Energy autonomy in robots through Microbial Fuel Cells

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The ability of robots to operate with minimum human intervention, independent of the energy supply, is often enough to term an agent autonomous. However, there is a clear distinction between computational ability and energy obtainment. These have already been identified as *computational* autonomy and *energetic* autonomy [1]. Battery-operated robots, for example, demonstrate computational autonomy but not energetic, whereas solar-powered robots demonstrate both provided that sufficient energy is available.

Energetic autonomy is particularly important as robots will be required to extract energy from the environment. In many ways robots will face the same problems as animals.

A robot powered by live microorganisms can utilise as fuel a wide range of organic substrates of the types found in agriculture or food wastes. This implies that robots can be designed to operate in a range of habitats where they can exploit various forms of energy sources and hence illustrate a different (perhaps higher) level of autonomy. We believe this is the first step towards a truly energetically autonomous robot.

Microbial Fuel Cell (MFC) technology offers the potential of exploiting microbial metabolism to produce electrical energy. This is a good way forward, as the robot will incorporate in its behavioural repertoire actions that involve search and get hold of food and also remain inactive until energy is sufficient to do the next task. This will be a paradigm shift in the way action selection mechanisms have been designed so far.

A MFC is a *bio*-electrochemical transducer that converts *bio*-chemical energy to electrical energy, in roughly the same manner as a normal fuel cell. Microbial fuel cells fall under the proton exchange membrane (PEM) fuel cell category, since that is the solid electrolyte used in the system. The MFCs used for this line of experiments were of identical design and structure to the ones previously used for EcoBot I. The difference in these fuel cells was the *bio*catalyst employed, i.e. the culture of microorganisms. In this case it was decided to employ sewage sludge obtained from anaerobic activated samples (Wessex Water Scientific Laboratory). The choice of this microcosm proved to be advantageous for a number of reasons some of which are ease of preparation, growth media and substrate diversity, and unmodified physicochemical conditions. Furthermore, MFCs incorporating sewage sludge are producing as much as 10 times more power than that produced by the MFCs using *E. coli* and mediator. Figure 1 below shows a picture of the EcoBot II.

EcoBot II, which builds on its predecessor, EcoBot I [2,3,4] performs environmental monitoring, powered solely by microbial fuel cells (MFCs). It is integrated with a wireless transmitter connected to a temperature sensor, so that temperature information can be fed to a terminal that is away from the robot. The sensed and transmitted data does not have to be temperature. It can be anything that is in relation to the environment of the robot like for example, toxic levels, humidity or an indication of its internal state, such as pH, fluid substrate level etc. This can be extremely valuable in remote area access and monitoring. The robot consists of eight MFCs that suffice for both tasks. This is the first reported robot in the world powered by MFCs that has the ability to transmit wirelessly information about its environment. In contrast with its predecessor (i.e. EcoBot I), EcoBot II utilises raw foodstuffs such as dead flies or rotten fruits. It is also the first in the world to employ the gas (O_2) diffusion cathode, which in terms of autonomy is extremely important. What is novel about our work is the integration of MFCs fed with *raw* substrate and utilising O_2 from air with a small scale robot.

Figure 1 below is a picture of the EcoBot II with the O2 cathode MFCs onboard and Figure 2 is a labelled schematic diagram of the robot.

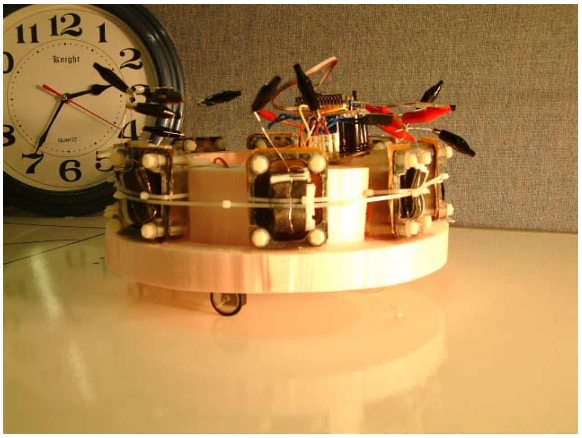

Figure 1. EcoBot II fully assembled with the wireless transmitter and temperature sensor on top.

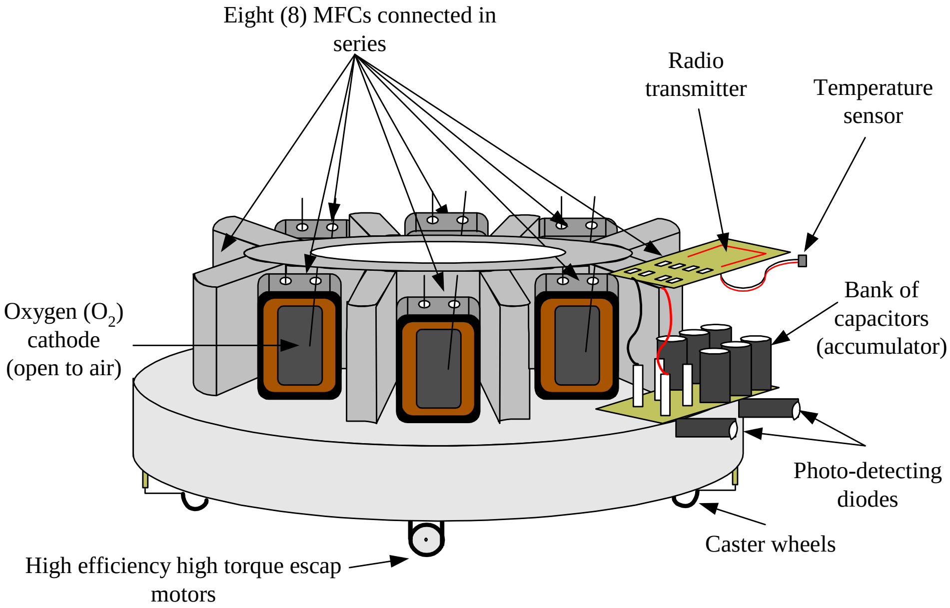

Figure 2. Schematic diagram of EcoBot II with labelled parts.

The whole concept of the experimental set-up with EcoBot II is shown below in Figure 3. In essence, the robot moves towards the light source whilst at the same time wirelessly transmitting information. This is performed in a ‘pulsed-mode’ behaviour. What this means is that the robot employs a ‘waiting pattern’ in its operation to allow for energy to accumulate in the onboard bank of capacitors. Once this is achieved, the energy is transferred to the wireless transmitter and to either or both of the actuators (motors) according to the signal from the photodiodes and the agent moves for a few centimetres transmitting temperature information, until it runs out of energy again. It will again remain ‘idle’ for the amount of time required to accumulate energy and repeat its little step towards reaching its goal (light source).

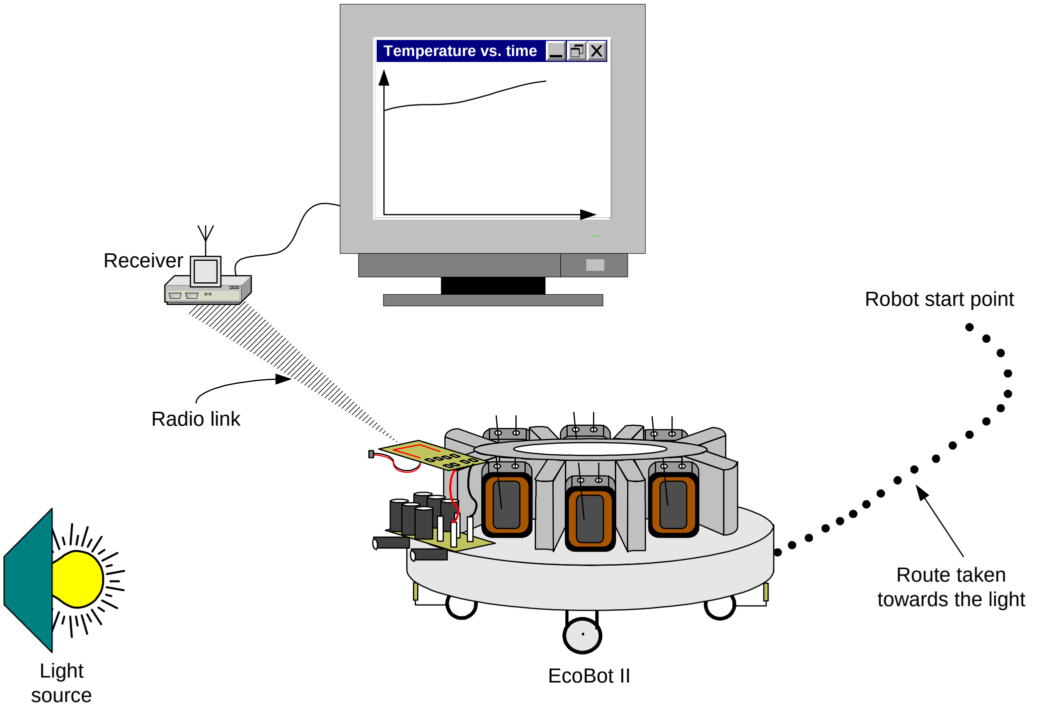

Figure 3. Experimental set-up: EcoBot II with the O_2 cathode MFCs moving towards the light whilst transmitting the temperature to a base-station. The maximum (indoors) range of transmission is 30m.

EcoBot II is not the first robot in the world to use bacteria. The first was Wilkinson’s Gastronome (Chew-chew) in 2000, which employed chemical Fuel Cells to charge up a bank of Ni-Cd batteries [5]. Power was generated by E. coli fed with refined sugar, and a synthetic mediator (HNQ) enhanced the electron transfer process to the chemical fuel cells.

As far as MFCs are concerned, we are not the first group in the world to exploit sludge, and certainly not the first in the world to use the O_2 cathode. To the best of our knowledge the first sludge MFC reported in the scientific literature was from Habermann and Pommer back in 1991, in which case they had a stack of MFCs running continuously for 5 years [6]. In later years, Park and Zeikus (2002) had done some significant experiments with sludge, E. coli and neutral red [7]. And more recently, but certainly before us, Logan’s group at Penn Sate, have illustrated power generation from sewage sludge and more importantly with and without using a proton exchange membrane.

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