EcoBot-III: a robot with guts

Ioannis Ieropoulos[1], John Greenman[2], Chris Melhuish[1] and Ian Horsfield[1]

[1]Bristol Robotics Laboratory, University of the West of England, Bristol Business Park, Coldharbour Lane, Bristol, BS16 1QD, UK
[2]School of Life Sciences, Faculty of Health & Life Sciences, Frenchay Campus, University of the West of England, Coldharbour Lane, Bristol, BS16 1QY, UK
ioannis.ieropoulos@brl.ac.uk

Abstract

This paper describes the work carried out to develop EcoBot-III, which is a robot with an artificial digestion system. The robot is powered by Microbial Fuel Cells (MFCs) and it is designed to collect food and water from the environment, digest the collected food and at the end of the digestion cycle, egest the waste. EcoBot-III operated successfully for 7 days when fed with anaerobic or pasteurized sludge, before mechanical failure required human intervention. Work is ongoing to improve the mechanics and thus extend the artificial agent's operational lifetime.

Introduction

Autonomous behavior for artificial agents implies prolonged operational periods with minimum or no human intervention. This is important (and can also be considered as vital) for a variety of tasks/missions, generally categorized under 'remote area access'. Up until recently autonomous robotic behavior, was primarily seen as a computational challenge, where robots are developed with processing skills that allow action selection and decision making, but with the element of energy and energy collection taken for granted. Work by numerous groups has indicated that true autonomy needs to take into account the collection of energy from the environment (akin to biological agents) and build it in the robot's behavioral repertoire (McFarland, 1990; Steels and Brooks, 1995; McFarland and Spier, 1997; Spier and McFarland, 1997). Thus, over the recent years, energetic autonomy has received increased attention from the robotics community as a vital feature for autonomy and self-sustainability (Spier and McFarland, 1996; 1998; Melhuish and Kubo 2004; Ziemke 2008; Kubo et al. 2009). The robot pioneers Gastrobot, Slugbot and EcoBots have demonstrated how this notion may be realized, through the integration with real microorganisms living inside Microbial Fuel Cells (MFCs) (Gastrobot, EcoBots) and the collection of real food from the environment (Slugbot) (Kelly et al. 2000; Wilkinson, 2000; Greenman et al. 2003; Ieropoulos et al. 2003; Melhuish et al. 2006). This integration between biology and machines has been described as (artificially) symbiotic and has resulted in the introduction of a new class or robots known as Symbots (Melhuish et al. 2006).

The present study addressed the twin issues of energy autonomy and bio-regulation. Biologically inspired mechanisms and strategies were explored, to provide full energy autonomy to a new robot that *produced its own energy* from biological material (e.g. plant or insect material) which it collects and processes using MFCs. The work focused on the construction of a complete MFC-based self-regulating energy system which necessitated exploring mechanisms for (1) collecting, ingesting (eating) new substrate (2) removing waste material (3) maintaining internal homeostasis and (4) performing appropriate behavior for the foraging/ acquisition of food.

The work described in this paper, builds on EcoBots I and II and had the following main aims: **(i)** To build the individual prototype mechanisms for ingestion for EcoBot's artificial gut using MFC technology; **(ii)** To develop embedded low-power controllers capable of sensing and on-board actuation to maintain internal homeostasis; **(iii)** To design and build a novel egestion mechanism to allow the evacuation of waste material from both the MFCs and the digester unit; **(iv)** To design and build a system with which it will be possible for the robot to collect liquid food and water from the floor or wall of an arena (EcoWorld arena); **(v)** To integrate all components and systems to demonstrate self-sustainable operation of EcoBot-III. This demonstration will include ingestion of fresh food source, digestion and egestion of waste material in order to continue performing its assigned tasks.

The following sections describe the development of EcoBot-III - the third in a series of self-sustainable agents – with an artificial digestion system that collects its energy from the environment and 'lives' on microbial metabolism.

Materials and Methods

In the first phase of the study, the work focussed on the design and testing of engineered prototypes of sub assemblies for power production (MFC stacks), artificial gut circulation, food ingestion and their integration into a work bench demonstrator. The ingestion system needed to supply the anodic chambers with an organic substrate (food). It had to maintain appropriate separation between the stomach-like collecting pouch and the anodic chamber. Early experiments explored the possibility of designing a system that attracts insects (flies) using pheromone bait and traps the flies in a fluid reservoir. Later experiments focussed on using alternative feed substrates (broths and pure substrates), which the robot accessed from a wall-mounted feedstock reservoir.

A biologically-inspired controller for homeostasis was also prototyped. This was used to model, in control-theoretic form, the biological negative feedback loops typical of regulatory mechanisms for homeostasis. Of particular importance to EcoBot, given its continuously low energy levels, was a model of the regulation of energy intake that takes into account the modulation of this system by internal temporal cycles for ingestion. The controller is generalized to regulate the internal parameters of the robot with electronic sensor boards for temperature and fluid levels (with option for pH or other sensor systems if they possess low power requirements).

Microbial Fuel Cells

MFCs are bioelectrochemical transducers that convert biochemical energy (generated by microbes) directly into electricity. They consist of two half-cells; an anode, which is the bacterial side and has negative polarity (electron generating) and a cathode, which is the oxidizing side and has positive polarity (electron accepting) and the two are separated by an proton selective membrane (PEM) (figure 1). Microbes in the anode chamber can be in either planktonic (suspended in liquid solution) and/or biofilm forms (attached to the electrode surface) and transfer electrons to the electrode either via electroactive metabolites naturally released by the microbes or direct conduction, via conductive pili (nanowires).

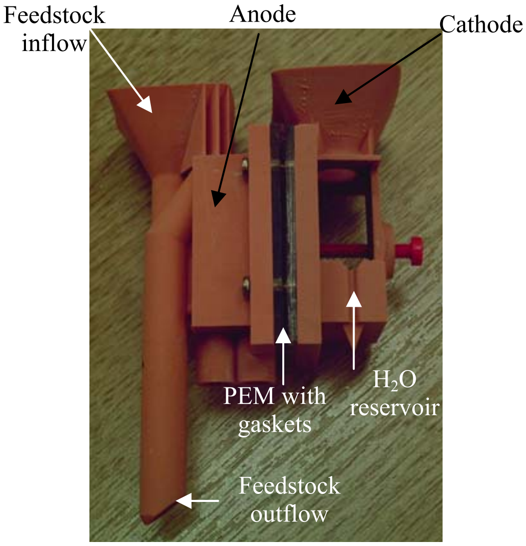


Figure 1: Photo of the terracotta colored (Nanocure® photo-polymer) final assembly of a MFC; labels show the various parts and features of the design. Inside the anode and cathode chambers (not shown in photo) are the carbon veil electrodes (67.5cm^2 total surface area for each electrode).

MFCs are a new technology, in the sense that only now can they produce sufficient power to make them drive useful applications. The open circuit voltage and maximum sustainable power output of a single MFC is approximately 0.7V and 50μW respectively, suggesting that a plurality of MFCs will be required to drive an application such as EcoBot.

A related question is "can stacks of MFCs produce enough energy at a fast enough rate to drive a physical entity that could move and support the weight of its own energy generating system (MFC stacks, stomach, tubes, electronics, accumulators, motors and pumps). The weight onboard the robot had to be as low as possible and all actuators, motors and pumps had to function at the lowest possible power consumption. Earlier findings demonstrated that power density improves with decreasing size of individual MFCs (Ieropoulos et al. 2008). This formed the basis for EcoBot's final design.

A total of 48 MFCs were employed onboard EcoBot-III and they were configured in a circular fashion (figure 2). This was in order for the open-to-air oxygen-diffusion cathodes to be facing outwards in order to maximize oxygen (from free air) exposure. The 48 units were stacked in 2 tiers so that overflowing liquids (feedstock from the anodes and water from the cathodes) from the top tier could fall directly into the corresponding MFC units in the bottom tier.

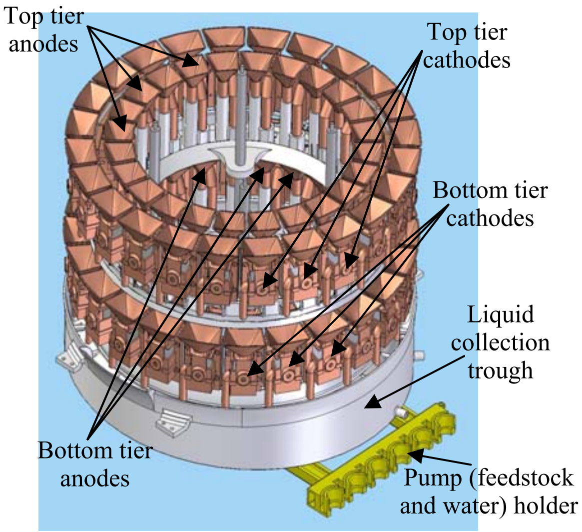


Figure 2: CAD snapshot of the MFC stack onboard the middle part of the EcoBot-III chassis.

Isolated liquid (feedstock and H_2O) distribution

When connected in stacks, MFCs behave like batteries and are thus prone to 'shorting' and system failure if brought in fluidic contact. This may be the result of (i) feeding multiple units from a common feedstock bottle, (ii) feeding one MFC unit directly from another in continuous flow or even (iii) if the structural material of MFCs is hygroscopic. This is particularly relevant when there are elements of the MFC network in series. Series connection is a pre-requisite since single units or units in parallel do not produce enough voltage (at max sustainable power) to drive electronic modules nor charge up accumulators. Energy at a voltage below 500mV is insufficient to be usefully harvested. It was therefore necessary to build-in to the EcoBot-III design a method of breaking this fluidic linkage and allowing the isolation between all functional units of the robot, whilst still being fed and/or hydrated from common sources. The problems of common feeding have been previously identified (Ieropoulos et al. 2008). This was the main idea behind the introduction of a ‘carousel’ feeding mechanism, which distributes food and water in a sequential-isolated manner (see figure 4), which also alleviates the problems arising from feeding the bottom MFCs directly from the ones above.

Fluids (substrate feedstock to anodic chamber; water to the cathodes) had to be circulated on board the robot, with all the attendant challenges of “wet engineering”. This meant that the overflowing fluids from the MFC stack were collected in a trough (see figure 3) and periodically recycled back into their respective reservoirs (food into stomach; water into distribution nozzle).

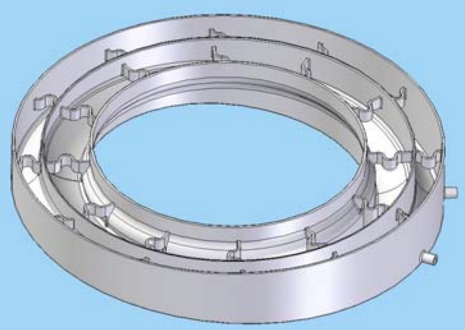


Figure 3: CAD image of the fluidic collection trough – inner channel (food), outer channel (water). Return ports are shown on the side. N.B. This is the bottom part of the image in figure 2.

Carousel feeding/distribution mechanism

As mentioned before, a sequential distributor was built-in to the EcoBot. This was a carousel-like mechanism which was motor-driven to increment its state by one position at a time so that all the MFCs can be fed and watered in an isolated manner (figure 4).

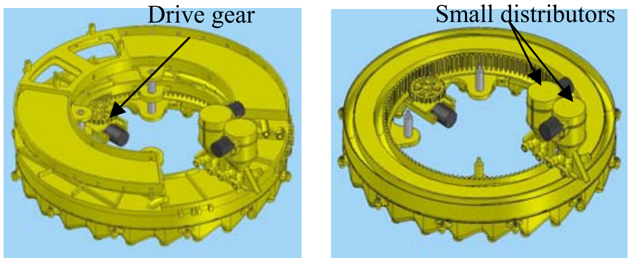


Figure 4: (Left) CAD snapshots of the carousel feeding mechanism; (right) the complete carousel feeding mechanism uncovered. Outside channel is for water and inside for feedstock. Funnels at the bottom of the part are the inlet nozzles for each MFC unit.

The carousel unit has additional smaller motor-driven distributors in order for food and water to be distributed over 4 outlet ports – in essence feeding 4 quartiles at the same time. The amount of fluid flowing per feed and water dose was intentionally superfluous so that the 4 MFCs on the top tier would overflow into the corresponding 4 MFCs on the bottom tier, during each feed or hydration.

Ingestion, digestion (stomach), fly-trapping and egestion of waste

One of the main objectives of this study was the design and development of mechanism(s) to allow the intake and processing of food and evacuation of the waste products e.g. recalcitrant and inorganic matter. To this effect a digestion unit was designed (figure 5) which incorporated a conical hat with added features (UV light, pheromone pocket, and liquid collection lip) to allow the ingestion of either liquid food or flies. In addition, the bottom part of this digestion unit was designed to allow the sedimentation of heavy-weight particles and was connected to a peristaltic pump, which allows the excretion of this material, in an effort to rid the microflora in this digestion unit from the accumulation of poisonous waste by-products, e.g. acid waste.

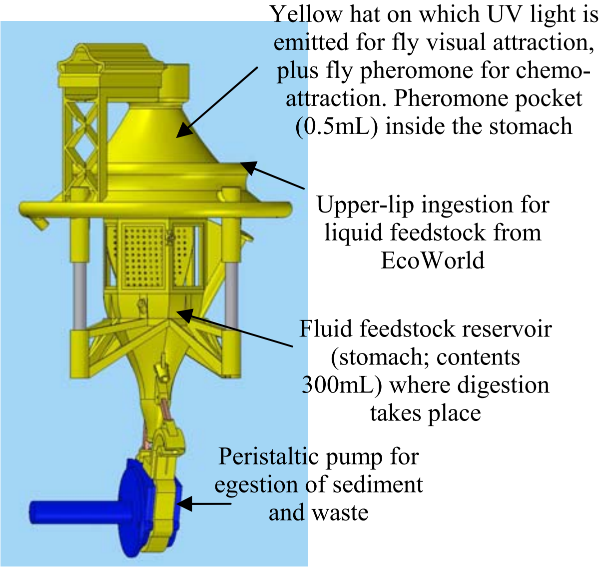


Figure 5: CAD image of the stomach unit with the ingestion, digestion and egestion features. The underside of the conical hat (not shown) is black and the stomach has transparent windows to ensure that flies remain trapped.

EcoBot-III was designed to operate on two feeding strategies; one attracting insects (flies) using pheromone bait and UV-light (as a visual stimulus), in order to lure and trap the flies in a fluid reservoir and the other collecting liquid food supply (complex broth or pure substrates) from a feeder mechanism from the side-wall of the test bed arena (see below). Visual attraction is by UV light LED’s flashing periodically on the yellow surface of the stomach hat and chemical attraction is by using the fly sex pheromone Z-9 tricosene – only as a primer.

Onboard accumulator

However good the stacks of MFCs may be, power is still insufficient to run all actuators simultaneously and continuously. Energy storage, action selection processing and pulsed behavior patterns must be embedded. This was the core of the electronic circuitry which employed a capacitor bank acting as the energy accumulator.

Initially 0.408F capacitance was used (60 x 6800μF electrolytic capacitors 6.3V), which subsequently doubled to 0.816F (120 x 6800μF electrolytic capacitors 6.3V). The voltage operating range (V_{dis} = 2.96V; V_{ch} = 1.9V), was dictated by the symmetry around the intersection point between the actual capacitor charge curve and its first derivative.

Control architecture overview

Figure 6 below illustrates the actual embedded ultra-low power microcontrollers, *in situ*, for sensing and on-board actuation to maintain homeostasis. The main list of components is: microcontroller board (PIC46F20); startup isolator; 3.3V and 5V PSU board with onboard comparator; input board; output board; H-bridge board; level sensor board; pump driver board; photo eye boards; UV LED driver board.

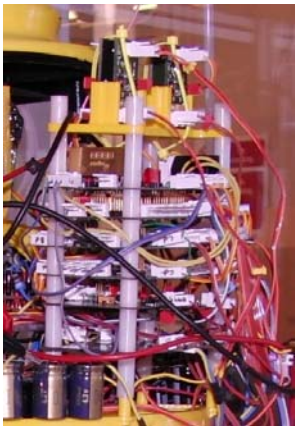


Figure 6: Control hardware onboard EcoBot-III, connected and running

EcoWorld (the robot arena)

The arena was constructed out of transparent Perspex and contained the robotic track and the water and liquid feedstock distribution mechanisms (figure 7).

The internal temperature was controlled by thermostatic fan heater to maintain the temperature at 30 ± 5 °C. The dimensions were 70cm x 100cm (floor area) x 67 cm height. Two microprocessor controlled feedstock distribution mechanisms (one for liquid nutrient, one for water) were designed and built, each with radio connectivity. The system distributes a fixed fluid volume on to the robot in response to the robot making contact with the micro switch.

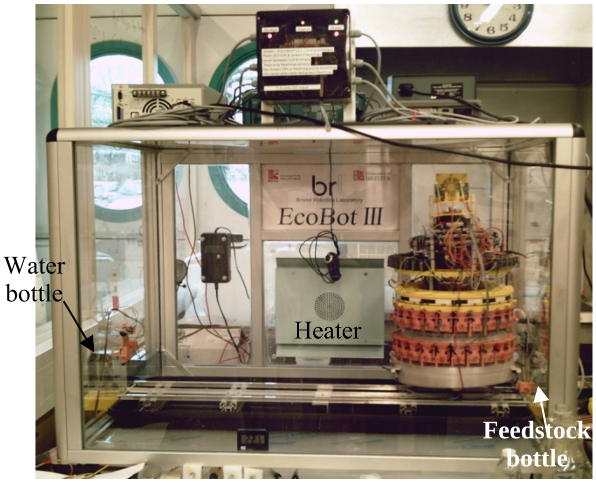


Figure 7: EcoWorld finished with EcoBot-III on its robotic track inside. The external (arena) microcontroller is shown on the top, with water and liquid feedstock bottles shown on the left and right, respectively.

EcoBot-III

The final prototype EcoBot-III is shown in Figure 8. This is the resultant platform that integrates all the aforementioned functional units. The robot has the following physical characteristics: height, 63cm; diameter (outer), 29cm; weight (with full stomach, MFCs and trough), 5.88kg.

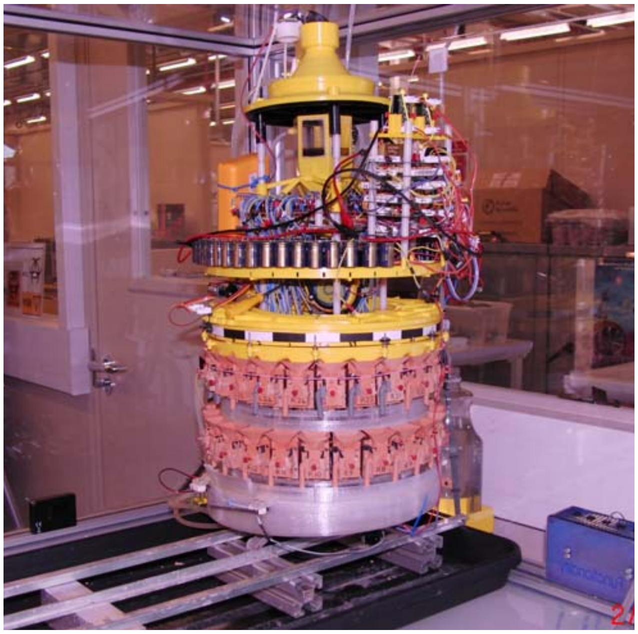


Figure 8: EcoBot-III in its final state and in the EcoWorld. The whole robot is made from 3 different rapid prototype materials: Nanocure® resin for the MFCs, yellow ABS for the more intricate parts due to its soluble scaffolding and polycarbonate (ISO) for the more 'heavy duty' parts.

As previously mentioned, EcoBot-III has been constructed in such a way, that there is only one waste evacuation mechanism. Microbial Fuel Cells have been developed with a continuous flow design, by which excess fluids (useful and useless) overflow to the outside and below. The current EcoBot consists of 2 tiers of MFCs. Fluid flows from the header tank (digester) into the MFCs of the first floor, which when full (6mL total volume) overflows directly into the MFCs of the level below. Overflow from the bottom MFC tier is collected into a trough, which loops back into the header tank, thereby allowing the re-circulation (and hence further utilization) of useful 'waste' that has overflowed from the MFCs. Eventually, undigested or indigestible waste will accumulate inside the digester unit, which has been designed with a central port for evacuation. This is located at the bottom of the digester, so that heavy weight particulates can settle. A heavy duty peristaltic pump has been modified and fitted at the bottom of the header tank, so that it can be periodically actuated to allow some of this semi-solid waste material to evacuate the digester in the form of a pellet. The solid (or semi-solid) waste evacuation is at the moment performed on a time basis (once every 24hrs). The semi-solid stomach contents may be periodically agitated (not part of the current design), using a high-speed dc motor with a flexible long shaft to bring solids into suspension and allow their re-distribution through the MFC network.

Results

EcoBot-III is designed to collect and utilize flies, however experiments in which live flies are introduced into the robot's arena (EcoWorld), in order to evaluate its autonomous behavior based on only 'insect-diet' are ongoing and have not been completed. The data presented herewith, are from the experiments in which EcoBot was manually fed with fly-juice (sludge that had been fed with flies) and also in which EcoBot successfully collected pasteurized sludge (artificial wastewater) from its environment.

Fly attraction

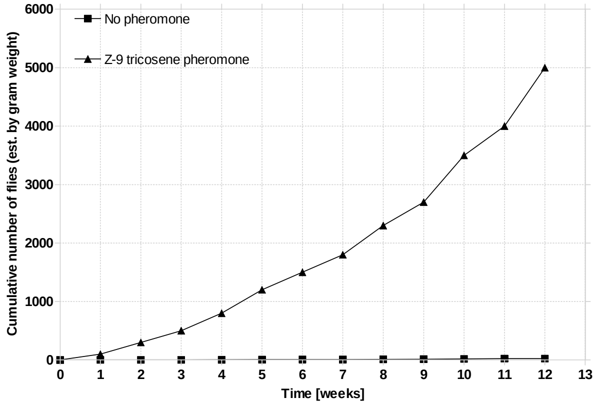


Figure 9: Comparison between fly-traps working with the chemo-attractant pheromone (triangle symbols) and without (square symbols; control).

Although live flies were not introduced in EcoWorld, the effectiveness of the Z-9 tricosene pheromone against a control was still of interest, since the stomach of EcoBot-III is designed to accommodate a small volume (0.5mL separate pocket inside a 300mL digester) of this chemical as a primer. Experiments using conventional fly-traps with the Z-9-tricosene pheromone (28mL in 2L) and without (control) have shown a remarkable difference (figure 9).

EcoBot-III telemetry data

EcoBot-III is designed to communicate with a basestation for reporting data such as time stamping, voltage of the onboard accumulator, task identity, fluid level status for the stomach and trough and also origin and destination in the arena. A snapshot of the telemetry data received from the real EcoBot-III experiments is shown below in figure 10.

```
0:7:53:11,E,52,LF,2.963,11010101
0:7:53:15,OFF,1.951,11010101
0:8:47:56,E,54,LF,2.950,11010101
0:8:48:0,OFF,1.932,11010111
0:9:41:42,E,54,LF,2.966,11010111
0:9:41:46,OFF,1.935,11010111
```

Figure 10: Exemplar of a string of telemetry data received from EcoBot-III when running in EcoWorld. In this particular example, the robot is moving towards the left feedstock distribution (looking at the arena from the front), and it is actuating every 54 minutes.

The incoming data (red boxed transmission) can be interpreted as follows (from left to right): **Days**: **Hours**: **Minutes**: **Seconds**, **Energy actuation** (as opposed to timer triggered actuation), **Time between actuations**, **Task** identification, **Capacitor Voltage**.

Binary data string (MSB→LSB): Arena right feedstock and H_2O distribution (1 = not there yet); Arena left feedstock and H_2O distribution (1 = not there yet); Stomach **low** fluid level (1=full, 0=empty); Stomach **high** fluid level (1=full, 0=empty); Trough feedstock **low** fluid level (1=full, 0=empty); Trough feedstock **high** fluid level (1=full, 0=empty); Trough H_2O **low** level (1=full, 0=empty); Trough H_2O **high** level (1=full, 0=empty).

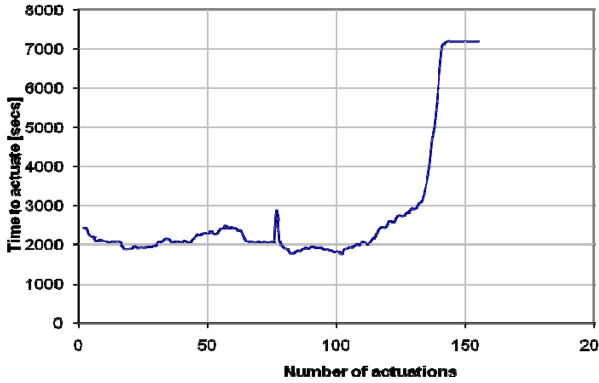


Figure 11: Time to fire vs. number of actuations for feedstock distribution via carousel mechanism. EcoBot-III operating for 5 days, feeding on anaerobic sludge that had been given dead flies.

Data from experiments completed using EcoBot-III are shown below in figure 11. This is the processed version of the telemetry data received from EcoBot during a 7-day experiment, when EcoBot was feeding on flies (>10 in 300mL of stomach contents). The data show that the robot was actuating (feeding the MFCs) every approx 30 minutes, until a mechanical failure occurred at the 111th actuation, at which point the time to fire increases exponentially.

EcoBot-III has a defense mechanism, by which it triggers actuation using a timer (after 2 hours) if during this period energy has not accumulated to the pre-set threshold at the correct rate (flat line at the end of the curve). All other actuations have been filtered out to show only those related with feeding – this could have been done for any of the actuations. In reality the total number of actuations (including hydration) was twice as many (309 firings) as shown in figure 12.

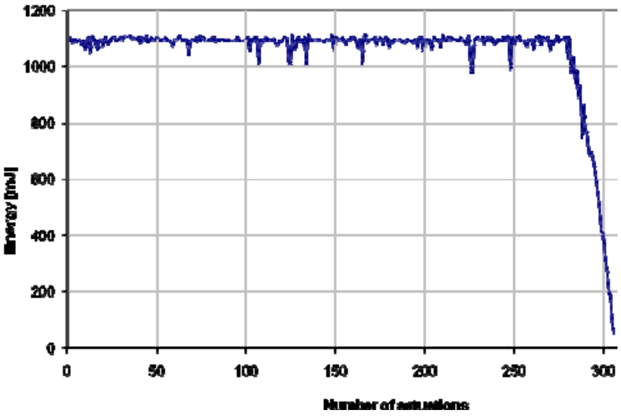


Figure 12: Total energy generated per actuation

Liquid feedstock (synthetic wastewater with 20mM sodium acetate)

In this experiment, EcoBot is employing the second feeding strategy, which is utilizing liquid food from the arena wall.

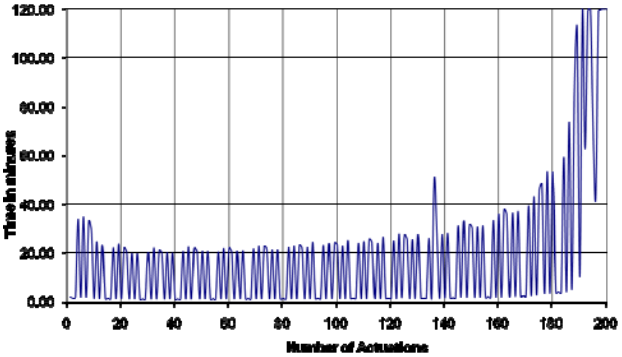


Figure 13: Time between actuations when EcoBot was feeding from the arena.

The liquid feedstock was artificial wastewater consisting of nutrients, minerals and carbon energy source (20mM acetate), but was deprived of any microbial growth that is found naturally in wastewater. This was in order to ensure that the energy is coming from this feedstock and not from exogenous (and newly introduced) microbes.

Figure 13 below shows the relationship between the number of actuations and the time (in minutes) it took for each actuation to fire.

As can be seen from the graph above, the time varies depending on the actuation, since different actuations use different amounts of energy and therefore take longer (or not) to occur. The increase in time between actuations is an indication that EcoBot is slowing down (MFC exhaustion; possible blockage; feedstock leakage due to blockage shorting MFCs out). The distribution of energy for each actuation is shown below in Figure 14.

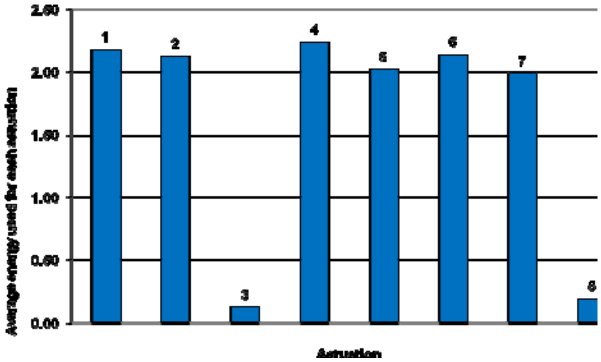
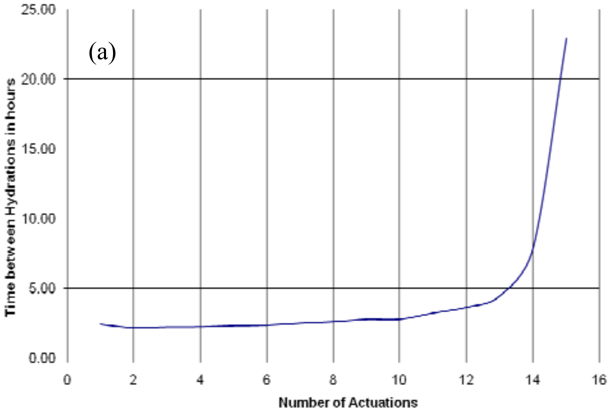


Figure 14: Energy usage per actuation; the numbered actuations are as follows: 1) water distribution (hydration) of cathodes; 2) feedstock distribution (feeding) of microbial anodes; 3) carousel indexing one position; 4) feedstock recycling into the stomach; 5) locomotion; 6) egestion; 7) UV light attractant; 8) single UV flash before each actuation.

As an exemplar of all actuations, onboard water distribution to the cathodes was further analyzed, as shown below in Figure 15.



The data in Figure 15, show a stable behaviour in terms of this particular actuation for the vast majority of hydration cycles, up until the point that the performance begins to slow down, at which point the time between actuations increases exponentially. Equally, the energy spent per hydration cycle is stable within ±10%, up until the system performance deteriorates. When EcoBot operates correctly, then the graphs for all actuations are constant.

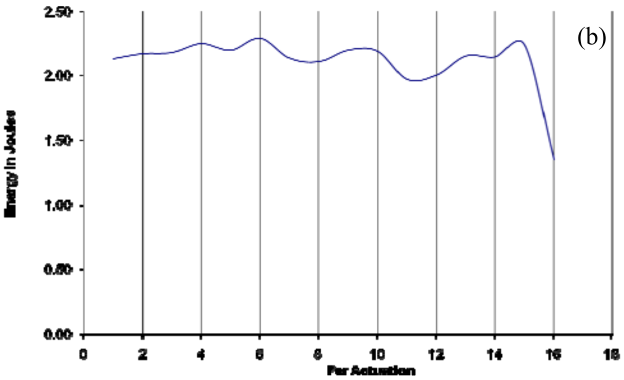


Figure 15: (a) Water distribution to MFC cathodes; (left) time between water distribution in hours; (b) average energy per water distribution actuation.

On this particular occasion, the EcoBot performance deteriorated due to the fact that the robot was dehydrated and did not make it to the water distribution mechanism on the side wall of the arena. The experiment started (intentionally) with an empty onboard water trough reservoir but with fully moistened MFC cathodes, to investigate whether it would make it to the water point. In addition, extra actuations were introduced (UV single flash before every actuation) and waste evacuation at the end of each actuation sequence. In reality, waste evacuation takes place only once in a day and there is no UV single flash before each actuation. These experiments are currently ongoing.

Discussion

Developments in energy-autonomous robots using microbial fuel cells (MFC) can be expected to be attractive to industry in two areas. Firstly, the MFC technology itself may eventually reach a development stage where it produces comparable energy densities with those of ‘domestic’ batteries and therefore provide an alternative, carbon-neutral, power source. This could lead to stand-alone appliances such as sensors, alarms, telecommunications, low energy lights, small pumps or actuators, small motorized systems (fans, robots) and trickle chargers for charging car batteries. Possibly the technology could be scaled sufficiently to generate energy from large ‘reservoirs’ of biomass such as those found in sewage treatment works. These fuel cells can also utilize waste products (such as acetate) from current fuel cells which are being employed to generate hydrogen thus improving the overall efficiency.

Autonomous robots powered from MFCs will have a wide range of applications and will be attractive to industry. The finding that MFCs can utilize waste (sludge) suggests that the technology can be considered as a useful novel method for tertiary wastewater treatment. Regarding their application into Symbots (i.e. EcoBot) provided their energy supply is sufficient for them to function and carry out their tasks, it may not matter that they are neither the most efficient nor the quickest; sufficient is all that matters. Therefore, it is easy to envisage energetically autonomous robots employed for monitoring of farm land and crops, sewers and also for marine exploration in non-sunlit waters.

Energy autonomy. It is clear from our work that as long as EcoBot is performing correctly within its working environment and is provided with food and water via the arena (EcoWorld), it continues to function well. It can gain sufficient electrical energy from organic food to continue motion on its track, to collect water and food when needed and distribute these to the MFCs. It has sufficient energy on board to also perform other exemplar tasks such as elimination of non-digestible components by controlled ejection of “waste”, sensing (of temperature and light), data processing and radio transmission of logged data.

Bio-regulation. When mixed-culture “ecologies” are transplanted into EcoBot, they consist of a wide diversity of different groups and species of microorganism. Further groups of microbes may also be introduced, depending on the nature and source of the food – e.g. rotten fruits and vegetables and sludge carry with them their own microbes (essentially responsible for the rotting). The physicochemical environment within EcoBot (albeit different to the microbe’s original natural environment) is nevertheless a suitably selective environment for the more robust microbes’ survival and growth. The microbial community that finally adapts to this system, will still be sufficiently diverse to function. Clearly, some species that do not like the prevailing environment will diminish in population number (be selected against) whilst others that can adapt will be enriched. Electroactive species of microbe appear to be enriched as biofilms around the anodic electrodes. Within the stomach-digester (artificial gut) the main types of species (in a low dissolved oxygen environment) are likely to be strict and facultative anaerobes, and the main pathways by which they will gain energy will be via fermentation. Polymeric food molecules (starch, chitin, proteins, saccharides) are hydrolysed by microbial enzymes to give monomeric molecules that can be taken up by the cells. Fermentation produces organic acids as the main end-products of metabolism, including acetate, propionate, butyrate, lactate, formate, alcohols and carbon dioxide. The acids produced would normally be expected to reduce the pH. The organic acids (e.g. acetate) are circulated to the MFC units where electrogenic species utilise them by oxidation, through the abstraction of electrons (via the electrode) and producing carbon dioxide and more protons. However, the build-up of acids (and resulting low pH) does not appear to occur, possibly because of one or more of the following reasons: (i) the anaerobic sludge microbes forming into robust and stable biofilms, naturally buffering their surroundings (concomitant production of ammonia and other basic molecules at a rate which neutralises the pH); (ii) loss of acids through volatilization; (iii) effective removal of protons by the MFC cathodic system (PEM and cathode).

The latter mechanism appears to be the most important and the system maintains pH homeostasis throughout continuous operation. Alternative designs of cathode employ closed chambers with either chemical electrolytes, fast running water or aerated water. All these systems require high amounts of energy to remain operational and help catalyse the reaction: $O_2 + 4e^- + 4H^+ \leftrightarrow 2H_2O$ [+0.82]. In the cases where the chemical electrolyte is fully reduced, or the water/air stops flowing, then the cathodic system no longer acts as the oxidising half-cell, and the H^+ ions generated in the anode (cations) cannot find their electrochemical path through to the cathode, thus accumulating to lethal levels for the microbes. The open to the air/periodically moistened cathode, might not be as efficient as the aforementioned alternatives at the initial stages of the MFC lifetime, however it continuously improves with time and eventually outperforms all other systems, especially in terms of longevity. It would be interesting to see (as part of future work) what happens if the robot is fed acid or alkaline mixtures of feedstock, or whether acid build-up does occur when the MFC are electrically disconnected.

Nutrient acquisition behavior. In the programming of EcoBot, nutrient acquisition is triggered by contact with the feed and water distribution mechanisms of the arena, at which point the behaviour changes so that the robot feeds and hydrates all MFCs, before it moves away to do other functions. Provision for different behavior patterns has been made so that the robot can move towards the feed/water distribution points when fluid levels are low or indeed when energy levels from the MFCs are low. This is what we would term as 'hunger' simulation.

Conclusions

As the development of MFCs continues (using smaller units which make for more powerful stacks), then the ability to utilise MFC-stacks on board robots will become more attractive and commonplace. This study shows the feasibility of the Symbot approach, albeit being far from fulfilled. It may not be a perfect system and still a proof-of-concept prototype, however, it is the authors' conclusion that EcoBot-III demonstrated energy autonomy, when fed with nutrient rich liquid feedstocks and within the boundaries of its environment.

To the best of the authors' knowledge, this is the first example of a robot, which integrates real life and machine in a symbiotic manner (Symbot) for digestion and autonomous operation as an exemplar of artificial life.

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