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Energetically autonomous robots: Food for thought

Chris Melhuish · Ioannis Ieropoulos · John Greenman · Ian Horsfield

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Abstract This paper reports on the robot EcoBot-II, which is designed to power itself solely by converting unrefined insect biomass into useful energy using on-board microbial fuel cells with oxygen cathodes. In bench experiments different 'fuels' (sugar, fruit and dead flies) were explored in the microbial fuel cell system and their efficiency of conversion to electricity is compared with the maximum available energy calculated from bomb calorimetry trials. In endurance tests EcoBot-II was able to run for 12 days while carrying out phototaxis, temperature sensing and radio transmission of sensed data approximately every 14 min.

Keywords Artificial autonomy · Energy autonomy · Pulsed behaviour · Microbial fuel cells · Oxygen cathode

1. Introduction

1.1. Overview

Our study aims to address a number of important issues for genuinely energetically autonomous robots. This report describes the robot EcoBot-II which is able to power itself solely by converting unrefined biomass, in the form of insect or plant material, into useful energy. EcoBot-II employs a number of microbial fuel cells [MFC] with an anaerobic sludge microbial ecology and raw foods such as insects, fruits or vegetables. The fuel cells generate electricity which is accumulated until sufficient energy for a task is available. The energy is then released and the cycle begins again. For the proof-of-concept robot EcoBot-II, three exemplar tasks of actuation, sensing and communication are demonstrated. All three tasks are powered only by 'digestion' of raw substrate. Firstly, the robot can selectively activate its wheels; secondly, it can take a temperature measurement and thirdly, transmit the temperature measurement via an on-board radio transmitter.

Truly autonomous robotic systems will be required to abstract energy from the environment. 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 (McFarland and Spier, 1997; Holland, 1998). With this in mind our long-term goal is the creation of a robot, which can generate energy from unrefined biomass. This energy must come from the robot's environment and the constraint of carrying out tasks which require, in total, more energy than that available at start of the mission, should be satisfied. In this respect our definition of an autonomous robot is more akin to Stuart Kauffman's definition of an autonomous agent "a self-reproducing system able to perform at least one thermodynamic work cycle" (Kaufmann, 2000)—but without the burden of self-reproduction!

There are several examples of such robots that have been built to comply with this definition. For example, NASA's 'Spirit' (Squyres et al., 2004) employs solar panels to power their explorations of Mars and have demonstrated their impressive ability to be self-sustaining. However, there will be many domains in which solar energy is not available or

C. Melhuish (✉) · I. Ieropoulos · J. Greenman · I. Horsfield
Intelligent Autonomous Systems Lab, CEMS Faculty, University of the West of England, Coldharbour Lane, Bristol BS16 1QY, UK
e-mail: Chris.Melhuish@uwe.ac.uk

I. Ieropoulos · J. Greenman
Faculty of Applied Sciences, University of the West of England, Coldharbour Lane, Bristol BS16 1QY, UK

appropriate such as in marine environments, sewers or when constrained to operate only in the dark. 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 plant or insect material) into power for essential elements of behaviour including motion, sensing and computation. This requires an artificial digestion system and concomitant artificial metabolism or, as in the case of EcoBot-II, a rapprochement between an engineered artefact and a biological system—the robot symbiote.

For robots we have a choice of generating the energy either off-board or on-board; both have advantages and disadvantages. For example, the idea of collecting biomass, in the form of mollusc pests- slugs, by a group of robots and depositing them into a collective external digester unit to generate electricity has been suggested (Greenman et al., 2003). The digester facilitates methanogenesis and the gas is passed through a methane fuel cell generating electricity which is stored and 'tapped' by the robots. This idea is somewhat akin to the system employed by leafcutter ants which bring leaf cuttings back to the nest and grow a fungus on them. The fungus is then harvested and provides energy for the colony. Another mechanism is for the robots to have methane fuel cells onboard and draw off methane from the digester. Such a system has the limitation of reducing the range of the robots in their mission task as well as the foraging radius even though it has been suggested that the 'mobility' radius of this type of robot can be extended using a form of energy sharing based on the principle of trophallaxis observed in some species of social insects (Kubo and Melhuish, 2004).

On-board biomass converters have the obvious disadvantage of the need to expend energy carrying the associated extra mass of the converter but, assuming that biomass can be found and ingested, the range is not restricted. The robot EcoBot-II, discussed in this paper, employs this option by incorporating a number of microbial fuel cells in its chassis which are described in more detail in the next section.

The first robot to generate energy from refined fuel (sucrose) using MFCs was Wilkinson's Gastrobot (Wilkinson, 2001). Ieropoulos et al. (2003a, b, 2004) also built a robot (EcoBot-I) which employed a refined fuel (sucrose) and was capable of phototaxis. Pragmatically, in dealing with real world issues these robots had three serious problems. Firstly, they both used a refined fuel not unrefined biomass. Secondly, they both employed artificial mediators (methylene blue, HNQ) in the anodic chamber which were eventually degraded and could not be easily replaced from the environment. Similarly, they employed ferricyanide as an oxidising agent in the cathodic chamber which, again, was used up and could not be easily replaced from the environment. Although the idea of MFC powered robots utilising unrefined substrates has been mooted, this has never been attempted. EcoBot-II successfully addresses these issues by using unrefined biomass (e.g. dead flies), natural mediators (sulphide system see below) and air cathodes. However, EcoBot-II does not yet actively 'catch' its food or remove its own waste and these important issues will be addressed in the next phase of research.

The implications of adopting such a strategy may have an impact on the manner in which researchers and designers of autonomous systems incorporate this constraint in their mission requirements. There are a number of important issues for robots required to extract food from the environment. 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 'interrupting' its mission to forage or take advantage of energy resources such as a fallen apple. We therefore envision truly autonomous robots capable of exhibiting homeostasis, i.e., maintaining a state of internal equilibrium, which is however different from its external surroundings by the automatic control over physico-chemical variations, by means of internal feedback and external 'behavioural' mechanisms.

1.2. Microbial fuel cells

Microbial Fuel Cells (MFCs) have been in existence since the early 1900's (Potter, 1912). Since then, this area has been under investigation to strengthen the knowledge of the biochemical, electrochemical, thermodynamic and kinetic mechanisms that exist and cause the various reactions to take place within these cells. MFCs are bio-electrochemical transducers that convert the biochemical energy produced by bacteria metabolizing unrefined substrates into electricity. In their simplest form, they consist of two compartments, an anodic chamber (–ve, i.e. electron generating) and a cathodic chamber (+ve, i.e. electron accepting) which are separated by a proton exchange membrane. The two electrode terminals are connected to an external electrical load, through which electrons generated at the anode, can flow. The anode compartment accommodates the microbes and the cathode 'closes' the system by accepting the electrons.

With regard to the anodic compartment, at least three different types of MFC can be distinguished. These have recently been termed 'generations' (Gen-I,-II,-III) and the categorisation depends on the electron transfer mechanisms

employed between the bacterial cells and the electrode surface (Ieropoulos et al., 2005a).

MFCs employed in this study, incorporated mixed bacterial sludge cultures found in sewage that are probably a hybrid between Gen-II (sulphate reducing) and - III (anodophiles). In these systems, bacteria metabolise the given substrate(s) and produce biochemical energy used for their maintenance and routine, as well as waste products. Some bacterial species produce electro-active metabolites (e.g. H_2S^-, FeII, pyocyanin, plastocyanine) which act as electron 'shuttles' from the bacterium to the electrode or to other species (Rabaey et al., 2004; Hernandez and Newman, 2001; Bond et al., 2002; Sigfridsson, 1998). In addition, anodophilic bacteria attach to the electrode surface directly using that as their end terminal electron acceptor (Bond and Lovley, 2003). It is also possible that several bacterial species can utilise some of the waste products excreted by other microbes in the same consortium.

The advantages of using consortia with a large diversity of mixed species are numerous and lie with the wide substrate utilisation capability of such cultures. These microcosm systems can be subjected to a cross-feed regime of entirely different substrates and still offer stability and higher levels of power compared to other types. In addition to the above, the fact that these systems can be used for wastewater utilisation, makes them very attractive for scientific research by many workers in the world (Min and Logan, 2004; Liu et al., 2004).

Electrons that have been transferred to the electrode surface then flow through the external circuit as current (I) and end up in the cathode. This is due to the electrophillic attraction that exists between the two electrodes. At the bacterium cell electron abstraction stage, hydrogen ions (protons H+) are released into the anolyte. These species flow through the proton exchange membrane (PEM), into the cathode and hence the system is in equilibrium. We have used two cathode systems; the liquid ferricyanide ($K_3Fe[CN]_6$) chemical cathode and the oxygen (O_2) gas-diffusion cathode. In the case of the ferricyanide cathode, protons are taken up by the buffer found in the chemical solution up to the saturation point. After this stage the continuous incoming of protons into the cathode has a negative effect on the pH of the electrolyte, which eventually degrades completely. As a result, the anode pH begins to decrease, since no more protons can be consumed by the cathodic half-cell and this has a detrimental effect on the overall MFC performance. On the other hand, in the case of the O_2 cathode, protons combine with electrons and O_2 molecules from free air to form water, thus never saturating the system (with protons) and as a result oppose any decrease in pH.

In this paper we explore the use of MFCs as the power generators for a robot capable of exemplar tasks of actuation (phototactic locomotion), sensing (temperature) and communication via a radio link. MFCs are bench tested for their ability to employ different types of biomass including plant and insect material. For these bench tests both ferricyanide and oxygen cathodes were used and results compared for MFCs which were run until exhausted. Efficiency of energy conversion was calculated from the maximum available energy deduced using bomb calorimetry which had to be conducted on the insect and plant material. A second set of experiments were then carried out with the MFCs mounted on and powering the EcoBot-II robot.

Since we are interested in genuine autonomy we eschewed the use of the ferricyanide as the oxidising agent in the cathode. However, one set of short distance experiments using a ferricyanide cathode with flies in the anode were conducted to provide a baseline for comparison. Since the preferred cathodic system was oxygen (free air) a more extensive investigation was undertaken with oxygen cathodes and three types of substrate: sucrose, peach and flies. Lastly, we measured the longevity of the oxygen cathode and fly substrate combination by carrying out endurance trials lasting typically up to 12 days.

2. Materials and methods

2.1. Activated sewage sludge samples

Activated sewage sludge samples were provided by the Wessex Water Scientific Laboratory (Saltford, UK). The samples were collected from the Cam Valley urban wastewater treatment plant, which mainly deals with domestic waste and very little industrial waste. The plant is designed for a population equivalent of 6,000 (360 kg BOD day^{-1}) and has a sludge age of hours. Activated sludge samples were taken from the aerobic process tank, in which suspended solids were 99.8%.

2.2. Cultivation and harvesting

The sludge samples were mixed with nutrient broth (25 g l^{-1}) on the day of sampling (Oxoid, Basingstoke, UK) and given 24 h at room temperature before any further experimentation. The nutrient broth medium was sterilised by autoclaving at 121°C for 15 min. For biomass quantification, sludge subsamples (2.5 mL) were then serially diluted (1:1000) until within the linear range of optical density at a wavelength of 660 nm ($OD_\lambda = 660$ nm). The spectrophotometer used was a CamSpec UV-M301. The 660 nm wavelength was chosen to allow the comparison with previous work (Park and Zeikus, 2002). The sludge samples were then directly added into the MFCs for use in either the robotic and/or bench experiments.

2.3. Microbial Fuel Cells (MFCs)

The MFCs design and operation apart from the ones employing the oxygen (O_2) cathode were the same as described previously (Ieropoulos et al., 2003a, b, 2004). The MFCs employing the O_2 half-cell were different in the cathode design which was a completely open frame of the MFC shape and size therefore leaving the electrode exposed to the air. Whatman® filter papers, grade-1, (Fisher Scientific Ltd, Leicestershire, UK) of the same surface area as the carbon electrode (270 cm^2), were folded inside the electrodes to improve moisture retention. The total mass of the MFCs with the liquid ferricyanide and O_2 cathodes was 105 and 78 g respectively. Electrode surface area, liquid chemical catholyte composition, internal resistance and data capture were the same as described previously (Ieropoulos et al., 2005a).

2.4. EcoBot-II

EcoBot-II was made of two pieces of lightweight styrene material, placed one on top of the other. The bottom piece, which was the largest, had a height of 2.5 cm, an external diameter of 27 cm and a hole through the middle with a 14 cm diameter. The top piece was 5 cm high, with an external diameter of 22.5 cm and also had the same sized hole cut through its middle. Around the circumference of the top piece, eight rectangular 'pockets' were carved with 5.5 cm width and 5 cm depth, to accommodate the eight onboard MFCs. On the left and right of the under-side of the bottom styrene piece, two dc geared *escap*®-205 motors (Portescap, Switzerland) were attached to provide motion. The motors were modified to operate down to a maximum of 5 V, thus making it possible to operate with lower input voltage ranges. Balance of the robot was achieved with two caster wheels that were placed on the front and back of the under-side of the bottom styrene. The total mass (no MFCs onboard) was 140 g and the overall height was 10 cm. Depending on the type of cathode system used in the MFCs, the overall mass of EcoBot-II with the onboard MFCs was 780 g (O_2 cathode) or 980 g (Fe[CN] cathode). EcoBot-II is shown below in Fig. 1.

The robot was designed to have three different types of behaviour; (a) perform phototaxis, (b) sense the ambient temperature and (c) transmit data over onboard radio link. In order to perform phototaxis, two infrared-rejection photodiodes (VTB8440B, Pacer Components, Berkshire, UK) were cross connected with the two motors, to have differential drive and therefore move towards the source of light. A 1-wire® low-power temperature sensor (DS18S20, Maxim-Dallas) was used for sensing temperature which was connected to the onboard wireless transmitter (rfPIC12F675, Microchip) for temperature data transmission. The communication system used was the rfPIC kit™ 1 Flash development. Figure 2 illustrates the block diagram of the EcoBot-II circuitry.

Electrical energy produced by the MFCs was stored into the bank of capacitors until an upper threshold was reached. At that point, the energy was released and distributed to the two photodiodes, two motors, temperature sensor and wireless transmitter (actuators). The energy distribution to the motors depends on the information coming in from the two photodiodes and the data transmitted is what is sensed by the temperature sensor. This continued to occur until a lower threshold was reached, in which case the circuit ceased to operate until enough energy was accumulated in the capacitors once again. This was a repeatable process performed for as long as the bacteria were viable.

2.5. Bench MFC experiments

2.5.1. Comparison of substrates

Refined substrates were compared for their ability to act as suitable fuel for the MFC. These were tested at 0.005%, 0.01%, 0.02%, 0.04% and 0.08% for all substrates apart from chitin which was only tested up to 0.02%. The refined substrates, which were representative of major food classes, were sodium acetate (BDH, Dorset, UK), casein (Sigma, Dorset, UK), chitin from crabs (Sigma), sodium lactate (Sigma), pectin (BDH), starch (BDH), sucrose (BDH) and xylose (BDH). In all cases, these were prepared in gram-weight/volume (w/v) final concentrations. All experiments were carried out at room temperature.

2.5.2. Investigation of natural sources of chitin

Two sources of chitin were investigated to identify which would be more suitable for the robot runs in addition to the refined form of this complex polysaccharide. These were prawns (crustacean organisms) and flies (insects). The final w/v concentration was 0.1% (wet weight) which was equivalent to 0.025 g per 25 mL anodic volume. For the purposes of this experiment, flies and prawn shells were selected from our lab stock to be of identical weight ($\pm 5\%$) always ensuring that the insect and the exoskeleton of the crustacean would be fed in one piece.

2.5.3. Comparison between ferricyanide and oxygen cathodes

Sucrose (refined CE source), peach (pectin source) and flies (chitin source), were the three substrates chosen to be used as fuels in the comparison experiments between the two different types of cathode. Substrates were added at 0.1%

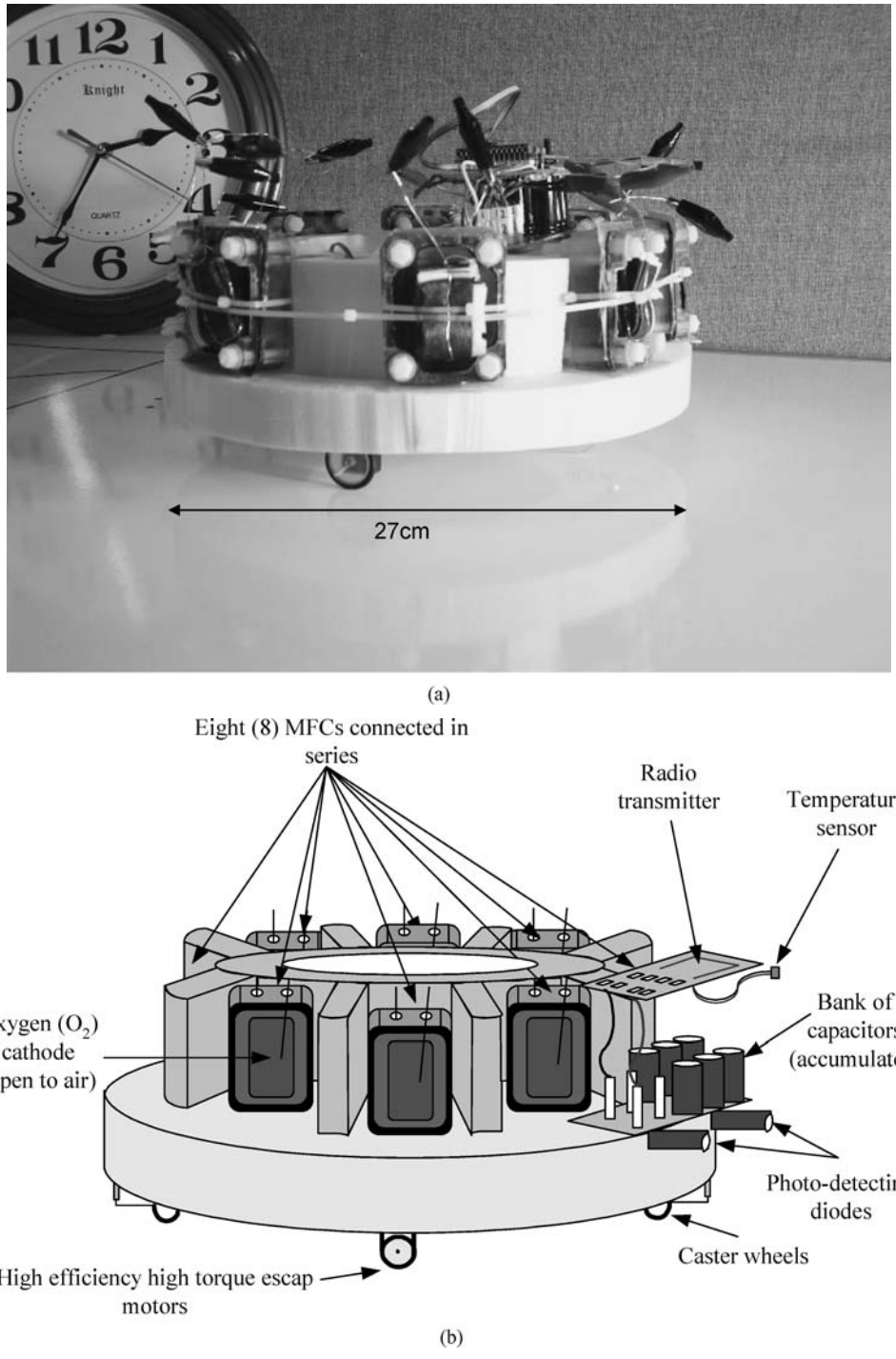


Fig. 1 (a) Photograph and (b) schematic diagram of the EcoBot-II fully assembled. The MFCs appear around the top of the circumference with the oxygen cathode facing outwards and are connected in series

w/v final concentrations. These experiments were repeated three times at room temperature using identical replicates of fresh biocatalyst from the same source. Oxygen diffusion cathodes were typically moistened with 3 mL of artificial sea water (ASW) for the first 5–7 days of the experiment. Ferricyanide catholytes were not replenished at any stage of the experiment.

2.5.4. Endogenous Substrate Depletion Runs

For all EcoBot-II experiments eight identical MFCs employing either the ferricyanide or O_2 cathode were set-up for a duration of 24–48 h. At first the MFCs were left open circuit and then individually fully discharged through a 2.7 kΩ electrical load prior to feeding and connecting them to the

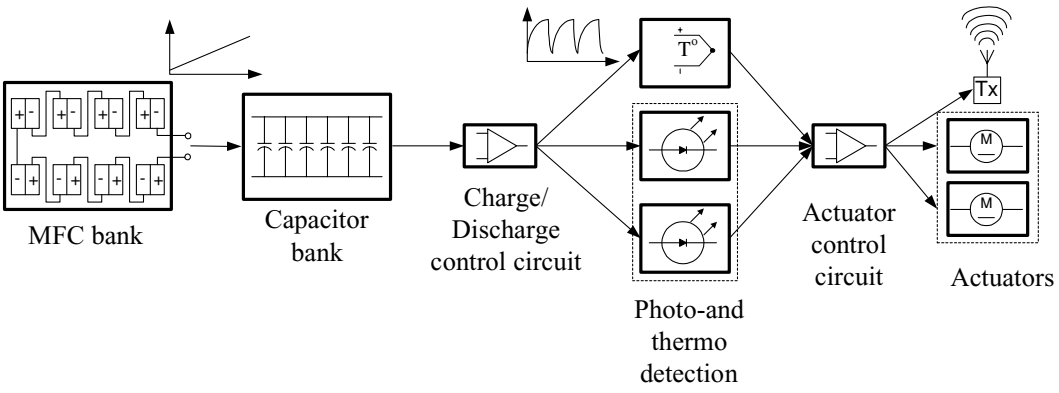


Fig. 2 Block diagram representation of the EcoBot-II circuit

EcoBot-II. The MFCs were then fed with 0.1% w/v appropriate test substrate and the increase in power output was recorded for a short period of time (typically 10–15 min). After this, the MFCs would be connected to the robot to commence the endurance runs.

2.6. EcoBot-II endurance experiments

2.6.1. Short distance (50 cm) runs

Experiments, in which the O_2 cathode was employed, were repeated three times over periods of three days for each substrate (sucrose, peaches and flies). Substrates were given at 0.1% w/v concentrations for each run. Oxygen cathodes were moistened twice at the beginning and towards the middle of each run. Experiments were started early in the morning of each day (07:30–08:00) when the ambient temperature was approximately the same. Depending on the time taken for the robot to cross the finish line, there was a typical 15–18 h window between each run, in which the MFCs were being disconnected from the circuit. The robot was placed at the same start position for all the repeat runs, which was at a 90° angle and 50 cm away with respect to the light source. Temperature and time data were recorded in real time using a desktop pc.

In addition, runs repeated for flies but using ferricyanide as the catholyte employed only the fly substrate (0.1% w/v) and were also repeated three times over a period of three days. In these experiments the MFC recovery time window between runs was ∼22 h.

2.6.2. Long distance (Continuous) runs

These experiments employed MFCs in which the anodic bacterial cultures were fed with flies and the cathode used was the O_2 diffusion system. Runs were repeated two times at room temperature and the distance of communication between the EcoBot-II transmitter and desktop pc receiver was restricted to around 20 m. The robot, in both cases, was placed at the same starting position which was at a 90° angle and 6 m away with respect to the light source. The bacteria in each MFC were fed with 0.1% w/v flies (equivalent to 1 fly per MFC) at the beginning of the experiment and the O_2 cathodes were moistened once a day in the morning with 3 mL artificial seawater (ASW). Rainwater (10 mL/week) was also added to the anode compartment of the MFCs to replace the water lost through osmotic pressure diffusion that existed between the two half-cells.

2.6.3. Temperature data reception

The temperature data wirelessly transmitted from EcoBot-II were received by the receiver module (rfPIC kit, rfRXD0420, Microchip Technology Inc.), which was connected to a remote computer. The frequency of communication was 433.92 MHz and the data acquisition was performed using Microsoft's® multi-threaded teletyping (MTTTY), which is a virtual RS232 serial port terminal, operating on the TTY communications protocol (baud rate = 9600). The maximum indoor distance of communication was approximately 30 m.

2.7. Bomb calorimetry

Bomb calorimetry was performed to calculate the heat capacity of the housefly species (*Musca domestica*) that was used in our experiments. The bomb calorimeter used was Gallenkamp Autobomb S/N SG94/10/092. The bomb was pressurised with O_2 at 25 atm and the bomb calorimeter was calibrated with benzoic acid. The temperature increase of 2 kg of water (2.55°C ±0.2%) when 1 g of benzoic acid was burned was in line with literature. Hence, the water equivalent of the calorimeter was calculated to be 559.339 g ±0.5%). The energy evolved during the combustion of any sample, can then be calculated by using Eq. (1):

$$\text{Energy evolved} = \Delta T \times (\text{mass of water} + X) \times c \qquad (1)$$

Table 1 Comparison of the current and power output from individual MFCs fed with 8 different refined substrates. These were chosen as representatives of the main food groups where they are found as the principle substrates. The total duration of this experiment was 7 weeks (47 days)

Substrate	Natural source	Current (μA)	Power (μW)
Acetate	Bacterial fermentation products	117.5	24.9
Casein	Dairy products, protein	112.2	20.7
Chitin	Insects, crustacean, molluscs	145.1	33.0
Lactate	Bacterial fermentation products, dairy products	113.1	20.5
Pectin	Fruits, vegetables	94.0	15.0
Starch	Corn, potatoes, wheat, rice	77.7	10.4
Sucrose	Green plants (cane, beet)	117.8	21.8
Xylose	Wood sugar	105.5	19.1

where ΔT is the change in temperature as a result of the combustion, X is the water equivalent of the calorimeter (in this case 559.339 g), C is the specific heat capacity of water (4.186 $Jg^{-1}{}^{\circ}C^{-1}$).

The average mass of one insect was ca. 0.02 g and the dry weight was ca. 0.004 g which suggests that approximately 75–80% of the total insect mass is water. Flies were dried at 110°C for 90 min and 0.5 g samples were used in the repeat calorimetry experiments. The weight of the crucible used in the calorimetry was 8.5677 g and the Ni-Cr wire was of the same mass (0.0122 g) in all repeats.

3. Results

The results presented in this section are from the MFC experiments carried out to determine the substrate with which bacteria were to be fed and cathode system to be employed and the EcoBot-II runs and the bomb calorimetry performed to calculate the energy content of houseflies.

3.1. Bomb calorimetry

The temperature change evolved (ΔT) from the bomb calorimetry repeats was 1.025°C ($\pm$0.5%). By using Eq. (1), the calculated energy evolved for 0.5 g dry weight fly samples, was 10.96 kJ ($\pm$0.5%). Hence, the energy per single fly (ca. 0.004 g dry weight) was calculated to be 87.68 J ($\pm$0.45%)

3.2. Microbial Fuel Cell (MFC) bench experiments

3.2.1. Comparison of substrates

Initial experiments were carried out to investigate different types of substrates or fuels that can be used as the energy source for the bacterial cultures. Even though these are carbon energy (CE) sources that can be found in nature, not all bacterial species can break them down. The large bacterial diversity that exists in the sludge consortium, suggests that a large number of CE sources can be utilised and this was the main objective of this series of experiments. Table 1 below shows a comparison of 8 different refined substrates and the data shown is from individual MFCs.

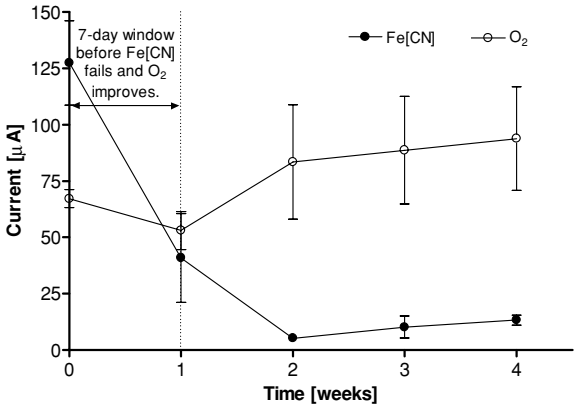
As can be seen from the data above, amongst the substrates that can be easily extracted from plants or insects without any further processing, chitin seemed to be the most preferable item on the bacterial menu with pectin being second best. Chitin is the main constituent of the exoskeleton of insects, crustacean organisms and molluscs whereas pectin is a complex acidic polysaccharide found in fruits and vegetables.

3.2.2. Investigation of natural sources of chitin

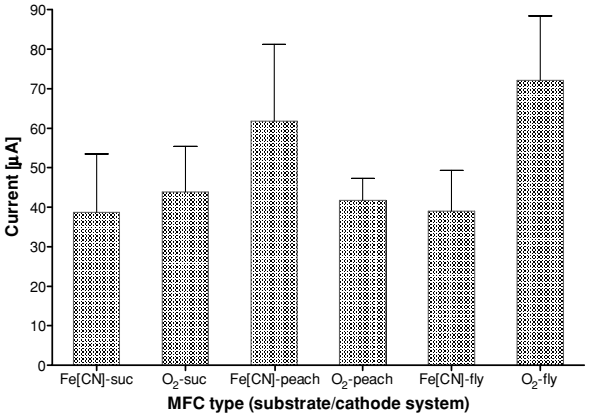
In the following stages of the investigation, the objective was to examine whether these CE sources could be readily extracted and utilised in the MFC, directly from the environment or whether further mechanical or enzymatic breakdown would be required. Prior to that and for the purposes of this study, a different experiment was carried out to identify which source of chitin may be best in terms of accessibility and energy output. The chitin particles (refined form) used in the initial experiments were derived from crabs, but considering the difficulties involved in processing crab-shells, it was decided to try prawn shells instead and dead flies. Table 2 below shows a comparison between the current and power output from the refined form and the two different natural sources of chitin. Data shown is from individual MFCs.

Table 2 Comparison of current and power output from individual MFCs fed with different sources of chitin. Substrates were given at 0.1% w/v final concentrations. Flies and prawn shells were given in whole pieces

Chitin source	Current (μA)	Power (μW)
Refined chitin (from crabs)	119.7	15.6
Flies (whole insect)	197.0	38.7
Prawn (whole exoskeleton)	202.0	42.8



(a)



(b)

Fig. 3 (a) Typical current response over time from MFCs working with either the O_2 or the Fe[CN] cathodes. (b) Current output comparison, between MFCs employing either the Fe[CN] or O_2 cathode half-cells and fed with selected substrates (sucrose, peach and flies). The total duration of this experiment was 1 month (27 days). MFCs were fed three times and the substrates were given at 0.1% w/v final concentrations each time. Data shown (mean ± SE) are from 18 individual MFCs: 3 for each combination of substrate and cathode

3.2.3. Comparison between ferricyanide and oxygen cathodes

These experiments were carried out to test whether a simple and low cost O_2 cathode half-cell could work in combination with the raw substrate-fed anode system. Initially (Fig. 3(a)) it seemed that the MFCs with the Fe[CN] cathode gave twice the amount of power that was produced by the MFCs using the O_2 cathode. However, after normally 1 week, the MFCs with the O_2 cathode were exhibiting an improved performance with high and stable levels of power. The experiment lasted 4 weeks (27 days) during which the three target substrates were tested against the two types of cathodic systems. In all cases, after the first week, the power from the ferricyanide cathodes degraded and the O_2 cathodes improved. Average comparative data (from individual MFCs), for the total duration of this experiment, are shown in Fig. 3(b).

3.2.4. MFC exhaustion runs

Figure 4 below shows a typical exhaustion cycle for the MFCs prior to feeding them and connecting them with EcoBot-II. Initially the MFCs were left open circuit in order to allow for bacterial adjustment to the new environment. Substrates were fed into the MFCs immediately before connecting them to the EcoBot-II.

3.3. Endurance tests using the EcoBot-II platform

3.3.1. Short distance-oxygen (O_2) cathode

The oxygen cathode was the main focus of our research as such a system is more likely to be integrated with an autonomous agent. Therefore it was decided to carry out a more extensive investigation by trying both refined and unrefined

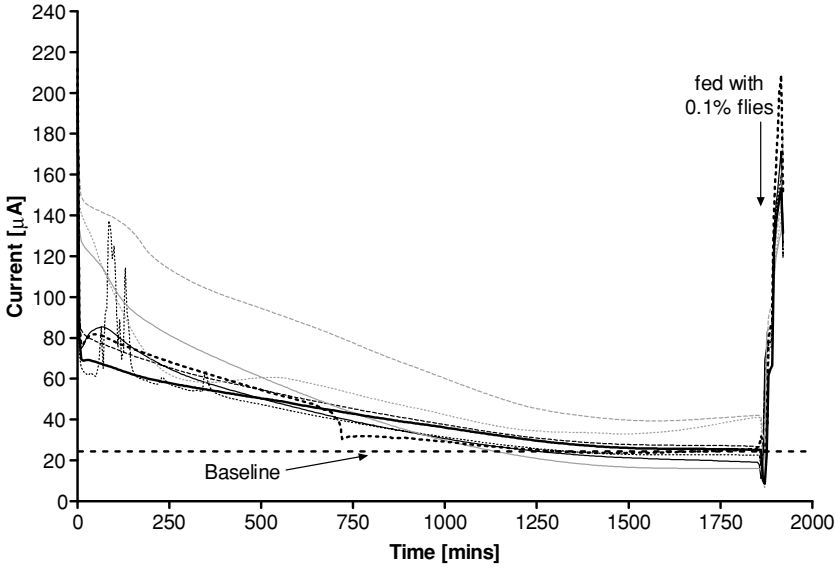
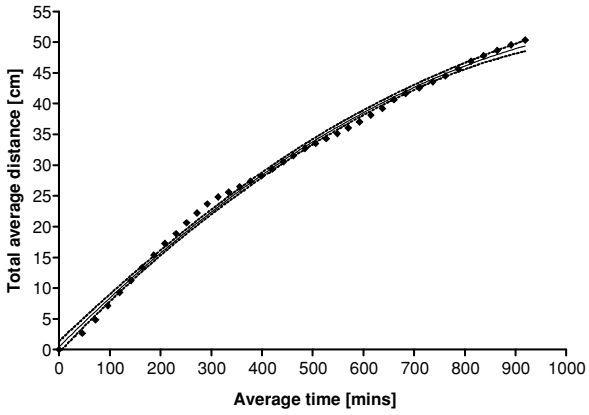
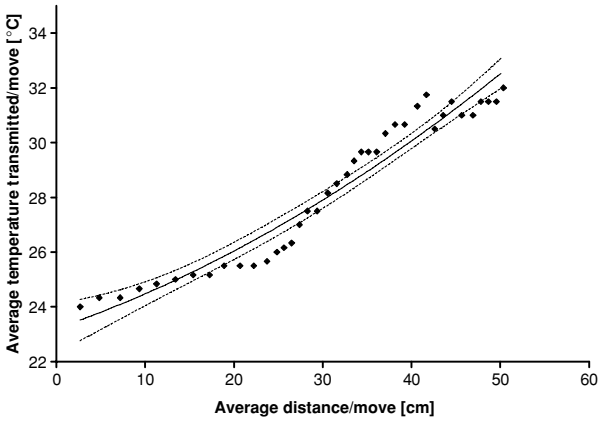


Fig. 4 Typical MFC exhaustion cycle and feeding prior to connection with EcoBot-II for eight individual fuel cells. Arrow indicates point of feeding. Data shown is from the exhaustion cycle for the short distance experiment (50 cm) in which the Fe[CN] cathode was employed. Substrate used was 0.1% w/v wet weight flies



(a)



(b)

Fig. 5 (a) Average distance against average time and (b) temperature gradient for the 3 EcoBot-II runs, in which the MFCs were fed with 0.1% (w/v) sucrose and employing the O_2 cathode. Data shown is the mean from the three repeats (♦) with the non-linear regression curve fit (solid line) and ±95% confidence interval (CI) (dotted lines)

substrates as fuels. These were sugar, rotten peaches and flies and the runs for each substrate were repeated 3 times over a distance of 50 cm for the same final gram-weight/volume concentrations. The results derived from the runs in which the sludge bacteria were fed with sucrose, (0.1% w/v) are shown below in Fig. 5(a) and (b).

The next substrate that was utilised as a fuel in the EcoBot-II runs were small pieces of rotten peach, at the same wet-weight/volume (w/v) concentration (0.1%). The results from the three repeats are shown below in Fig. 6(a) and (b).

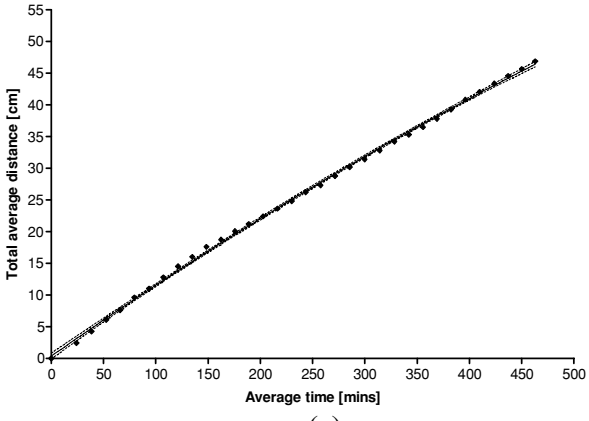
Figure 7 below illustrates the temperature transmitted by EcoBot-II from the runs in which the bacteria within the MFCs were fed with flies. The total time taken for the robot to cover the 50 cm distance was on average 6 h and 10 min. (The graph illustrating the time-distance relationship for this particular substrate has recently been reported (Ieropoulos et al., 2006)).

3.3.2. Short distance-ferricyanide cathode

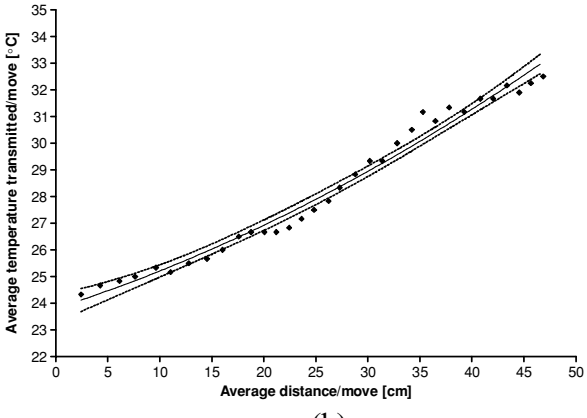
The first EcoBot-II runs were carried out with MFCs employing the liquid Fe[CN] cathode and fed with flies. The experiments were taking place once a day, during the same time, when the ambient temperature changes were similar. Experiments were repeated 3 times over a distance of 50 cm and the results are shown below in Fig. 8(a) and (b).

3.3.3. Long distance (Continuous) runs

In these endurance runs, as was the case in the previous experiments, the MFCs were exhausted at first and then fed. The preferred substrate for this series of experiments was flies (0.1% w/v), which was in line with the objectives of the work. The robot was left in an open arena, moving towards a light source, sensing and transmitting temperature



(a)



(b)

Fig. 6 (a) Average distance over time and (b) temperature gradient produced from the 3 runs of the EcoBot-II in which the MFCs were fed with 0.1%(w/v) rotten peach pieces, moving towards the halogen lamps. Closed symbols (♦) are the mean data from the three repeats and the solid line is the non linear regression curve fit. The two dotted lines on either side (b) are the ± 95% CI

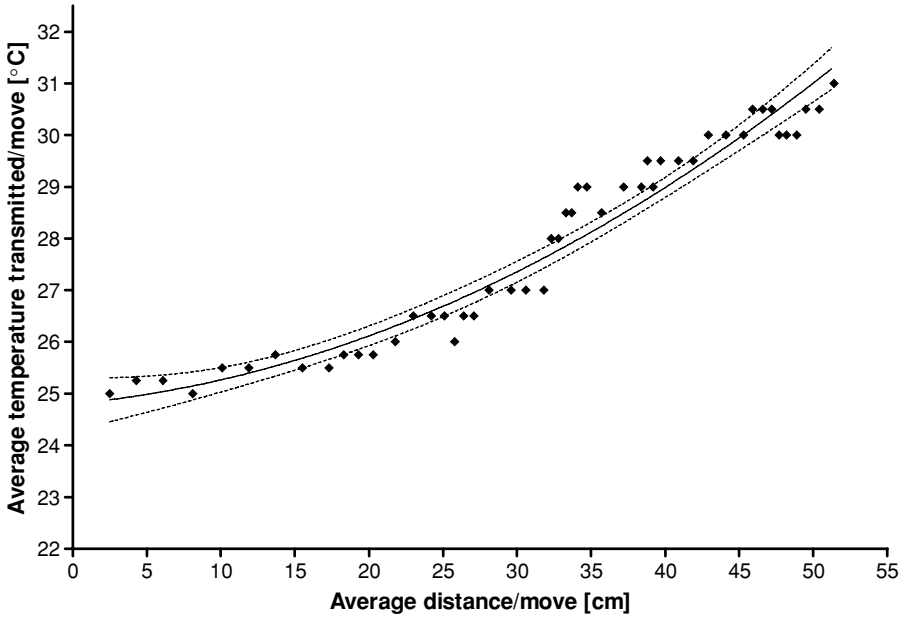
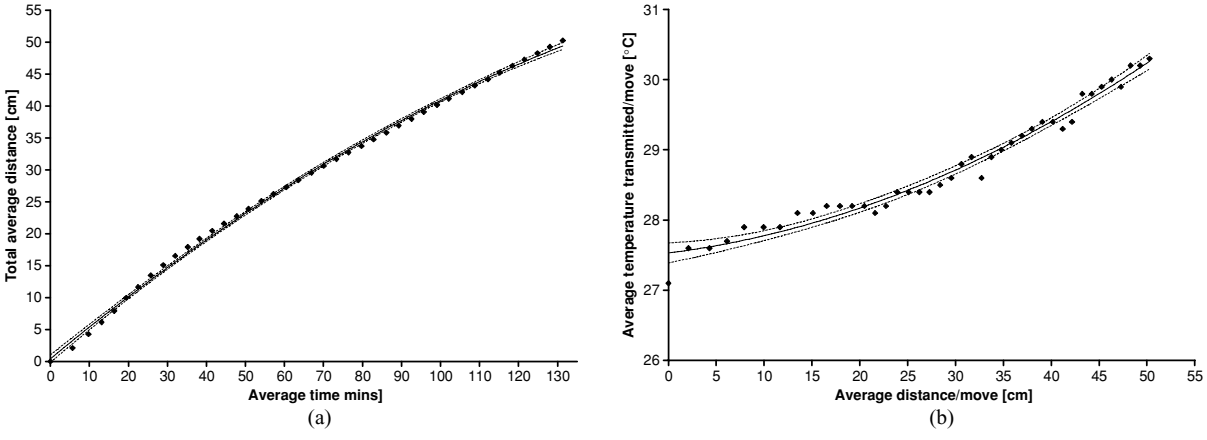
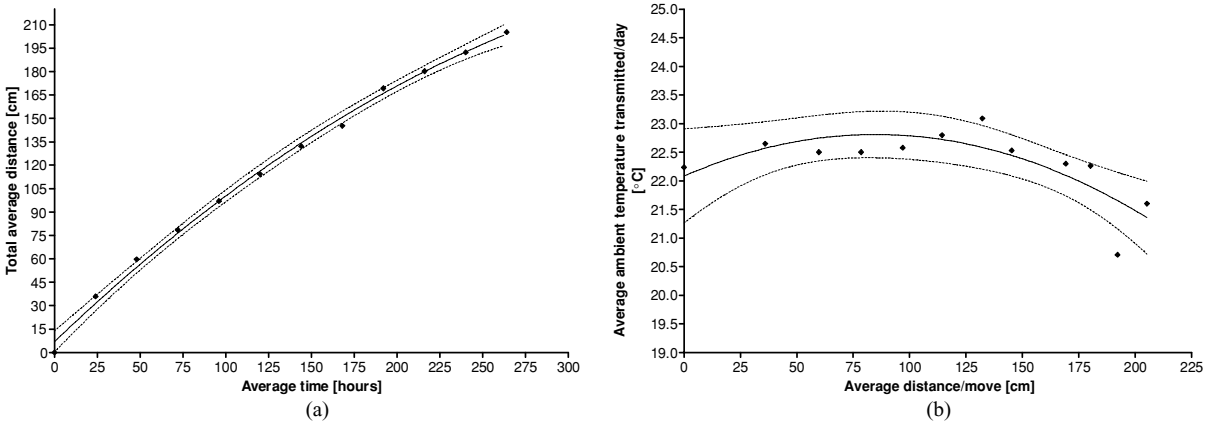


Fig. 7 Temperature gradient over the 50 cm distance for the EcoBot-II fed with flies and employing the O_2 cathodes. Data shown is the mean (♦) from the three repeats with a non linear regression curve fit (solid line) and ± 95% CI (dotted lines)



(a) (b)

Fig. 8 (a) Average distance over time and (b) temperature gradient over the 50 cm distance from the three EcoBot-II trials running on fly insects and using the Fe[CN] cathode. (♦) are the mean data from the repeat experiments with non linear regression fit curve (solid line) and ± 95% CI (dotted lines)



(a) (b)

Fig. 9 (a) Average distance covered over an average period of 11 days and (b) temperature data transmitted from the EcoBot-II to the base-station receiver for the endurance test. Although the robot was performing phototaxis, the halogen lamps were still sufficiently distant not to cause the sensed/transmitted temperature to rise

Table 3 Energy efficiency for the different types of MFC. Total duration for these experiments was 27.43 days. The experiments were repeated 3 times; data shown is the mean value from the 3 trials and the maximum recorded value from the best trial

MFC type	Energy input (J) (Heat content from bomb calor)	Energy output (J) (data recorded)		Efficiency η (%)	
		Mean	Max	Mean	Max
Sucrose-Fe[CN]	1275 (17 kJ/g)	31.67	57.69	2.48	4.52
Sucrose-O_2		2.83	5.93	0.22	0.47
Peach-Fe[CN]	123.75 (1.65 kJ/g)	42.95	61.63	34.70	49.80
Peach-O_2		11.85	19.19	9.58	15.51
Fly-Fe[CN]	263.04 (21.92 kJ/g = 87.68 J/dry wt fly)	27.75	36.03	10.75	14.21
Fly-O_2		40.30	56.18	15.90	22.16

Table 4 Energy efficiency for the different EcoBot-II runs. Also shown in the table are the number of times that the robot moved and the time taken for it to reach the goal (short distance runs) or full exhaustion (long distance runs)

EcoBot-II	Input (J)	No. of moves	Time Taken (hours)	Output (J)	Efficiency η (%)
	Short distance (50 cm)				
Flies 0.1%-Fe[CN]	701	40	2.19	2.55	0.36
Sucrose 0.1%-O_2	3400	38	15.32	2.43	0.07
Peach 0.1%-O_2	330	38	7.71	2.43	0.75
Flies 0.1%-O_2	676	42	6.19	2.67	0.39
	Long distance (continuous)				
Flies-Fe[CN] moist[a]	701	296	45	18.51	2.64
Flies-water moist	701	150	264	9.5	1.35

[a]Data not shown. Long distance experiment in which the open cathodes were moistened with 3 mL of the same concentration (0.1 M $K_3Fe[CN]_6$) as the liquid catholyes, once a day over two days.

information. The open cathodes were moistened with artificial seawater once every 24 h for the first five (typically) days of the experiments.

The average endurance period was 11 days and the average distance covered was 2 m. The halogen lights were placed at a distance of 6 m with respect to the start point, and therefore no temperature gradient was established, which means that the data transmitted was the ambient temperature.

Figure 9(a) and (b) show the average distance covered over 11 days and the ambient temperature data transmitted during these runs respectively, for the EcoBot-II with the O_2 cathodes.

The energy efficiency data of MFCs running on different substrates and cathode systems as well as the energy efficiency from the EcoBot-II runs operating on the different MFC systems are summarised in Tables 3 and 4 below.

As can be seen from the results, the average power output from a single MFC is ~ 20 μW at a working voltage of 0.35 V. Peak values range from 150–200 μW at voltage levels ranging between 0.4–0.5 V.

4. Conclusions

Microbial fuel cells have been shown to be capable of converting raw unrefined substrate in the form of insect or plant biomass into 'working' energy for a real robot. Furthermore, air cathodes have been employed in the MFC construction. Previous MFC powered robots have used refined fuel (e.g. sucrose), synthetic redox mediators in the anode and chemical oxidizing agents in the cathode. On the contrary, EcoBot-II employed unrefined fuel, natural mediators in the anode and O_2 from free air in the cathode and it was still possible to generate useful energy. For our robot, EcoBot-II, 8 MFCs were linked serially and each 'fed' with a dead fly. This was sufficient to provide the necessary energy to move the robot approximately 2 cm, sense temperature and transmit the sensed data via an onboard radio transmitter. This work cycle was repeated approximately every 14 min for a period of 12 days.

At this early stage of MFC development each MFC used provides only tens of microwatts at around 0.7 V. Useful 'working' energy is generated by accumulating the supply from such a relatively small power source. This mode of cyclic 'store and release' activity is referred to as 'pulsed behaviour' and for many autonomous robotic applications it may be acceptable—one can imagine a robot sensor network where each sensor is active for a relatively short period of time while otherwise accumulating energy for a known period prior to a regular transmission of sensed data. In contrast a sensor could continue accumulating energy while waiting for some triggering event which requires reporting immediately. Pulsed behaviour will also have an impact on the temporal dynamics of the way in which robots execute their action selection policy. Doing 'nothing' is an important option; choosing not to carry out actions in the short term gives a robot

opportunity to do things in the longer term which require large amounts of energy. This could not be achieved unless the robot had 'sacrificed' earlier opportunities for short term gain. At the same time this will have to be balanced with the energetic requirements of internal 'metabolic' and 'housekeeping' processes such as keeping temperature and pH within lethal boundaries (Ashby, 1952) by either internal regulation (e.g. increasing flow rates) or external behaviour (e.g. moving into shadow on a hot day). Thus, as energetically autonomous robots become more sophisticated there is likely to be an increasing processing overhead involved with the monitoring of internal and external state as well as planning and action selection—all requiring energy. Moreover, energetically autonomous robots will also have to expend energy in obtaining or ingesting their food as well as voiding waste material.

It has been shown that different types of unrefined biomass can be used by MFCs. Suitable flora could be employed which best match available biomass. Thus one could imagine some robots with specific substrate requirement—'specivores'. In contrast, some microbial flora could be less specific in their biomass intake akin to 'omnivores'. Moreover, microbial flora can adapt to different substrate over time through ecological selection or enrichment and/or differential gene regulation. These allow the microbial flora to exploit different types of food material. It may also be possible to create a series of MFC digesters where each one deals with specific food types or possibly could utilise waste products of a previous stage. For example, *Geobacter sulfurreducens*, an anodophilic bacterium, can easily consume acetate which is a common waste product from bacterial metabolism (Ieropoulos et al., 2004).

EcoBot-II represents an exemplar of microbe-robot symbiosis, which can be described as the system whereby consortia of microbes are well adapted to growing in steady-state within the anodic system that is provided by the robot. The feeding of nutrients to the microbes is also supplied by the robot and in return the robot extracts electrical energy from the microbial consortia to perform required tasks over long periods of time.[1]

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[1] Biological oxygen demand.