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Flora Health Wireless Monitoring with Plant-Microbial Fuel Cell

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Abstract

We propose a self-sustainable wireless sensor node capable to monitor both environmental data and flora health state, exploiting a Microbial Fuel Cell combined with a plant. This bio-electrochemical system is used both as a power generator to supply the wireless embedded electronics and as a biosensor for estimating the status of the plant. We demonstrate that the sub-milliwatt power provided by the fuel cell is enough for achieving an energy-neutral smart sensor that samples and sends data. Moreover, the rate of the harvested power is correlated with the health of the flora living in symbiosis with the bacteria colony. The proposed system has been conceived to address the needs of future smart agriculture applications, providing an unobtrusive and energy neutral monitoring system open to a broad range of applications, thanks to the bacteria species that populate almost any soil on Earth.

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Keywords: microbial fuel cell; embedded system; wireless sensor; energy harvesting, low power design; power management; smart agriculture

1. Introduction

A Microbial Fuel Cell (MFC) is a special bioreactor used to produce electric power exploiting chemicals reactions of specific electrogenic bacteria. Even if this property is well known in literature, it is still not employed in everyday applications. Despite MFCs have been used in some interesting applications for environmental purposes such as wastewater treatment [1], a small size MFC can operate correctly and can provide enough power for electronic devices, only with a careful electronic design, because the power produced by a small MFC is usually in the

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sub-milliwatt range. A MFC operates thanks to some specific bacteria capable to produce electricity during metabolism [2]. Such bacteria are quite common and easy to exploit because present in many soils and aquatic environments on Earth [3]. Two specific electrodes enable the gathering of the charges and permit to use the electric power acting as a bacteria-based battery.

Starting from a previous work [4], this paper presents the use of a MFC in combination with a plant, which creates a “bio-system”, called Plant-MFC (PMFC), and a schematic representation is shown in Fig. 1. This combination permits to amplify the power produced by a simple MFC, because the substances excreted by the plant roots during photosynthesis are nutrients for the bacteria communities that boost their multiplication, eventually incrementing the chemical reactions in the MFC.

Generally, healthier the plant and its photosynthesis activity, higher will be the power generated by the PMFC [5]. The power density of a PMFC depends also on several other factors, and a deterministic correlation between flora health and power generation is challenging. Nevertheless, the principle could still be used, and thanks to the characterization of each specific bio-system, the determination of operating regions of the MFC that indicates if the photosynthesis is well active or silent is possible. This knowledge permits to understand the long-term plant health.

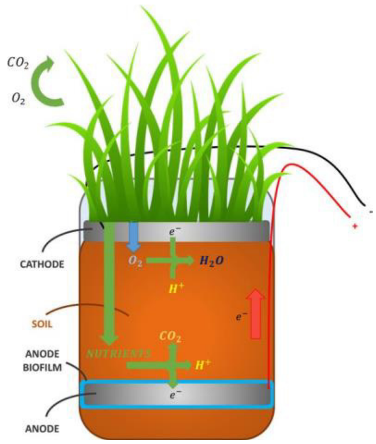

Fig. 1. Schematic representation of a PMFC

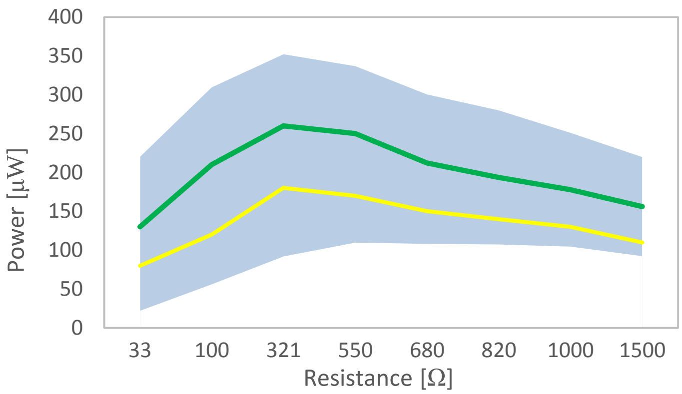

Fig. 2. Measured output power of a PMFC with moderate photosynthesis activity (upper line) and of a MFC without plant (lower). The area represents the variability in different conditions

2. MFC flora sensor

Typically, a MFC operates thanks to two electrodes: an anode, deep into the soil, where the electrogenic bacteria are concentrated and release electrons during metabolism of nutrients, and a cathode, near the surface, where oxygen from the environment is used in the reduction of electrons. Electrons collected by the anode at the bottom of the MFC, create a current loop which closes to the cathode, where chemical reactions with oxygen produce water. The usual reactions involved in a MFC are:

- Reduction at the cathode (oxygen rich): $O_2 + 4\,H^+ + 4e^- \rightarrow 2\,H_2O$
- Oxidation at the anode (acetate-like oxidation): $CH_3COO^- + 4\,H_2O \rightarrow 2\,HCO_3^- + 9\,H^+ + 8\,e^-$

The bacteria specie affects the function of the cell, since different reactions can take place at the anode according to the presence of different nutrients for the bacteria colony, in fact the introduction of a plant changes the equilibrium, because it releases some organic compounds through its roots (i.e. glucose and organic acids), thanks to photosynthesis. The key product of photosynthesis used by the bacteria colony is the glucose, that is a fundamental nutrient for boosting the bacteria colony and the operation of a MFC. Also other organic compounds demonstrated to boost the performance of a MFC [6]. When the bio-system PMFC is built, the soil in the surroundings is affected by the status of the plant and therefore the output power generated by the cell changes accordingly. The main function of the plant is to provide some nutrients to the bacteria by means of photosynthesis reactions and because of that, an unhealthy plant will degrade the performance of the PMFC system that would run out of nutrients. In this way, monitoring the output power means also having a measure of the activity of the flora that is growing in the same environment. We characterized a simple bio-system reproduced in our laboratory, measuring average output power in the range from 200 to 300μW. Some of the measures are shown in Fig. 2 and highlight how the presence of the plant increases the average output power sourced by the cell, keeping the same load.

3. Plant health monitoring

To monitor the health state of the plant, it is important to evaluate the output power of the PMFC in relation to its history (long-term behavior). A simple voltage reduction can be negligible as some periodic changes are normal in the MFC functions (for instance, temperature, pH or soil moisture variations change the performance of the MFC). On the contrary, a long term and persistent reduction of power can be a sign of inefficiency of the system and in particular of the plant disease. A PMFC has a slow response in time to external events (because of the presence of the soil), showing a slow decrease of performance when no water is supplied. Because of that, there is no need of checking frequently the power status of the PMFC, and regular measurements at very low rate are enough.

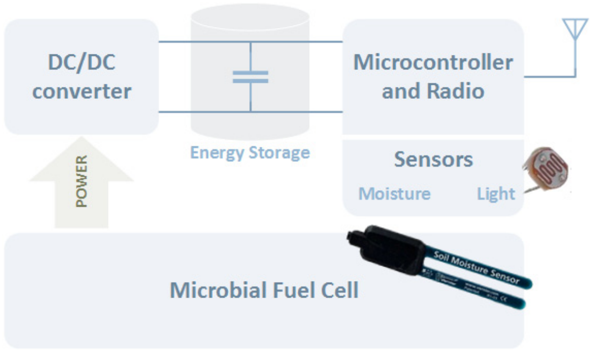

Fig. 3. Block scheme of the sensor node

Fig. 4. Picture of the wireless prototype

Some different monitoring techniques can be implemented to check the power supplied by the MFC, i.e. a direct measurement of the output power or, as in the implemented prototype, through the time needed to charge the capacitor used as energy reservoir for the electronics. We chose to implement a sensor node capable also to measure the surrounding environmental parameters (i.e. light intensity, soil moisture) and to send this data thanks to a low power radio. To further reduce the overall energy consumption, wake-up radio mechanisms could be added to the system, as presented in [7, 8] or advanced compressing techniques [9, 10, 11] can reduce the data size. Fig. 3 represents the schematic block of the hardware, while the realized prototype is shown in Fig. 4.

The regulation of the voltage supply is based on a DC/DC converter that enables MPPT (Maximum Power Point Tracking) operations and charges a supercapacitor. The microcontroller uses the energy stored in the supercapacitor to measure and send the data with a low power radio. The resulting implementation is energy neutral, because it harvests the energy, needed to operate, directly from the monitored system (i.e. the PMFC). The purpose of the smart sensor is twofold: monitoring both the environmental conditions and the plant's health. The measurement of the power sourced by the PMFC is achieved in an indirect way: the frequency of the data sent with the radio to a gateway is proportional to the available power. In fact, the time to charge the capacitor gives a measure of the power that the PMFC provides and therefore the frequency of the received data is a measure of the power sourced by the bacteria-based battery. In an experimental assessment, a timer with 15 minutes interval is set between sampling and sending new data. This permits to measure the duty cycle resulting from the time needed to recharge the supercapacitor. Lower duty cycle values are produced by longer time to charge the capacitor, then lower power delivered by the PMFC to the system, as shown in Fig. 5.

Fig. 6 shows the output voltage of the monitored PMFC, providing a further prove of the decrease of cell performance when nutrients concentration diminishes. Note the difference in voltage when the PMFC is loaded, which is shown in the box of Fig. 6.

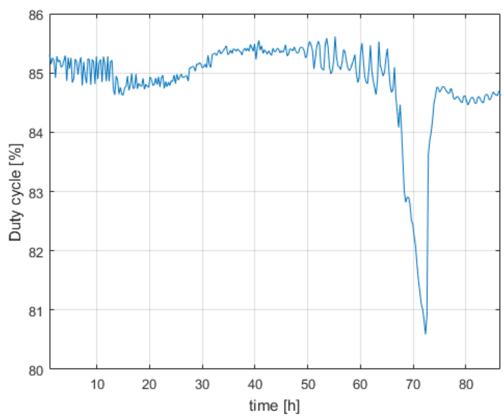

Fig. 5. Duty Cycle measured during a long run test. Lower duty cycle values indicates a reduced photosynthesis activity of the plant.

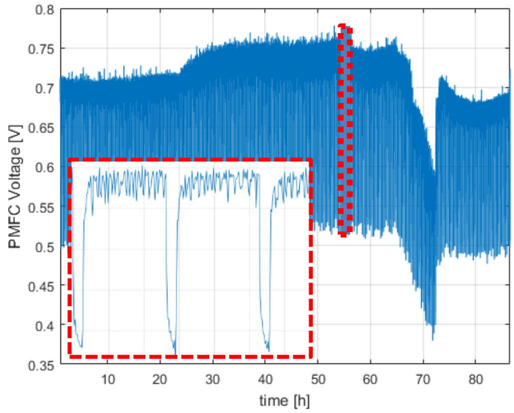

Fig. 6. PMFC Output Voltage measured during the same long run test. Notice the decrement (at ~70h) in correspondence of the nutrients reduction in the soil.

4. Conclusions

We presented the design of a battery-less monitoring system for plant health status, which exploits innovative microbial fuel cell as joint power supply and biosensor for assessing the long-term health of the flora living in the surroundings. The application includes a smart sensor, powered only by the PMFC, with wireless connection to report environmental data. A preliminary prototype has been built and characterized for several weeks of operation.

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