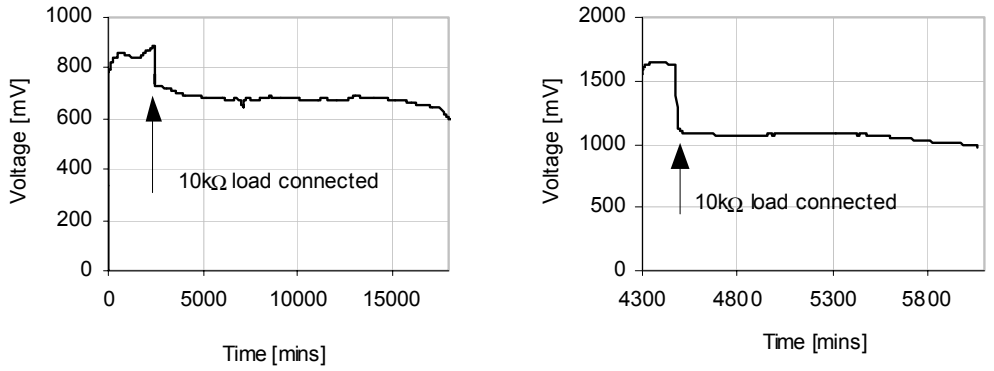
Figure 2. Current (I) and Power (P) output vs. time for the analytical MFC (a) with and (b) without NaCl and amino acids added to the anode.

Following these experiments and the robot runs, our efforts focussed on improving the MFC efficiency. Figure 2 (a) illustrates this improvement, not so much in terms of power output but in terms of longevity. The same power output was produced but for a duration of 10 days. In this case, NaCl was added in the anolyte to enhance conductivity and also to minimise differences in the osmotic pressure between the two half-cells. Furthermore, for pH stability, an amino acid (glutamine) was added and also the substrate concentration was reduced. The latter is of great importance since it is imperative for the microorganisms to be given exactly the quantity of substrate they require and not anything in excess. Experiments have indicated that excess substrate can have inhibitory effects (results not shown).

3.2 The second Generation MFCs

This section reports on the work that has been carried out to develop the sulphide MFC and the methods followed to improve its performance. One of the most important properties of this generation of fuel cells is the ability to store energy in chemical form. Even when no

power is drawn from the MFC (open circuit), sulphide (H_2S) is still being produced and stored at the electrode surface. H_2S also reacts with the clay and slate particles found in the anode, and at high pH it is entrapped by the molecules of the two materials. Hence, when a load is connected and power is being drawn, the voltage drop is relatively small. The use of clay and slate was previously suggested mainly for two reasons [10]. Garden clay and slate have excellent buffering characteristics, which make them ideal for pH control. Furthermore, within the MFC confinement, the two materials can simulate ocean or river sediment conditions, which are the natural habitat of the microbe. One reason for this is that the clay and slate particles settle on the bottom of the anode compartment thus forming a 'sediment', which is a barrier to oxygen.



(a) (b)

Figure 3. Voltage output and loading response from (a) a single 50mL volume sulphide MFC and (b) a 12-stack mediator MFC

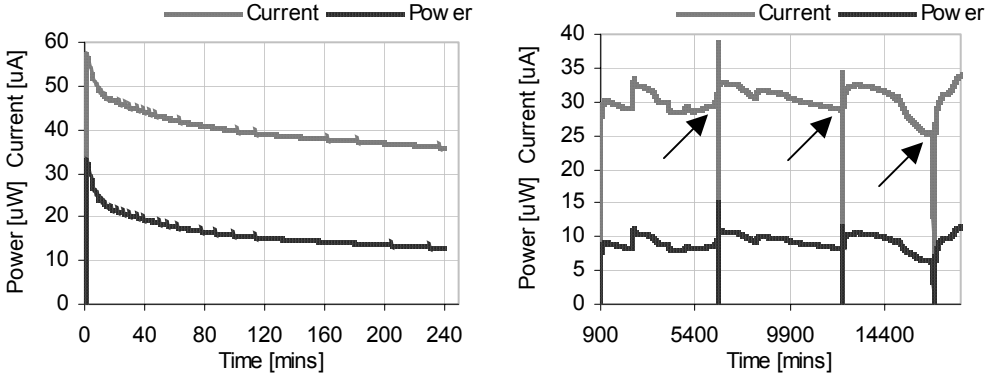
Figure 3 (a) shows the voltage output from a single analytical sulphide MFC. Initially and for ~36hrs the fuel cell was left open circuit (no load). At the point indicated by the arrow a 10kΩ resistive load was connected. The longevity was greater than that of Figure 2 (a), i.e. the experiment lasted for two weeks and only after the 12th day the output level started decaying. Under maximum power transfer (MPT) conditions the voltage should drop to 50% or less as this was the case with previous fuel cell experiments. However the loaded voltage (V_L) dropped by 21%, which is consistent with the original idea that the fuel cell acts as a chemical energy accumulator and could therefore be tolerant to even 'heavier' loads for short periods.

The graph in Figure 3 (b) is from the Gen-I experiments in which 12 MFCs were connected in a series/parallel configuration employing *E. coli* and NR as the mediator. There were four groups of three fuel cells connected in series, which were then connected in parallel. Theoretically, the voltage should be triple and the current should be quadruple that of a single fuel cell and the voltage drop when a 10kΩ load is connected should not be that dramatic. However, the voltage dropped by 36% to 64% of the open circuit voltage, and after 4 days the level dropped below 50%. Results in Figure 4 indicate that a single Gen-II MFC is superior to 12 Gen-I MFCs in terms of periodic loading, response time and longevity.

3.3 The Third Generation MFCs

G. sulfurreducens were cultured anaerobically at 30°C for 24 hours, centrifuged at 6,000 rpm for 30min and then resuspended using phosphate buffer and dithiothreitol to remove

any oxygen. The MFCs prior to starting the experiment were flushed with 80% N_2, 10% CO_2 and 10% H_2 to keep the confinement anaerobic. Shown below in Figure 4 is the data from the experiment in which the effect of the electrode surface area on the MFC performance was investigated. The normal surface area (180cm^2) was used as the control, and both twice and half that were tested. Figure 4 (a) illustrates the starting current and power from the control MFC for the first 4 hours, which is comparable with the previous two generations experiments. Initial anolyte compositions consisted of buffered substrate and bacterial culture only.



(a) (b)

Figure 4. (a) Starting and (b) continuous semi-batch current and power from Gen-III MFCs

The experiment lasted for almost one month (26 days - data shown up to day 12) in a semi-batch mode, i.e. the MFCs were fed periodically. This was done aseptically every 4 days by first removing the anolytes completely, using sterile syringes and then replacing them with freshly prepared substrate solutions prior to N_2 flushing and reconnection to the load resistors. The fact that the power rose to the same level as before (Figure 4 (b)), which was well above the 'background' level recorded with only buffered substrate solutions, suggests that this was the reducing power of the *G. sulfurreducens* monolayer. It also implies that the microorganisms in planktonic form do not contribute to the MFC power output, since they are not attached to the electrode surface. This is a very important result especially in terms of building a continuous flow system for an autonomous agent as the constant fluid flow will not affect the MFC performance. Diagonal arrows indicate the points in time when the anolytes were replaced with just buffered substrate. The first time, the replacing substrate was 5mM (w/v) acetate, the second time was 12mM (w/v) acetate and the third time was 12mM (w/v) sucrose.

4. Discussion

In a batch-mode (closed) system where there is no exchange of fluids, feeding has to be done manually and acid waste builds up. On the other hand, in a continuous flow (open) system, liquid solutions are being replenished and food is provided at a constant flow rate. The latter is how living organisms function, hence it is by far superior to the former, which is only used for experimental purposes.

In Gen-I MFCs, this would have a negative effect on the performance, which has been experimentally proved (results not shown), since it is the planktonic cells, which will be washed away that provide the reducing power. Even if immobilisation onto the electrode surface is to be employed, which will most certainly be inferior to a natural biofilm

formation, the system will still depend on the electron transfer efficiency of the mediator, its concentration and resilience to light and oxygen. Empirically this system proved to be the least efficient.

Gen-II MFCs, in a sense have their own biofilm formation. Clay and slate, solidify the anolyte and provide the substrate that underneath, *D. desulfuricans* form their own multilayer. Since the anolyte is solidified and provided that special micro-pore filters are used, the two remaining species in planktonic form – *E. coli* and *Pr. mirabilis* – will be protected from being washed away especially the latter, which is a highly motile microorganism and can 'stick' to almost anything.

The properties of *G. sulfurreducens* in Gen-III MFCs are ideal for a continuous flow system, even though the results shown in this paper are inferior to those of Gen-I and Gen-II. The fact that the electrode surface becomes the microorganism's natural oxidant in its metabolism implies that the current production can be maximised by simply increasing the electrode surface, without having to worry about the internal resistance. This system together with Gen-II MFCs are currently undergoing tests in pursuit of further performance improvement. Both systems need minimum substance replenishment and maintenance and provided they are fed with only the substrate, they can go on producing power for long periods of time. The two *Pseudomonas* species will no longer be needed in Gen-II MFCs since the waste of this fuel cell (acetate) can be utilised by the Gen-III MFCs.

The loading response is a critical parameter in a multi-level system, since its design may be such that continuous MFC power production will not be necessary. The envisaged agent will comprise both Gen-II and Gen-III MFCs as parts of a multilevel system used interchangeably that will give the robot a *pulsed-behaviour*. This has an impact in the manner in which MFCs would be employed by an autonomous robot since managing a varying energy source using action selection mechanisms is not trivial and it is very much different to managing a constant energy source.

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