Self-sustained Energy Solutions for Embedded Information Processing in Cyber-Aquatic Systems

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1. Introduction

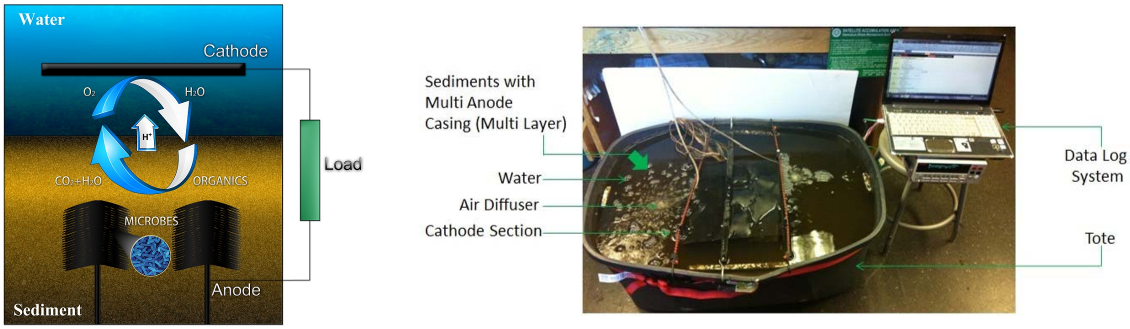
Water covers more than two-thirds of the Earth's surface area and represents a virtually untapped frontier of knowledge for humankind. While long a source of fascination, aquatic environments are now understood as vital to our national security, environmental and climatic health; important for natural disaster prediction; as sources of nutrition and novel medications; as sources of energy and commercial resources. Deployment of multiple time/space scale cyber-aquatic systems has far-reaching social, economic, and scientific implications. Thus, new scientific principles and engineering tools are needed to transform the ways in which we observe and understand the sparsely sampled oceans, estuaries, lakes and rivers. While significant progress has been made in algorithm and protocol development, it was realized recently that energy sustainability is a pivotal challenge to attaining reliable performance. In particular, battery power alone cannot support the sustainable operation: frequent recharges and maintenance are costly if not impossible for practical underwater applications. Recent advances in renewable energy such as energy harvesting from the environment have shown great promise. However, most existing techniques such as solar and wind harvesting are not applicable to the underwater environment. Other techniques such as those based on vibration and thermoelectrics offer low energy availability incapable of supporting the demanded performance. This position statement will discuss several emerging techniques to deal with the dual challenges to the development of cyber-aquatic systems with respect to (1) what self-sustained energy solutions are available in the underwater environment and (2) how to achieve sustainable performance for systems powered by renewable energy.

2. Biomass-based Marine Sediment Energy Harvesting

Microbial fuel cells (MFCs) exploit bacterial metabolic activities associated with the redox reaction to generate electrical energy directly from biodegradable substrates. Natural waters are rich of diverse microorganisms and nutrients that are ideal for energy harvesting by marine sediment MFCs. This research team has carried out an extensive study and established significant experience in this field. While utilizing MFCs for large scale power generation is still far from being practical, powering underwater embedded systems such as sensors is feasible as these systems typically require an average power in the range of microwatts to watts.

The electrical current generated from the MFC originates from the reactions in which some dissolved bio-chemical species are oxidized on the anode while the oxygen is reduced on the cathode. Figure 1(a) shows the basic principle of the marine sediment MFC for underwater energy harvesting. The anode is buried in the sediment to support the growth of microorganisms and collect the electrons generated in the sediment. These electrons pass through an external circuit (e.g., sensors) and reach the cathode, which is immersed in the water to utilize dissolved oxygen as electron acceptors and react with the electrons transferred from the anode.

This research team has developed a prototype marine sediment MFC [1] (see Fig. 1(b)). The MFC consists of several arrays, each array constituted multiple anodes associated to single cathode. The total volume of the MFC is about $0.10m^3$, with dimensions-length: $32cm$, width: $32cm$, and height: $65cm$. The system has a stacked column of three anode casings and an cylindrical expanded metal frame structure made of stainless steel to guard against potential bioturbation. Each anode casing contains nine anodes, and one cathode is connected with three anodes. The MFC consists of a total of twenty seven anodes buried in the sediments, and nine cathodes floating $5cm$ above the sediment casings in the water. Measured results show the peak harvested power density of $190mW/m^2$ at a current density of $125mA/m^2$, all normalized by the cathode surface area. Compared with traditional chemical fuel cells that need pure reagents (e.g. oxygen, hydrogen, and methane), costly electrode materials (e,g. noble metal, platinum), high temperature



(a) (b)

Figure 1 (a) The principle of a marine sediment MFC. (b) A prototype marine sediment MFC developed at UConn.

and high pressure, the marine sediment MFC demonstrates some distinct features including (1) operation under normal temperature and pressure, (2) self-sustainable reagents (organic substrates in water, oxygen in air and water), (3) eco-friendly bio-electrochemical reactions, and (4) easy to operate and maintain at low cost.

2. Characterization of Energy Non-determinism for Improving System Sustainability

Most renewable energy sources can be generally categorized as semi-deterministic. For example, solar radiation is neither complete random nor fully deterministic. It is not difficult to accurately predict solar harvesting performance based on the descriptive models established using historical data. In contrast, a high level of uncertainties is demonstrated by underwater energy harvesting. A new challenge for powering underwater systems with marine sediment MFCs is the large variations and temporal-spatio non-determinism in the energy availability. Since the inherent uncertainties in energy availability strongly affect the way in which the energy can be used, understanding the related system implications is critical for cyber-aquatic systems to achieve sustainable performance

Due to the highly dynamic underwater environment, different processes in both water bodies and sediment beds control the energy harvesting in MFCs. It is expected that the energy conversion process in MFCs is not static but certainly varies across underwater locations with different temperatures, rates of water flow, and organic concentrations in the sediment. While the energy output of a single MFC device is still limited by the current technologies, a network of distributed MFCs has shown great promise to support various cyber tasks, in particular for distributed systems that need long-term autonomous operation. One key issue for the energy harvesting in marine MFCs is the heterogeneous nature of ocean water (e.g., oxygen concentration, flow rates) and sediment conditions (e.g., nutrient concentration, microorganism concentration) at multiple temporal and spatial scales. When a network of MFCs collectively provide the energy for distributed systems, the nutrients around the MFC sediments (acting as the anode in MFCs) will be gradually used up by microorganisms. In the meantime, the nutrients in sediments could be replenished by the water flow assuming that enough momentum transport is taking place at the water-sediment interface. Additionally, the oxygen concentration in ocean water (acting as the cathode in MFCs) show spatial variations with seasons and flow rates. These dynamic processes need to be characterized in a statistical manner. It is needed to investigate the statistical computational models for assessing the collective behaviors of spatially distributed MFC devices in water bodies and sediment beds, supported by the measured data from both lake field and sea field experiments. These models will not only improve the efficiency and scalability of underwater energy harvesting, but also provide an essential interface to the system management at the cyber (e.g., network) layer. A deep understanding of these issues is critical to the sustainable deployment

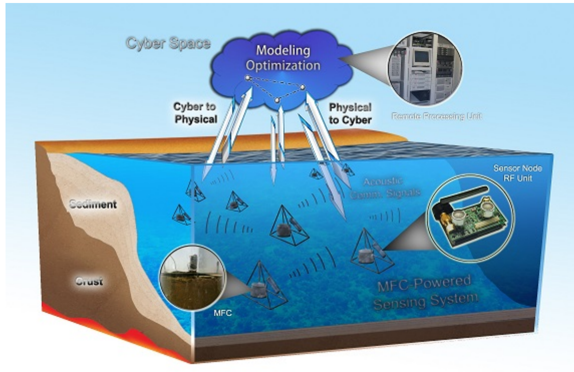


Figure 2 Illustration of a cyber-aquatic system.

and operation of cyber-aquatic systems, as the performance of these systems is ultimately determined by the energy availability.

3. Self-sustained Sensing, Signal Processing, and Communication

Exploiting renewable natural resources to power autonomous and distributed embedded systems, such as wireless sensor networks (WSN), self-organizing microrobots, and medical implantable devices, has gained significant interest recently. One specific technology, currently investigated by this research team, is a coastal undersea sensing system (see Fig. 2) that features *in situ* dedicated signal processing, high data rate acoustic communications, and self-organizing networked static/mobile sensors for critical missions such as harbor intruder detection [2]. As marine sediment energy harvesting is inherently non-deterministic due to the dynamically changing underwater conditions, it is critical to improve the energy efficiency of self-powered systems for reliable and durable cyber operations. While a lot of effort has been directed towards the power reduction and performance improvement, few results exist in jointly exploiting the properties of renewable energy sources and domain-specific information that is typically available in the design of cyber-aquatic systems. As the performance of these systems relies upon the interaction between application requirements and energy availabilities, these two components need to be bridged so that effective solutions can be derived.

This research team has investigated several embedded information processing techniques targeted specifically to the systems powered by renewable energy sources. These techniques include *link and energy adaptive UWB-based sensors* for sensing applications [3], *soft-thresholding orthogonal matching pursuit for efficient signal reconstruction* for baseband signal processing [4], and *energy-adaptive RF modulation* and *energy adaptive pulse amplitude modulation for IR-UWB* for RF front-ends [5]. By exploiting the statistical properties of renewable energy and domain specific information in cyber-aquatic systems in a coherent manner, these techniques achieve much better performance than the corresponding conventional techniques.

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