Artificial symbiosis: Towards a robot-microbe partnership

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Abstract

The development of the robot EcoBot II, which exhibits some partial form of energetic autonomy, is reported. Microbial Fuel Cells were used as the onboard self-sustaining power supply, which incorporated bacterial cultures from sewage sludge and employed oxygen from free air for oxidation in the cathode. This robot was able to perform phototaxis, temperature sensing and wireless transmission of sensed data when fed (amongst other substrates) with flies. This is the first robot in the world, to utilise unrefined substrate, oxygen from free air and perform (three) different token tasks. The work presented in this paper focuses on the combination of flies (substrate) and oxygen (cathode) to power the EcoBot II.

1 Introduction

The notion of autonomy has been amply used in artificial intelligence, over the recent years. In very broad terms, it describes the ability of a robot to operate with minimum human intervention. More emphasis, however, has been given to the ability of a robot to perform computational tasks with minimum human intervention (computational autonomy) rather than to the collection and management of energy (McFarland and Spier, 1999). Energetic autonomy has not been explored to the same extent as computational autonomy and it may be very important to do so, especially in designing autonomous agents.

When energy collection and management become fundamental for developing autonomous robots, then novel implications emerge for roboticists. For example, the onboard energy supply may not be enough for continuous operation but instead only suffice for periodic actuation. This opens a ‘waiting’ window, of variable time length, which could be used to incorporate other behavioural aspects that may not be very energy expensive.

In the case of raw food substrate (plants, insects) being the energy source, the robot must be able to extract this from its environment and remove the waste produced. These are issues that have not been addressed in the past and thus may form a paradigm shift in the way autonomous robots are being designed.

This paper describes EcoBot II which exhibits some partial form of energetic autonomy through the integration with Microbial Fuel Cells (MFCs). The MFCs incorporated bacterial cultures from activated sewage sludge and were fed with flies. EcoBot II is the first robot in the world to be powered by MFCs containing bacteria from sludge fed with unrefined insects (flies) or fruits (peaches, apples, plums) and also employed the O_2 cathode. The work presented is from the set of experiments in which bacteria in the MFCs were fed with flies and the cathode used was based on the gas (O_2)-diffusion system.

2 Microbial Fuel Cell (MFC)

A Microbial Fuel Cell (MFC) is a two-compartment bio-electrochemical transducer. In the anode compartment, bacteria in an aqueous solution metabolise a given substrate and produce biochemical energy used for maintenance and routine tasks for survival. A small portion of this energy (in the form of electrons) is tapped from the bacterial metabolic cycle and then transferred onto the electrode surface, also found in the anode compartment. At this electron extraction stage, protons leak from the bacterial lipid wall into the liquid solution. Electrons and protons flow into the second compartment of the fuel cell, known as the cathode, through different routes. Electrons flow through an external circuit which is connected to the electrode terminals of both the anode and cathode and protons flow through a proton-exchange membrane that physically separates the two compartments. The MFCs used for these experiments, their physical size and electrode materials have been previously described (Ieropoulos *et al*., 2005a). A schematic diagram of the redox reactions taking place in a typical mediator-based MFC are shown in Figure 1.

2.1 Anode and cathode systems

Many single or mixed bacterial cultures have been used over the years as bio-catalysts in MFCs with each one having unique properties. For example, pure cultures of *E. coli* combined with synthetic electron shuttling mediators, were used in the MFCs powering Gastrobot and EcoBot I (Wilkinson, 2000; Ieropoulos *et al*., 2003a; 2003b; 2004). EcoBot II, on the other hand employed mixed cultures from activated sewage sludge. This strategy offered the advantages of higher power outputs, better stability and the potential to utilise a wide variety of substrates due to the diversity of the microbial community. Although activated sludge samples were aerobic at the collection stage, they could very easily be converted to anaerobic after the addition of the necessary nutrients to revive the inactive anaerobic microbes (anaerobes) and the removal of oxygen. This improved the performance of the ecosystem by nearly 100%. The improved anaerobic cultures were then injected into the MFCs, where they would be subject to exhaustion (discharging) through a resistor load, before being fed and integrated with EcoBot II.

Two systems are known to be used in the cathode half-cell of MFCs; the first, which is most commonly used, works with ferricyanide ($K_3Fe[CN]_6$) and the other with oxygen (O_2). Ferricyanide is a good laboratory standard used in analytical studies that is highly efficient, to start with, but degrades with operation time. This is mainly due to the continuous reduction of the oxidising agent (in the cathode) by the incoming electrons and also the taking up of the hydrogen ions (protons or H^+), which result in the need for replenishment. Oxygen, for the gas (O_2)-diffusion cathode on the other hand, is available from free air and offers a stable and in some cases improved performance over operation time. It does not suffer from H^+ ion accumulation and therefore a decrease in pH, which will have an adverse effect on the overall MFC performance. Electrons combine with H^+ ions and O_2 molecules to form water. The only condition is that the electrode must be kept moist in order for the H^+ ions to flow. In the work described here, since the cathode electrode was in an open compartment, (see Fig. 1) the moistening to initiate the reactions had to be done manually. The water production from the chemical reactions was, thereinafter enough to make the cathode half-cell self sustainable. This type of cathode was also ~20g lighter than the ones operating on ferricyanide. Clearly, in terms of autonomous mobile robots, the O_2 cathode system was more appropriate.

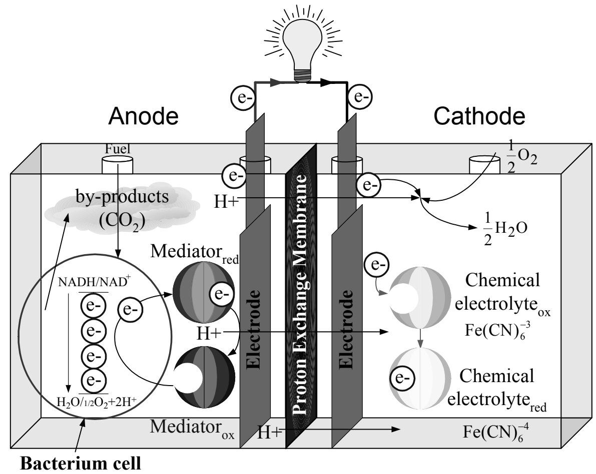

Figure 1: Redox reactions occurring in the anode (left) and cathode (right) of a typical mediator-based MFC

3 EcoBot II

The experiments reported in this paper were carried out using a simple, low-cost platform (Fig. 2). This consisted of light-weight styrene as the chassis, the electronic circuitry and two high torque motors. EcoBot II was constructed with carved 'pockets' on the upper chassis to accommodate and allow the exposure to free air of the O_2 cathode MFCs. When fully assembled, it weighed 780g which was ~180g lighter than EcoBot I.

Figure 2: EcoBot II with O_2 MFCs onboard. Fuel cell units were placed with the cathode facing outwards, so that the electrode could be exposed to air.

As was the case with EcoBot I, EcoBot II operated in bursts of energy. This has been previously described as 'pulsed behaviour' and it introduced the waiting window during which energy is accumulated to reach a pre-set threshold (Ieropoulos *et al*., 2003a; 2003b; 2004). None of the two versions of EcoBot incorporate any other behavioural aspect/task apart from energy accumulation. Instead, they were simply 'idle' for the time taken to charge the onboard accumulator.

One of the major differences between the EcoBot II and its predecessor EcoBot I, was that EcoBot II incorporated additional token tasks. On top of phototaxis, EcoBot II performed temperature sensing and data transmission of the sensed temperature. For temperature sensing, a 1-wire® low power sensor was used, which was connected to the onboard wireless microprocessor (rfPIC12F675) for data transmission. This resulted in the energy being distributed between the three tasks, instead of being used for phototactic locomotion (EcoBot I) and therefore it was slower than EcoBot I.

3.1 MFC exhaustion experiments

The MFCs that were used in the EcoBot II runs were first exhausted by individually discharging them through a resistor load. The exhaustion experiments (Fig. 3) were of sufficient length for the MFC power output to reach a pre-set baseline, but not to the extent that would prove lethal for the microbes. This was to ensure that the amount of residual nutrients and carbon energy (CE) sources were kept to a minimum and that the energy to drive the robot was derived only by the added flies. During the exhaustion cycle, which would typically last 24 hours, the O_2 cathodes were moistened once with artificial seawater (ASW). This was done for priming the cathodic system, before water production could begin at the electrode (pre-autonomous) surface and is indicated by the arrow pointing downwards. The arrow pointing upwards shows the feeding point and the horizontal dotted line is the baseline.

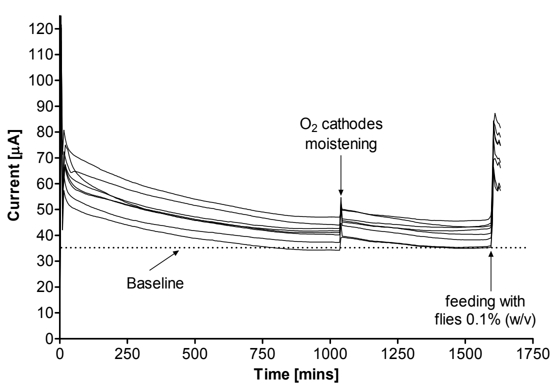

Figure 3: Typical MFC exhaustion cycle for eight different MFCs prior to connecting them with EcoBot II. Arrow pointing upwards indicates the point of feed with flies 0.1% w/v. This was equivalent to 1 fly / MFC. The baseline was set to 35µA.

3.2 Short distance runs

The short distance runs (Fig. 4) were carried out over 50cm and the duration of each run was variable depending on the charge/discharge cycle of the robot. The end of the run was signified by the robot reaching the light source in performing phototaxis. In order for EcoBot II to perform light seeking, the start point was (for all three repeats) at a 90° angle with respect to the light source.

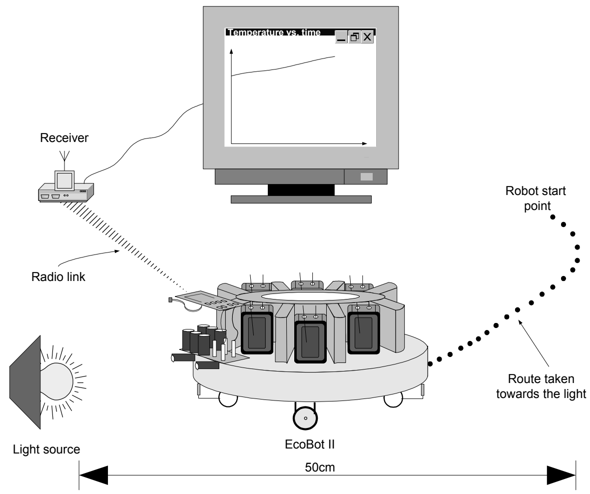

Figure 4: Experimental setup for the EcoBot II short distance runs. In order to perform light seeking, the robot was always placed at a 90° angle with respect to the light source.

Repeat experiments took place on separate days, starting at the same time of the day. In each case the MFCs were given 1 fly of identical mass, which was equivalent to 0.1% w/v, at the start of the run. During each run, the O_2 cathodes were moistened once with 3mL of ASW.

Figure 5 below shows the average data from the three repeat experiments. On average the robot was moving every 14 minutes for ~2-3 seconds before stopping again to accumulate. The distance covered for every move was ~2-3 centimeters. The closed circle symbols shown are the mean from the three repeats, and the solid line is the non-linear regression curve fit. As it can be seen, on average it took 6 hours to cover 50cm (8.3cm/h).

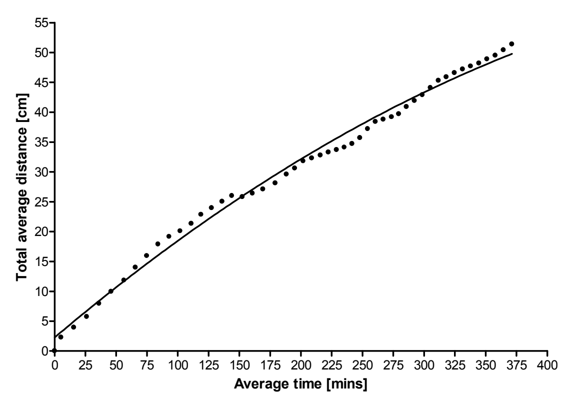

Figure 5: Average time taken during the three runs to reach the 50cm finish line. Mean data from the three runs are indicated by (●) and the solid line is the non-linear regression curve fit. The robot was moving in burst motions of 2-3 seconds that were taking place every 14 minutes.

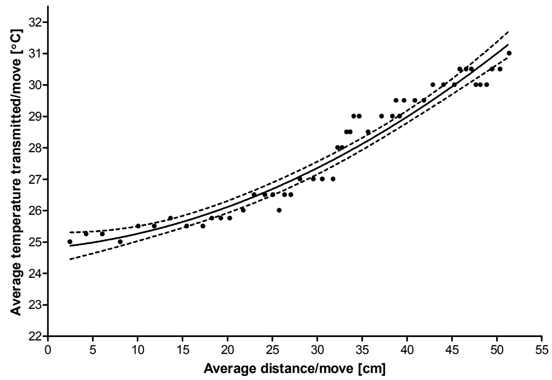

Figure 6: Temperature gradient produced as the robot was moving towards the heat emitting halogen light source. The solid line is the non-linear regression curve fit for the mean data (●) and the dotted lines on either side are the ± 95% confidence band (CB).

Figure 6 illustrates the temperature transmitted by EcoBot II as it was recorded by the base-station receiver. A temperature gradient from the start of the run towards the finish line was created by employing two halogen lamps as the light source. This was to test the temperature sensing capabilities of the robot. The data shown is the mean value (closed symbols) for the three repeats, with a non-linear regression curve fit (solid line) and ± 95% confidence bands (dotted lines).

3.3 Endurance runs

In these runs, the same experimental procedure was adhered for the individual exhaustion of the MFCs, prior to feeding and connecting them to EcoBot II. Bacteria in the anodes were fed with 0.1% w/v flies and in this case the robot was left in an open arena, to operate continuously until it came to a complete stop. This was done to investigate the length of time that the robot could operate continuously with the same bacterial culture in a non-continuous flow system and fed with a single fly/MFC. For the first stages of these experiments (first five days), the O_2 cathodes were being manually moistened with ASW, on a once a day basis.

Figure 7 illustrates the average time with average distance relationship, for these continuous long runs. On average, the robot operated for 11 days (maximum was 12 days) and the distance covered was 2 meters (maximum was 2.15 meters).

Figure 8 shows the average temperature reported by EcoBot II per day, whilst moving towards the light source. The halogen lights were placed at a distance of six meters with respect to the start point of the runs. Since the robot never got close enough to sense the heat given off, only the ambient temperature was transmitted.

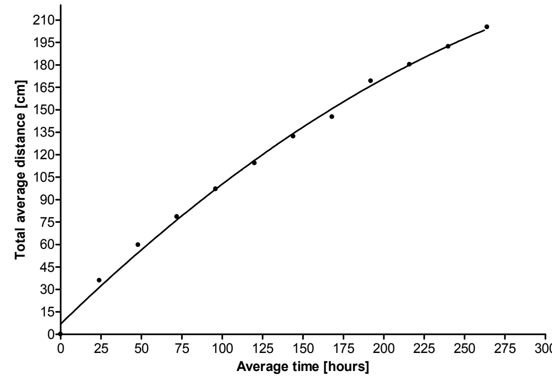

Figure 7: Average distance vs average time for EcoBot II endurance tests. Data shown (●) is the mean for the different repeats and the solid line is the non linear regression curve fit.

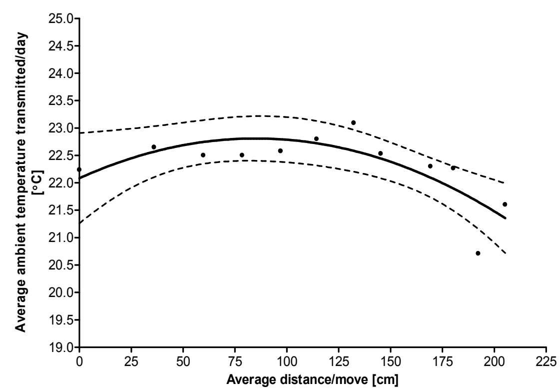

Figure 8: Relationship between the average ambient temperatures transmitted per day and average distance. The solid line is the non-linear regression curve fit for the mean data (●) and the dotted lines are the ± 95% CB.

4 Discussion

In this paper, EcoBot II is described which illustrates some of the key aspects of energetic autonomy, one of which is the extraction of energy from the environment. MFCs containing live bacteria were shown to utilise natural unrefined substrates, which could be found in the robot habitat. This widens the range of environments that an autonomous robot would operate in.

In order for a robot to be able to find and collect its own food, it may have to be built with a high level of software and/or hardware complexity and intelligence. For example, in the case of utilising fruits such as apples, it must incorporate location-recognition apparatus and in addition possess harvesting and breaking down mechanisms. In the case of insects, on the other hand, for example flies, fly traps based on pheromones could be integrated with the robot hardware. This type of trap, does not consume any electrical energy, and the fly attractant can last for long periods of time.

One other way of achieving self-sustainability, would be through the use of solar panels. Such a system would, however, need to have access (even infrequent) to solar radiation, which imposes limits to its autonomy.

Sewage sludge MFCs have recently been reported to exhibit accumulation properties in the form of sulphide and hence improved performance (Ieropoulos *et al*., 2005b). Activated sewage sludge samples have the ability of utilising common water pollutants such as sulphate, and excreting electro-active metabolites such as sulphide. It has been shown, that the longer the MFCs were left open circuit, the higher the burst of energy was upon load reconnection (Ieropoulos *et al*., 2005b). This implies that the performance of the robot can be greatly improved simply by changing the time constant of the charge/discharge circuit. This was not exploited in the EcoBot II experiments, and could potentially improve its performance by 10-fold.

From unpublished experimental data, we know that the MFC and as a result the EcoBot II performance could be improved by nearly 200%, when electrodes employed in the O_2 cathodes had previously been modified with ferricyanide fixation. This suggests that for the current cathode half-cell, the electrodes may need to be modified, in order to improve the system's performance during the initial stages of cathodic operation. This will of course depend on the rate of ferricyanide loss and degradation. However, after the electrode 'initiation' period, it will be of little importance if and when the fixed ferricyanide species degrade, since the cathode half-cell would have already become self-sustainable.

The ultimate design, taking nature as an example, would be a continuous flow system, operating on the robot. This will ensure continuous or at least periodic inflow of fresh nutrients and periodic outflow of waste. The latter is not as critical as the former, since the bacterial cultures are robust enough to withstand prolonged exposure to suboptimal conditions. However, if there are not enough nutrients in their environment, then the lack of microbial power could prove detrimental for the robot. The waste from MFCs containing sludge will be the parts of the energy source that cannot be utilised/broken down (recalcitrant materials) plus dead microorganisms. Provided the original sewage sludge inoculum has been screened for pathogens and is pathogen free, the waste can be safely composted and will be of no danger to humans and/or nature in general.

The continuous or periodic inflow of nutrients and substrates and the continuous or periodic outflow of waste products would form the major aspects of the robot architecture and behaviour. The energy to operate in this manner, would come from the onboard microbial ecosystem inside the MFCs. The live system will be providing and benefiting from the artificial system and vice-versa; this is what we call artificial symbiosis.

Autonomous robots will be extremely useful in missions, which are dangerous, undesirable or inconvenient for human beings. An autonomous agent could be used in underwater explorations feeding on plankton and sending useful information on the ecology of the ocean. On the other hand, it could be sent to monitor the sewer system of a city, and by cleaning blockages, generate energy for its maintenance. Organic waste produced at the domestic or industrial level might even be used as the fuel for such a robot that may be patrolling the premises.

5 Conclusions

Our work has demonstrated the feasibility of extracting electrons from biological substrates (insects, fruits) using mediator-less MFCs to power small robots. Furthermore, it has been shown that it is possible to use oxygen as the end-terminal-electron-acceptor of the MFC by modifying the cathode, compared to other systems (Wilkinson, 2000; Ieropoulos *et al*., 2003a; 2003b; 2004) to work with air.

EcoBot II can successfully perform token tasks including phototaxis, temperature sensing and data transmission. Functional performance has been shown to continue over twelve days.

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