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Microbial fuel cells powered adaptive wireless sensor network for wastewater treatment plants

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Abstract

Efficient monitoring and control of Waste Water Treatment Plant (WWTP) has turned into an important public issue as the cost of electricity continues to grow and the quality requirement of processed water tightens. Self powered Wireless Sensor Networks (WSNs) are more suitable for this application to monitor the status of the waste water. A novel Wireless Sensor Network (WSN) is proposed in this paper which integrates Microbial Fuel Cells (MFCs), Field Programmable Analog Array (FPAAs) to design a self-powered, highly flexible and adaptive system. The profusion of bacteria and chemical ingredients in waste water processing tanks provides materials for MFCs to convert chemical energy into electrical energy. The proposed system can work efficiently for years without hardware maintenance which can also be adaptive to changes in the working environment to achieve higher performance. The simulation of the system is done and the results of which can also be hardware implemented.

Keywords: *Microbial Fuel Cells, Field Programmable Analog Array, Self powered WSN*

1. Introduction

Water scarcity is the major problem that is faced all across the world. Although 2/3rd of the earth's crust is made up of water but all this water is not available for drinking and for other human activities. The major part of water that can be consumed is getting polluted because of human activities. This polluted and untreated water is causing abundant water borne diseases. Also because of improper use of water and lack of water treatment the problem of water crisis will further increase. Waste water treatment is a crucial step to save water as well as life.

Wastewater Treatment Plants (WWTPs) are one of the most energy consuming industrial facilities. Nearly 3% of the total electricity supply is consumed by WWTPs and approximately 30% of WWTP operating budgets are dedicated to electricity. In addition, the demand for electricity at WWTPs is expected to grow by 20% over the next 15 years because of population expansion and increases in water quality standards. As such, energy conservation has become increasingly important to WWTPs. Studies of energy efficiency optimization in both design and operations of WWTPs have been conducted over the past two decades.

Real time accurate monitors and controllers are required for energy efficiency optimization. Updating or replacing the existing infrastructure would be prohibitively difficult and costly to support a wired network of sensors. Wireless sensor networks are more suitable for waste water monitoring system as it has least impact on existing infrastructure. In WWTPs sensors are located in the inconvenient place for regular human maintenance, hence battery replacement is undesirable. Self-powered systems are more suitable as it provide maintenance free operation for many years. To meet these disputes a Microbial Fuel Cells powered adaptive wireless sensor network is proposed in this paper. This novel Wireless Sensor Network (WSN) integrates Microbial Fuel Cells (MFCs), Field Programmable Analog Array (FPAAs) and low power networking protocols into the sensors to make them self-powered, highly flexible and adaptive. The conversion of the bacteria and chemical ingredients in waste water processing tanks provides materials for MFCs to convert chemical energy into electrical energy.

FPAAs are inherently parallel, which offers ultra-low power consumption and greater flexibility for the sensor signal processing.Efficient analog signal processing technique must be used to efficiently consume the harvested energy. Computations in FPAAs are advantageous being parallel, since there is no central processor. Multiple sensor inputs can be processed simultaneously and in real time using independently configured and programmed circuitry within the FPAA. FPAA composed of large arrays of interconnected components, similar to FPGAs. The programmable and reconfigurable nature of these devices also leads to their high level of flexibility, since they can be configured to interface with and process a wide variety of sensors.

2. Background knowledge

2.1. WSN in WWTP

Wireless sensor networks (WSNs) are suitable for distributed sensing with lots of sensors, because they are cheap and easy to install since no wiring is required. This is appealing for applications in wastewater treatment plants, where the measured variables (for example dissolved oxygen concentration or ammonium concentration) depend heavily on the sensor location. However, there are typically hard constraints on the energy consumption since WSNs are battery driven. One interesting observation about wastewater treatment plants in general is that the system disturbances (incoming wastewater flow, ammonium concentration etc) are periodic, with a period of one day. This could be utilized in some repetitive control/iterative learning control strategy, where the daily input is iteratively updated each day. After a few days, when the input produces acceptable output errors, the WSN could stop sending measurements unless some threshold is violated.

This strategy could increase both the control performance, since it makes future predictions based on the periodicity of the disturbances, and at the same time increase the WSN longevity by reducing the energy consumption. Major advantages of WSN are Power consumption constrains for nodes using batteries or energy harvesting, Ability to cope with node failures, Mobility of nodes, Communication failures, Heterogeneity of nodes, Scalability to large scale of deployment, Ability to withstand harsh environmental conditions, Ease of use.

2.2. Energy Harvesting Sensor Node

Sensor networks with battery-powered nodes can seldom simultaneously meet the design goals of lifetime, cost, sensing reliability and sensing and transmission coverage. Energy-harvesting, converting ambient energy to electrical energy has emerged as an alternative to power sensor nodes. By exploiting recharge opportunities and tuning performance parameters based on current and expected energy levels, energy harvesting sensor nodes have the potential to address the conflicting design goals of lifetime and performance.

Energy harvesting refers to scavenging energy or converting energy from one form to the other. Applied to sensor nodes, energy from external sources can be harvested to power the nodes and in turn, increase their lifetime and capability. Given the energy-usage profile of a node, energy harvesting techniques could meet partial or all of its energy needs. A typical energy harvesting system has three components, Energy source, Harvesting architecture, Load. Energy source refers to the ambient source of energy to be harvested. Harvesting architecture consists of mechanisms to harness and convert the input ambient energy to electrical energy. Load refers to the activity that consumes energy and acts as a sink for the harvested energy. Energy harvesting can be divided into two architectures (i) Harvest-Use: Energy is harvested just-in time for use (ii) Harvest-Store-Use: Energy is harvested whenever possible and stored for future use.

Energy harvesting systems can also be categorized according to the energy source, such as solar, wind, water, motion, and pressure. Recent research in MFC provides feasible energy harvesting solution for waste water processing tanks when combined with low power signal processing and communication.

2.3. Microbial Fuel Cell

The unique working environment in wastewater processing tanks makes MFCs a feasible energy source. Research on MFCs has been conducted for more than four decades, and a lot of designs have been reported. In fact, researchers have suggested applying MFCs to provide electricity for a wide range of applications, from small portable electronic devices to robots. An example of an emerging technology with potential application to WWTPs is fuel cells. Like a conventional battery, a fuel cell uses two reacting chemicals separated by an electrolyte to produce an electric current. Unlike a conventional battery, however, a fuel cell is not charged prior to use. The chemical reactants in a fuel cell are fed continuously to the cell to provide constant power output. The reaction involves no combustion and no moving parts, and it produces little pollution. Heat generated in the process can be recovered and used in the facility.

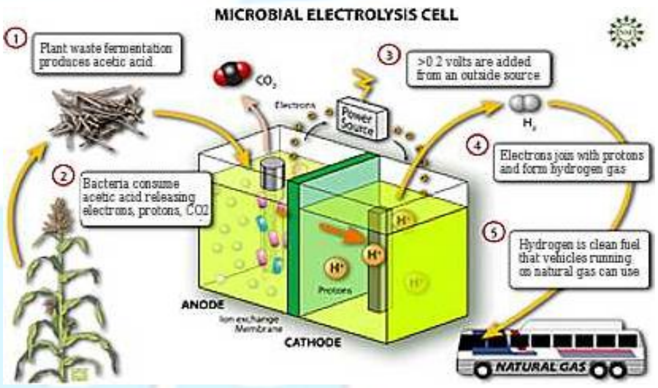

Figure 1: Microbial fuel cell

A microbial fuel cell is an electrochemical device capable of continuously converting chemical energy into electrical energy for as long as adequate fuel and oxidant are available. The design of a microbial fuel cell usually consists of two electrodes, anode and cathode, placed in independent compartments divided by a proton exchange membrane. In the anodic compartment, organic compounds (glucose) are oxidized by microorganisms, generating electrons and protons in the process.

When bacteria are placed in the anode chamber of a specially-designed fuel cell that is free of oxygen, they attach to an electrode. Because they do not have oxygen, they must transfer the electrons that they obtain from consumption (oxidation) of their food somewhere else than to oxygen -- they transfer them to the electrode. In a MFC these electrons therefore go to the anode, while the counter electrode (the cathode) is exposed to oxygen. At the cathode the electrons, oxygen and protons combine to form only water. The two electrodes are at different potentials (about 0.5 V), creating a bio-battery (if the system is not refilled) or a fuel cell (if we constantly put in new food or "fuel" for the bacteria).

By adding a small amount of voltage (0.25 V) to that produced at the anode in a MFC, and by not using oxygen at the cathode, it can produce pure hydrogen gas at the cathode! This is a modified MFC process we call the "bio-electrochemically assisted microbial reactor" or BEAMR process. This is a MFC operated in a completely anaerobic manner that uses the potential produced by bacteria, plus a small additional voltage (which could be produced by a MFC or other ways), that produces hydrogen through the recombination of protons and electrons at the cathode. Theoretically we need only 0.41 V to achieve this, so if the potential produced by bacteria could be increased (currently it is 0.3V), and the over potential (losses) at the cathode reduced, we could one day produce hydrogen gas without additional voltage.

2.4. Field Programmable Analog Array

It is critical to ensure that the sensor nodes are energy efficient. The most energy expensive operations of a sensor node are the data processing and sending/receiving of packets. While exploring energy conservative communication schemes is important, novel low-power computations must also be considered, which has led to the incorporation of FPAAs into our sensor nodes.

FPAAs are analog parallels of FPGAs, and they have been attracting a lot of recent attention from industry and academic research . They are comprised of a large array of analog components interconnected through a fabric of programmable switches. This large array of components enables highly parallel operations and significant flexibility of functions that can be performed. Non-volatile memories within the FPAAs allow them to be reprogrammed thousands or millions of times, while also ensuring that these devices will operate properly during intermittent power losses. By building larger, more flexible FPAAs, reconfigurable analog devices will become more analogous to today's high-density FPGA architectures. This will enable a very useful rapid prototyping system for analog circuit development. Recent advances in analog floating-gate technologies have shown it to be a viable alternative to traditional FPAA designs. Analog floating-gate circuits have shown tremendous gains in efficiency (a factor of as much as 10 000) compared with custom digital approaches for the same applications.

3. MFC Powered Adaptive Sensor Nodes

MFC-powered, adaptive, wireless sensor network for WWTPs is proposed. These sensor nodes integrate Microbial fuel cells (MFCs), Field programmable analog arrays (FPAAs), Low-power networking protocols. The abundance of bacteria and chemical ingredients in wastewater processing tanks provides materials for MFCs to convert chemical energy into electrical energy. Using FPAAs for the sensor signal processing has three main advantages: Ultra-low power consumption, highly parallelized computation, Greater flexibility.

Self-powered systems are always constrained by the energy harvesting mechanism and thus require efficient signal processing. Analog signal processing techniques have been demonstrated in which the power consumption is two to four orders of magnitude less than equivalent digital signal processing hardware. Computations in FPAAs are inherently parallel, since there is no central processor. Multiple sensor inputs can be processed simultaneously and in real time using independently configured/programmed circuitry within the FPAA, since these devices are composed of large arrays of interconnected components, similar to FPGAs. The programmable and reconfigurable nature of these devices also leads to their high level of flexibility, since they can be configured to interface with and process a wide variety of sensors.

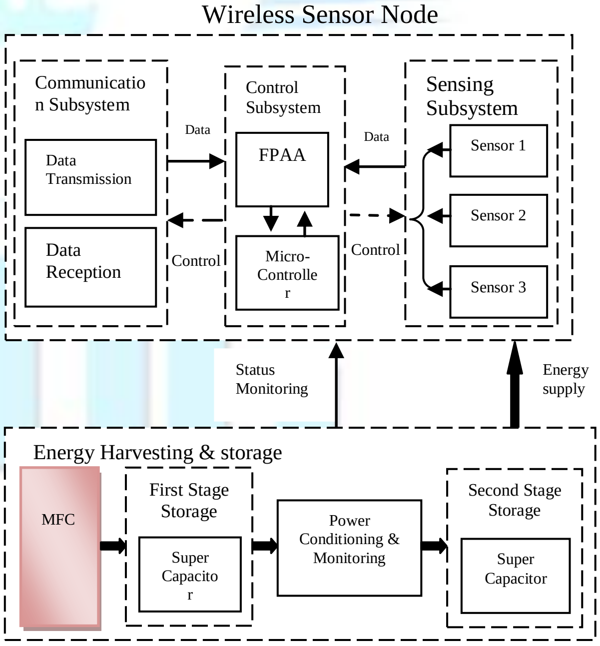

Figure 2: Sensor node Architecture

Figure 2 shows the architecture of sensor node, which consists of sensing, controlling, communication subsystem. The sensing subsystem collects data that represents the status of the wastewater processing tanks. For instance, the wastewater level, flow speed, temperature, and density of certain chemical ingredients and/or density of certain bacteria in the tank can be measured. A few issues depend on the specific application of the system, such as exactly how many sensing units are required, what kind of chemical reactions are monitored, etc. The communication subsystem addresses design issues at both the node and network levels. It requires further development and optimization given the integration with the FPAA and MFC. Each sensor node needs to adjust its behavior according to its energy level and those of its neighbours.

3.1. Energy Harvesting and Storage

MFCs are the prime energy source for the sensor system. It is a challenge to provide a stable, continuous power supply for a long period of time using MFCs. However, MFCs can be used to partially recharge or supplement batteries, thus extending their lifetime significantly, but the batteries eventually wear out. It is infeasible to replace batteries embedded in sensor nodes that are submerged in wastewater processing tanks. On the other hand, the theoretical lifetime of capacitors and super capacitors is orders of magnitude longer than batteries. Therefore, super capacitors are an integral part of the proposed harvesting and storage scheme, which minimizes sensor node maintenance.

The architecture of two-stage energy harvesting and storage system is shown in Figure2. Super capacitors are used as the energy storage device in each stage. super capacitor present in the first stage is charged by the MFCs directly. Super-capacitors have high charge-discharge efficiency (97−98%) and also do not suffer from memory effect. Super-capacitors have infinite recharge cycles, and therefore have no limit to the number of times they can undergo deep recharge and no need of complex charging circuitry. Super capacitor can also be used to buffer the available energy if the energy source is jittery, i.e., the super-capacitor is trickle charged and a stable discharge from the capacitor charges the battery.

The Power Conditioning and Monitoring (PCM) utilizes efficient power electronics to condition the power from the first capacitor for use by the sensing, processing, and communication subsystems. In this manner, the system supply is buffered through the PCM and super capacitor present in the second stage from any fluctuations resulting from the MFC energy harvesting. In addition to simple power conditioning, the PCM also monitors the output power levels in case a power loss becomes imminent. At such times, the PCM can signal the microcontroller and FPAA to take action to conserve additional energy or signal a power failure to a central monitoring station.

4. Hardware Implementation & Results

The system consists of two parts

1) Energy harvesting & storage

2) Wireless sensor node with FPAA

Figure 4: Experimental setup of MFC

Energy harvesting system with MFC is implemented Microbial fuel cells (MFCs) are bio-electrical devices that harness the natural metabolism of microbes to directly produce electrical power. Within the MFC, microbes act as a catalyst to break down sugars and other nutrients in their surrounding environment and release a portion of the energy contained within those molecules as electrical current.

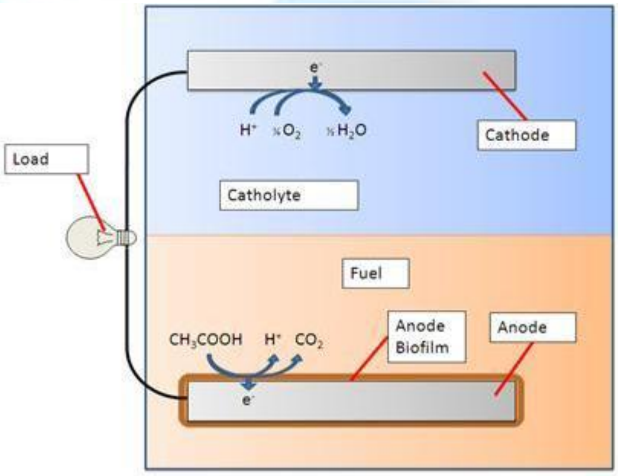

Figure 3: Pictorial representation of MFC

One electrode, called the anode, is placed in a nutrient-rich, oxygen-poor environment, while the other electrode, the cathode, is placed within an oxygen-rich environment. These two media are typically separated by a proton-exchange membrane that is permeable to protons, but impermeable to oxygen. If microbes are present within the anodic media, a bio-film will spontaneously develop on the anode surface. Once a microbial community forms on the anode, its natural metabolic pathways begin to break down the nutrients within the surrounding media, generating highly reduced biomolecules, such as NADH.

These biomolecules then donate electrons to the anode in one of three ways: 1) directly transferring from the molecule to the anode surface, 2) employing a secondary biomolecule to shuttle the electron to the anode, or 3) transferring the electron through conductive appendages, termed “nanowires”, propagated by the microbe. Once the electron has been transferred to the anode, it then travels to the cathode, where it reacts with an oxygen molecule and a proton, a by-product of electrogenic metabolism, to form water. Thus electrical current is generated and extracted by simply placing a load between the two electrodes.

4.1 Results Obtained

Eo(V) – Standard potential calculated from Gibbs free energy data

Electrode	Reaction	Eo(V)
Anode	$2HCO_3^- + 9H^+ + 8e^- \rightarrow CH_3COO^- + 4H_2O$	0.187
Cathode	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	1.229

Emfc(V) – Theoretical potentials for typical conditions in MFC

Conditions	Emfc(V)
HCO_3^-=5 mM, CH_3COO^- =5 mM, pH=7	-0.296
pO_2 =0.2, pH=7	0.805

MFC with an acetate oxidizing anode and an oxygen reducing cathode(pO_2 = 0.2. pH = 7) has cell emf of 0.805-(-0.296)=1.101V

5. Conclusion

MFC is implemented and the electrical current is generated between two electrodes. Experimental results obtained were found to be in close agreement with theory and simulations. Microbial fuel cells (MFCs) have shown great promise as a novel energy harvesting technology that can provide consistent, maintenance-free power for long periods of time, well beyond the lifetimes of sensor and communication hardware

The entire hardware model of the sensor system can be energized by the power generated by MFC. FPAA and advanced Micro controllers such as ARM or PIC series according to the requirement of the industrial scenario can be used for constructing the wireless sensor node.

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