Chip-On-Mud: Ultra-Low Power ARM-Based Oceanic Sensing System Powered by Small-Scale Benthic Microbial Fuel Cells

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***Abstract*— An ARM-based sensing platform powered entirely by small-scale benthic microbial fuel cells (MFCs) for oceanic sensing applications is presented. The ultra-low power chip featuring an ARM Cortex-M0 processor, 3kB of SRAM, and power management unit (PMU) with energy harvesting from MFCs is designed to consume 11nW in sleep mode for perpetual sensing operation. A small-scale micro-MFC with 21.3cm^2 anode surface area was connected to the on-chip PMU to charge a thin film battery of 1mAh capacity. A 49.3-hour long-term experiment with 8-min sleep interval and 1 sec wake-up time demonstrated the sustainability of chip-on-mud concept. During sleep mode, the system charges the 4V battery at 380nA from the micro-MFC generating 5.4µW of power, which can support up to 20mA of active mode current.**

I. Introduction

Benthic microbial fuel cells (MFCs) generate energy from the metabolic process of bacteria in marine sediment. For the MFCs to generate power, the anode must be in contact with bacteria in anaerobic conditions; the cathode floats in the water column where it is exposed to oxygen (Fig. 1). Electrical current generation is related to the surface area of the electrodes. The anode tends to be the limiting factor because increasing its size makes it more challenging to maintain anaerobic conditions. When these fuel cells fail in the field, it is often attributed to a failure at the anode due to organism aeration of sediment, and incomplete anode burial and insertion. Burial of microbial fuel cells in the ocean surface requires divers or sophisticated deployment technologies, which limit the practicality of large-scale mass deployment.

MFCs on the cm^2 scale are more easily hidden, more conveniently deployed, and have lower failure rates. Space and Naval Warfare Systems Center (SSC) Pacific has successfully deployed and tested prototype MFCs [1-2]. The voltage output level generated by MFCs is lower than most commercially available batteries at 0.4-0.75V and offers power levels in the 1-100µW range, which is not suitable for most commercial electronics. This voltage level is determined by the electrochemistry of the microbe system and cannot be easily changed. Additionally, because they operate as an open system in the marine environment, cells cannot be connected in series to increase voltage. Therefore, the electronics must be specifically designed to operate given these low voltage and power levels. In addition, the voltage level of an MFC cannot be assumed constant over a wide range of current draw. This leads to added difficulties in MFC and electronics design. The anode surface area should be chosen large enough to dampen voltage fluctuations as load current changes.

Energy harvesting circuits with MFCs have been previously reported in literature [3-4], but [3] is an incomplete system without computational or storage capabilities, and [4] relies on commercial components with >10mW power budget. The system proposed in this paper couples ultra-low power custom electronics with small scale (21.3cm^2) and low power (5.4µW) benthic microbial fuel cells, achieving a self-sustainable sensor system with user-programmable interface suitable for various underwater oceanic sensing applications. After a long-term experiment of 49.3 hours, the proposed system continues to operate with increasing battery voltage, demonstrating a stable system operation.

II. System Overview

A. Electronics

A custom ultra-low power chip (CTRL chip) was designed to harvest energy from benthic MFCs and perform processor operations. Fabricated in a commercial 180nm CMOS technology, this chip is part of a 1.0mm^3 die-stacked sensor node system [5]. As the main processing and housekeeping

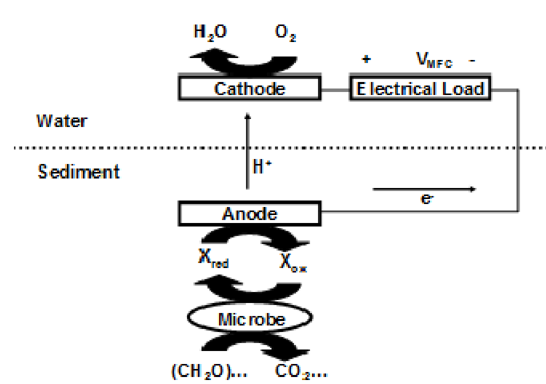

Figure 1. Operation principle of benthic microbial fuel cells [1].

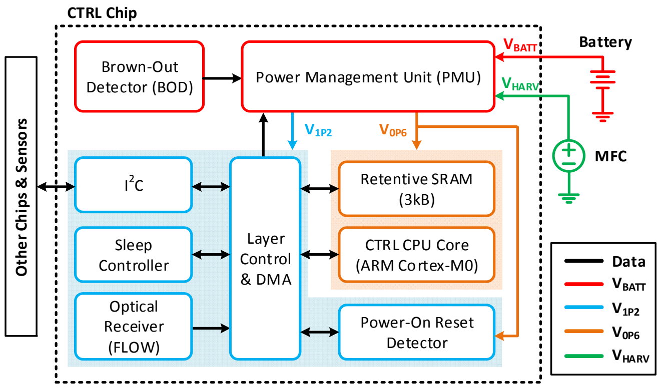

Figure 2. CTRL chip block diagram and external connections.

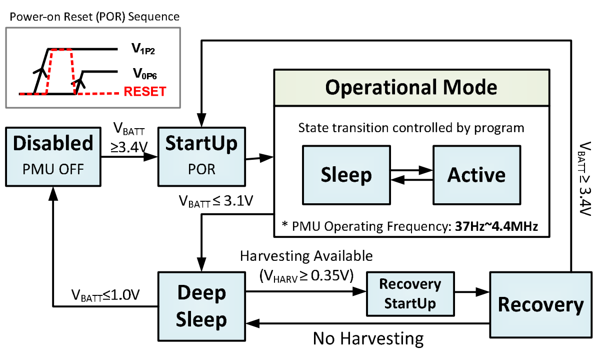

Figure 3. State diagram of PMU depending on harvesting conditions and battery voltage.

chip of the system, the CTRL chip features an ARM Cortex-M0 processor, 3kB of SRAM, I^2C interface with external sensor components, sleep controller, optical programming interface (FLOW), power-on reset detector (POR), brown-out detector (BOD) and a power-management unit (PMU) (Fig. 2). Various leakage power reduction techniques limit the overall chip power consumption to only 11nW in sleep mode, making it ideal for sensor applications with a duty cycled usage scenario.

The core operating at 400kHz can configure the sleep controller to schedule sleep/wakeup cycles of the whole system. In sleep mode, I^2C block, layer controller, and the core are power-gated. The SRAM is used for storing both instructions and data. Since the custom 8-T SRAM cell has an ultra-low leakage power [6], the SRAM need not be power-gated. Hence, the custom SRAM retains its states as long as 0.6V supply is present, avoiding the need of a non-volatile memory.

The main data interface of the CTRL chip is a modified I^2C protocol, which uses a time-divided pull-up/pull-down scheme that is still compatible with the standard I^2C protocol and yet avoids the use of conventional pull-up resistors that consume mWs of power [5]. The core can generate I^2C messages through the layer controller to talk to other off-chip I^2C-compatible components via a memory write instruction to a memory-mapped address. I^2C is also used to load the program instructions onto the memory. When wired I^2C connection is impractical, the optical receiver can be used to program the chip with light [7]. This option can be attractive for underwater operations, in which exposed wired connection can lead to corrosion or other physical damage.

The PMU takes a nominal battery voltage of 3.6V and generates two supply voltages, V_{0P6} and V_{1P2} (nominally 0.6V and 1.2V, respectively), that are used to power different components of the chip [8]. The PMU is also responsible for harvesting from a source (V_{HARV}) and recharging the battery while in sleep mode. Figure 3 shows PMU state transitions in response to battery voltage fluctuation. When the battery voltage stabilizes above 3.4V, the PMU enters Operational Mode and the system is activated. During Operational Mode, the system can switch between Sleep and Active Modes based on the user-defined program loaded on the memory.

The BOD continuously monitors the battery voltage, and when it detects that the battery voltage has dropped below 3.1V, it signals PMU to enter Deep Sleep Mode to prevent the battery from over-discharging [9]. During Deep Sleep Mode, all supply voltages are turned off and the system only consumes 185pW. Since SRAM is also powered down in this mode, its content is lost and the chip needs to be re-programmed. Harvested energy availability is monitored in while the system is in Deep Sleep Mode. The system enters Recovery Mode when sufficient power is detected. In this mode, the battery is recharged from the harvesting source until the battery voltage increases above 3.4V. At this point, the system returns to its normal Operational mode.

B. Small-Scale Microbial Fuel Cell (MFC)

Six micro-MFCs were set up for experiments in the laboratory environment inside an aquarium of size 45×90cm^2. Sediment from the Marine Corps Recruiting Depot marina in San Diego, CA was collected during low tide. The aquarium was filled with the 15cm-deep sediment. 25cm of salt water above the sediment was continuously exchanged with surface water pumped from the San Diego Bay.

The MFCs are comprised of graphite rod anodes and carbon fiber brush cathodes. The graphite rod anode was 1.9 cm in diameter. Three different anode lengths (2.5, 5.0, and 7.5 cm.) with a respective surface area of 7.1, 15.2, and 21.3cm^2 were evaluated as anodes for MFCs supplying power to the electronics. Electrical contacts for the anode were created by drilling a small hole (0.08cm) located 1.3cm from one end, through which titanium wire was threaded through the hole and tightly twisted for secure contact. The carbon-fiber brushes used as cathodes for each of the MFCs were identical (12cm length × 12cm diameter) and consisted of carbon fiber fixed in a titanium wire stem. The cathode was overdesigned to ensure that the device would be anode limited, in order to observe the limitations of <21.3cm^2 anodes.

Initially, the anodes were pushed into the sediment vertically with the titanium wire oriented towards the top of the sediment to emulate the deployment of a dart type MFC design. The cathodes were hung vertically in the overlying water. In order to condition the MFCs for use with the

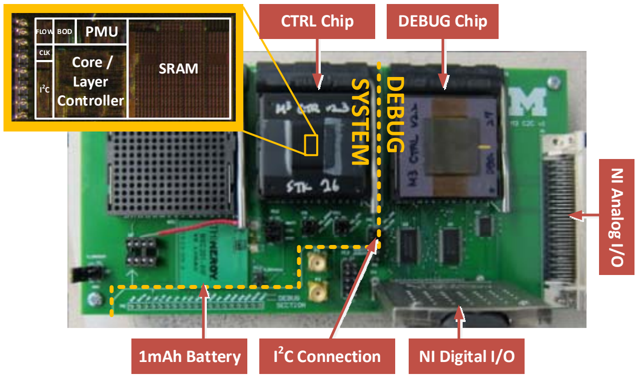

Figure 4. PCB board used for integration testing and die photograph of CTRL chip. Dashed line indicates boundary between SYSTEM and DEBUG sections.

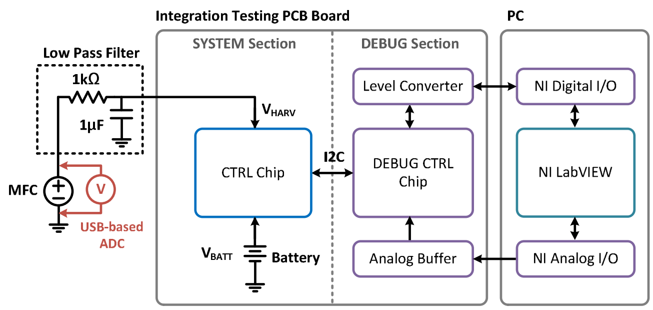

Figure 5. Block diagram of MFC + CTRL integration testing setup.

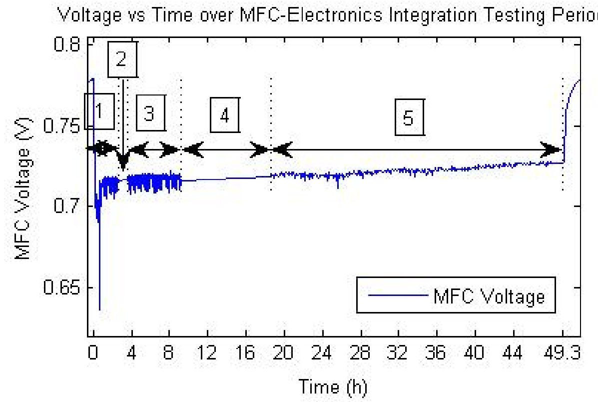

Figure 6. MFC Voltage verses time (in hours). The electronics were connected with the MFC at hour 0 and disconnected at hour 49.3. The electronics remained in continuous operation during this period.

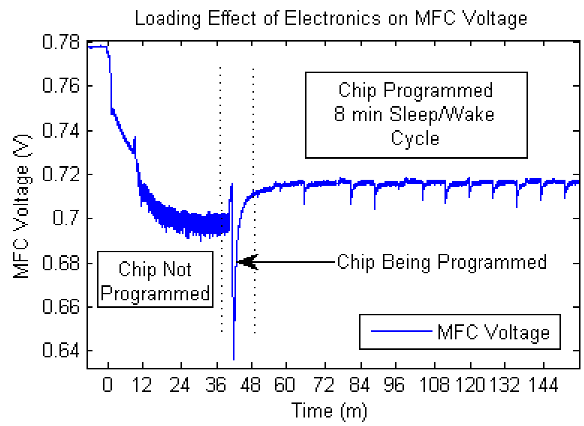

Figure 7. The MFC voltage verses time (in minutes) during the early period of electronics integration, Region 1 of Fig. 6. This figure more clearly shows the effects of loading the MFC and programming the electronics. The maximum peak to peak voltage difference is 20mV after the electronics are programmed.

electronics, they were operated under varying conditions to maintain a cell voltage greater than 0.5V. They were left under open circuit conditions for 24 hours followed by sequential loading of passive resistors. After 12 days, the MFCs were maintaining a voltage ranging from 0.6-0.7V while generating 17-22µW. A MFC with 21.3cm^2 anode was selected for system integration testing because of its stability and performance compared to the smaller MFCs.

III. Experimental Results & Analysis

A. System-Level Experiment Setup

A PCB board was designed for system integration testing with two sections: SYSTEM and DEBUG (Fig. 4). The SYSTEM portion was designed to mimic the die-stacked system in [5], by replacing the inter-layer bond-wire connections with PCB traces. It includes the CTRL chip, a commercial 4V 1mAh thin-film battery, and additional sockets for pressure sensor and other sensing modalities.

The DEBUG section of the board houses a DEBUG chip, which is a variant of CTRL chip that has additional peripheral circuitry for debugging purposes, such as a scan chain to override important system signals and observation blocks for I^{2}C and clock signals. The DEBUG chip interfaces through National Instruments (NI) digital and analog cards with a custom LabVIEW program and serves as the primary interface between the end user and CTRL chip. Its main role in this system is twofold: programming the CTRL chip and monitoring the I^{2}C wires to observe the status of the CTRL chip. The only electrical connection between the DEBUG and CTRL chips are the two I^{2}C wires and ground. Once the CTRL chip is programmed, the DEBUG section can be disconnected for field deployment of the system.

Fig. 5 shows the system-level testing connections. MFC was connected to V_{HARV} terminal of the CTRL chip, allowing the PMU inside CTRL chip to up-convert the ~0.7V MFC output and charge the battery at 4V. The DEBUG chip was used to transfer program code to CTRL chip via I^{2}C. The program writes a user-defined timer value to the sleep controller, and requests a "go to sleep" I^{2}C message at the end of program execution. The sleep controller then power-gates the core and I^{2}C block, entering sleep mode. After the internal timer expires, the sleep controller wakes up the core and the same program executes.

Prior to the long term experiment, an accelerated duty cycle test was performed with short sleep time of 7 sec. Intentional loop are inserted in the program to extend the wakeup time to about 1 sec, such that system operation could be easily verified by naked eye. After running the accelerated test for 2 hours, which corresponds to 900 repeated sleep/wakeup cycles, a long term experiment was set up with sleep time of 8 min. During the experiment, voltage and current in/out of the battery were monitored with a high impedance voltmeter and ammeter. With DEBUG chip being connected to LabVIEW, I^2C activity was also monitored, indicating proper program execution. A separate LabVIEW setup with USB-based ADC was used to record the MFC cathode voltage.

B. Long-Term Experiment

For the long-term experiment, a low-pass RC filter was placed on the output of MFC to decrease the impact of high frequency noise from the USB-based ADC on the stability of the CTRL chip. The RC values of 1kΩ and 1μF were used to give corner frequency of 1kHz, which is fast enough to track the change in MFC voltage over time. The DEBUG section was also disconnected, emulating a field deployment environment. With this setup, the integrated chip-on-mud system operated for 49.3 hours, demonstrating long-term stability and sustainability.

Figure 6 shows the measured MFC voltage vs. time over the 49.3 hour period, broken into five different regions. The MFC voltage was sampled at 2 samples per second in regions 1-4. Region 2 is a period of data acquisition failure that lasts for 1.5 hours. In Region 3 the data acquisition software is restarted and the sample rate continues to be 2 samples per second. Region 4 shows another data acquisition failure that lasts for 9.5 hours (overnight). In Region 5 the data acquisition software was restarted and the sample rate changed to 1 sample per 5 minutes to avoid further data acquisition failures. This region extends to the end of the integration experiment at hour 49.3, when the electronics are disconnected. The MFC voltage then begins to approach the open circuit voltage. The experiment was intentionally stopped by disconnecting the MFC from the chip, due to collaboration time constraints.

Figure 7 shows Region 1 in more detail, showing the loading effect of CTRL chip's PMU on the MFC, with the voltage dropping from 0.78V to 0.7V. When the DEBUG chip is used to initially program the CTRL chip, large current is drawn by the I^2C unit and layer controller, resulting in a further MFC voltage droop to 0.64V. Upon completion of the initial programming, the chip goes into sleep mode and the MFC voltage rises to 0.72V. Afterwards, voltage spikes begin to appear at uniform intervals, corresponding to the CTRL chip's duty cycle in which the chip wakes up every 8 minutes, executes the program for 1-2 seconds, and then goes back to sleep.

The voltage of the battery at the beginning of the long term experiment was 4.0908V. At the end of the experiment, the battery voltage was recorded at 4.0932V. This increase in energy stored in the battery over the course of the experiment confirms the capability of MFCs as a power source to keep the integrated system self-sustainable. The average current generated by the MFC during the integration period was 7.5μA. With the average MFC voltage being 0.72V during integration, this corresponds to 5.4μW of power generation.

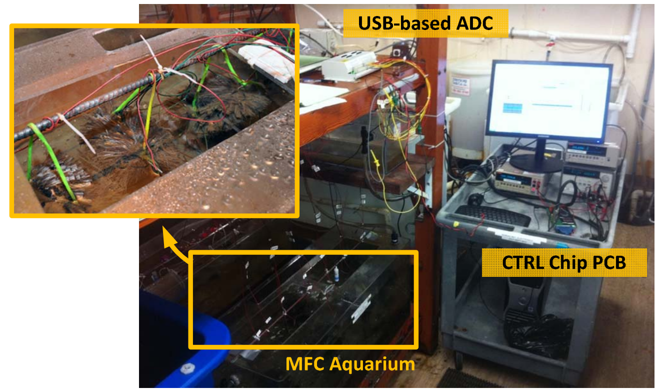

Figure 8. Experimental setup of chip-on-mud system integration testing.

The harvested current into the battery from the PMU harvesting circuit was 380nA during sleep mode. With a usage scenario of waking up every 10 minutes for 10ms to retrieve data from a sensor and storing it, the battery can supply 20mA of current during the active mode without losing net energy. Fig. 8 shows the experimental setup in a wet laboratory.

IV. CONCLUSION

The proposed chip-on-mud system offers perpetual oceanic sensing solution thanks to energy harvesting from micro-MFCs and ultra-low leakage standby mode. With commercially compatible I^2C interface and ARM-based core, the system offers user-friendly environment for third-party users.

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