Artificial control of microbial life: Towards a urine fuelled robot

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Abstract

This study describes the ongoing work with a Microbial Fuel Cell (MFC) stack, which will power the latest version of self-sustainable robots – EcoBot-IV – that uses human urine as the fuel. This paper reports on the dynamic electrical control, power management and hydraulic arrangement of the stack and the effects that these elements have on the rate of energy extraction and consequent shift in metabolism of the microbial ‘engine’. We demonstrate that a peripheral system that is manually controlled, can optimise energy extraction from the MFC stack and decrease super-capacitor (1.5F) charging times by 33%. Furthermore, it is shown that connecting MFCs in different cascade configurations can result in varying power outputs and metabolic activity in MFCs, and could dictate the way that urine is supplied to the bacteria.

Introduction

A Microbial Fuel Cell (MFC) is a bio-electrochemical device that generates electricity directly from waste, through the metabolic reactions of electro-active bacteria. A single MFC cannot produce sufficient energy to directly power electronic devices. One possible method for meeting these power levels is by stacking MFCs or by using energy harvesting systems, with unavoidable efficiency losses. Depending on the number of units and their electrical configuration in a stack, the overall voltage and current can be stepped up to useful levels for charging accumulators or running real applications.

Developing an intelligent microbial electrical system

Previous work has shown self-sustainable robots capable of simulating biological functions, such as food ingestion, digestion and waste egestion [1]. For example, EcoBot-III, a 6kg robot, utilised a stack of 48 Microbial Fuel Cells (MFCs) for energising a complex robotic platform, which performed energy intensive tasks. MFCs contain live microorganisms, whose metabolic reactions result in electricity generation and thus the association between living microorganisms and robotic devices has been described as artificial symbiosis, with these robots becoming known as Symbots [2].

Since then extensive experiments have taken place with MFC stacks to increase their performance and efficiency. The idea behind this work is to expand the knowledge from the self-sustainability perspective. The present study uses a novel monitoring system and an efficient way of storing energy harvested by MFCs, whereby dynamic reconfiguration of the electrical connections of a stack of 24 MFCs, decreased the charging times of a super-capacitor. In conjunction with that, the architecture of substrate distribution amongst MFCs is examined in 8 different cascade scenarios in an effort to analyse the effect that each scenario has on the overall performance and the waste remediation capability.

Monitoring ‘health status’ of MFCs in the stack

When operating in a stack, the performance of MFCs varies due to the collective internal resistance. It is therefore critical to monitor in real time the performance of each unit within the stack and understand the reaction of individual units when in stress, reversed or when fed and hydrated. Hence, a smart switch box was developed to connect the MFCs with the provision of dynamic re-configuration and also to monitor the voltage (or ‘health’) of each unit. This process is monitored in real-time with an Agilent 34970A (Hewlett Packard, USA). A special interface for monitoring and analysis was developed, which enables telemetry and control.

Hydraulic connection of MFCs

MFCs have been characterised as wet-batteries, and as such the fluidic configuration is equally important to the electrical connections for optimum performance. Thus the 24 MFC stack, which was fed with real human urine, was also examined under 8 different fluidic connections/cascade scenarios. Each scenario investigated the impact that a fixed electrical configuration with sequential units hydraulically connected have on (i) COD removal (a measure of waste treatment), (ii) power and current generation and (iii) internal resistance, by gradually adding units downstream. The purpose is to simulate a real environment scenario whereby a MFC stack is reconfigured electrically and/or fluidically on the fly, so as to meet the energy or remediating requirements of the robotic platform when environmental conditions, substrate content and flow rates change dynamically.

Results and Discussion

Results showed that the dynamic switching improved charge transfer by 35% of the energy stored in the super-capacitor, compared to a fixed electrical configuration that was applied in the previous EcoBot-III stack in order to charge the super-capacitor to 3 Volts. This novel technique is based on the dynamic connection of different units in series or in parallel depending on the different stages of super-capacitor charging, which achieves a faster rate of energy transfer, at a faster rate of metabolism by the constituent microbial community. Improvement in charging time was shown from 0 to 4 Volts when the dynamic reconfiguration was applied (Fig.1).

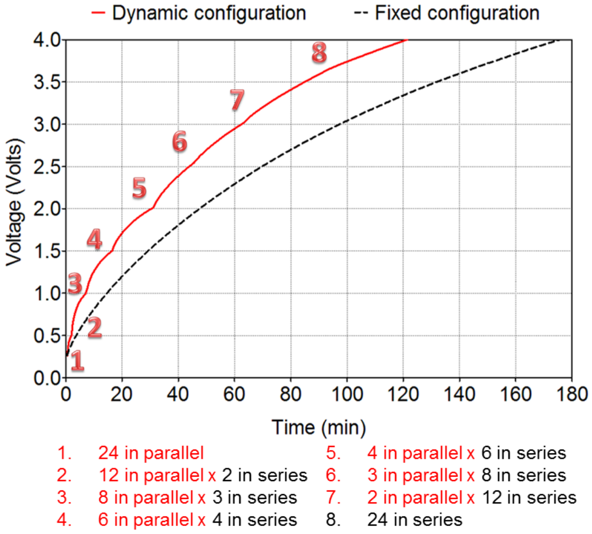

Figure 1. Charging of a 1.5F supercapacitor with the dynamic switching and a fixed configuration. Numbers represent the stack configuration.

The 24 unit stack was connected electrically in-parallel whilst MFCs were progressively added downstream in a cascade manner. The parallel MFC stack produced an initial power of 2mW, when the constituent MFC units were individually fed. However, when the MFCs were positioned in a cascade arrangement, with units placed downstream from each other, this created a substrate bridge whereby the 'used' outflow from the first MFC was gravitationally directed into the MFC below. A total of twelve isolated pairs of MFCs, achieved a 30% improvement over the overall performance compared to the individually fed stacked MFCs. The addition of a third downstream unit (forming 8 fluidically isolated triplets) reduced the overall performance but improved the COD removal. The same decreasing pattern in power from different electrical configurations was observed for up to six connected units (4 fluidically isolated groups). The addition of the eighth unit seemed to improve the performance, but the introduction of the twelfth element again affected negatively the output. Interestingly, all 24 MFCs in cascade displayed a 2-fold increase compared to the previous stage (12-pairs cascade mode) and similar to the levels of the three hydraulically connected elements. The main reasons for this difference in performance could be (i) the low flow rate that was constant the entire time, focused on the remediation factor, and (ii) the cascade effect, in which the organic load is depleted in the early stages of the cascade.

The dynamic electrical and fluidic reconfiguration regime employed in this study has demonstrated that it can affect/improve the performance of the MFCs. The electrical output of MFCs is *directly* related to the microbial metabolism; this effectively means that higher power output corresponds to a higher rate of microbial metabolism. In this way, the peripheral electronic control system 'governs' the biological kinetics.

Conclusions and future outlook

Artificial life strives to understand biological systems and processes through modeling, robotics and biochemistry. When the MFC technology is used onboard artificial agents, where one element is reliant on the other, then this can be used to better understand the role of metabolism in the process of action-selection in animals. The process need not follow an algorithmic approach, but rather exploit the sensory information provided by the constituent microorganisms generating electricity. In this way energy autonomy (collection and management) can form part of a behavioural repertoire, which has got 'survival' – in both the biological and artificial sense – as the highest priority, which becomes an inherent property in any task-oriented mission.

Based on this rationale, self-maintenance in EcoBot-IV can be distinguished in two interrelated levels that their ultimate goal is survival. The EcoBot is an exemplar of artificial agents that have 'searching for energy' built-in to their behavioural repertoire. Consequently, the bacterial 'engine' is the living 'user' that will profit from the functions that the mechatronic side will perform in order to remain operational through behavioural stability [3], [4]. In this context the MFC stack is an autonomous biological system that is fed and maintained by the automated mechatronics system, for the purpose of longevity. The basic function that EcoBot-IV will perform for maintaining viability, is that of efficient energy management [5] where energy loss due to unnecessary foraging is avoided. It is envisaged that EcoBot-IV will reconfigure the hydraulic as well as electrical connections of MFCs in the cascade/stack so as to maximise substrate utilisation of the onboard feedstock reserve that has been collected from the environment. This synergy will result in an adaptive behavior that will regulate the control and energy management systems for driving the robot in the most efficient way.

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