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Development of a wireless sensor network for algae cultivation using ISFET pH probes

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ABSTRACT

We present a wireless sensor network to measure pH, dissolved oxygen (DO), and temperature for use in algae cultivation. The pH is measured using ion sensitive field effect transistor (ISFET) technology, which is more robust and has a faster response than traditional glass pH electrodes. A custom circuit drives the ISFET sensor and interfaces with an ANT wireless network system. The wireless network consists of a network hub which can service up to 8 sensor nodes and a series of relays to transmit the data to a PC. The data is logged with a custom LabVIEW program. In this work, we demonstrate operation of this network using 5 sensors (3 ISFET pH, 1 DO, 1 temp), one hub, and two relay units. The network was used to collect data for 42 days from a 1600 L raceway tank growing *Scenedesmus dimorphus*. In that time, the network did not experience any failures beyond what can be mitigated with additional battery capacity and improved construction methods. At the end of the growth cycle, the daily variation in dissolved oxygen was observed to closely track the optical density measurements.

1. Introduction

Large scale microalgae cultivation has emerged as a strong candidate for contributing to biofuel demands in the future [1–4]. Many different methods of cultivating microalgae on a large scale have been proposed, including open pond systems and closed photobioreactor systems with a variety of techniques for introducing carbon dioxide, nutrients, and allowing excess oxygen to exit the system [5,6]. While the details of these systems may vary, most algae cultivation processes require close monitoring of growth parameters like pH, dissolved oxygen content (DO), temperature, nutrient concentration, optical density (OD), and other parameters to ensure optimal health and growth conditions in the microalgae culture [6,7]. For example, many systems use supplemental carbon dioxide [8–10] and therefore pH has special importance as a proxy measurement for the carbon dioxide content in the culture [11,12]. The pH is reduced by the addition of carbon dioxide, which forms carbonic acid when dissolved. When exposed to sunlight, the algae will consume this supply of carbon dioxide via photosynthesis, causing the pH to rise. At night, the process works in reverse as the algae respire and produce carbon dioxide.

Enclosed photobioreactor cultivation systems suffer from additional challenges that continuous monitoring can help alleviate. Photosynthesis creates oxygen which can accumulate to toxic levels within the reactor [13]. Also the temperature can become high enough to negatively impact the culture. Therefore it is important to continuously monitor the pH, DO, and temperature to ensure proper health of the culture in growing conditions that can rapidly change.

Large-scale algal cultivation creates additional monitoring challenges that are not typically encountered at the experimental or laboratory scale. A large-scale algae culturing facility should operate with a high degree of autonomy, especially in the case of systems that are located in remote locations such as offshore environments. Because of the difficulty of accessing all parts of the system constantly, a monitoring system in such a facility should require infrequent and minimal maintenance. Additional failure points are created with the use of long sensor cables and extension cables. Furthermore, long cable runs often require sensitive analog data, such as pH, to be amplified and conditioned to avoid errors due to noise [14]. A wireless system removes these failure points and saves the cost of lengthy extension cables for the sensors. Additionally, a wireless system can also relay the data digitally, thus preserving signal integrity.

In this work, ion-sensitive field effect transistor (ISFET) technology has been chosen to measure pH because of its potential for enhancing reliability through calibration stability and mechanical robustness [15]. Like a traditional glass pH electrode, ISFET sensors still require a reference voltage to be created through the use of a reference electrode. Therefore, the pH measurement is still subject to temperature sensitivity and drift, although ISFET technology is continuing to improve in those areas. In contrast to the traditional glass pH electrode, the ISFET does not require storage in a buffer solution and is more robust, allowing for easier cleaning and greater resistance to mechanical damage.

ISFET technology was first described in 1970 by Bergveld [16]. Briefly, the ISFET sensor probe behaves as a field effect transistor, where the

Abbreviations: ISFET, ion-sensitive field-effect transistor; OMEGA, Offshore Membrane Enclosures for Growing Algae; OD, optical density; DO, dissolved oxygen.

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gate voltage depends upon the number of hydrogen ions in the solution coming into contact with the gate material. Thus, the gate voltage changes as a function of the pH, which is the concentration of hydrogen ions in a solution. Additional circuit elements are required to maintain a constant current and voltage drop at the ISFET. The most common approach is to set a constant drain current (I_{DS}) by using a feedback control voltage (V_{GS}) applied between the gate and source of the ISFET. As the pH changes, this control voltage adjusts to keep I_{DS} constant, and therefore becomes the output signal from the circuit.

There are a large number of publications in wireless sensor network design that have informed the development process of the wireless sensor network described in this paper. Several examples exist of the use of wireless sensor networks in environmental monitoring, including agricultural applications as diverse as pig farming [17] and irrigation [18]. Numerous research teams have described design challenges associated with wireless sensor network design in a harsh environments, including high alpine environments [19], and oceanographic monitoring [20,21].

In this paper, a wireless sensor network is presented to measure pH, dissolved oxygen content, and temperature in an open raceway tank environment. Earlier phases of the development of this wireless sensor network were conducted in an experimental closed-system microalgae cultivation facility under development for offshore use, i.e. the NASA OMEGA (Offshore Membrane Enclosures for Growing Algae) project, and are described in [22]. This preceding work described the operation of a single wireless pH sensor installed in a closed-loop microalgae photobioreactor system at the OMEGA Project. In this phase of the development, a single wireless pH sensor was installed in parallel with a traditional wired glass electrode existing as part of the OMEGA project's monitoring system. This installation served as an initial test of the communication equipment transmitting a single data stream from point to point. Maintaining operation of the basic communication network over a 12-day period, and a comparison with the pH data from the OMEGA monitoring system provided insight into the possible failure modes of a larger network and yielded guidance on the next steps in evaluating the calibration performance of the ISFET sensor. In the course of that period, several communication interruptions unrelated to battery failures or other external causes were observed. These interruptions prompted the implementation of the watchdog timer presented in this work. The difference in pH measurement between this wireless ISFET and the OMEGA project's glass electrode averaged 0.43 pH units over this time period, with a standard deviation of 0.25. These results provided some degree of confidence in the accuracy of the pH measurements, but it was unclear if the observed differences were due to calibration and drift errors in the ISFET pH probe or the glass electrode. Therefore in this work, the ISFET pH probe was routinely recalibrated with standard pH solutions. These experiences informed the design of the sensor network presented in this work, which introduces the capability of multiple sensors measuring dissolved oxygen and temperature in addition to pH. Major design objectives of this work include long-term reliability and durability of the monitoring system in a wide range of environmental conditions that can be encountered in differing algae culturing configurations like offshore systems and open ponds.

2. Materials and methods

The wireless sensor network described in this work was installed in an open raceway tank algae culturing system maintained by the University of Nevada, Reno, College of Agriculture, Biotechnology, and Natural Resources. In contrast to previous stages of the development of this project, as described in [22], the installation presented here included the capability to gather data simultaneously from multiple sensors of differing types. ISFET devices with integrated temperature diodes (Model MO-P34) were purchased from Micropto (Milano, Italy). These were chosen for their price point and, as an OEM device, for the ease in which they could be readily integrated into a wide variety of circuitry. The circuit for the ISFET pH sensor used the feedback controlled source voltage configuration described in the manufacturer's recommendations. A constant current was applied to the integrated temperature diode with a Model REF200 IC (Texas Instruments, Dallas, TX) chosen to supply the required current using a minimal number of components, and the resulting voltage drop across the diode correlated to temperature. Dissolved oxygen content as a percentage of the saturation concentration was measured with a DO1200 sensor (Sensorex, Garden Grove, CA) and the output voltage was amplified via an instrumentation amplifier (Model AD627, Analog Devices, Norwood, MA) capable of scaling the output voltage to the A/D converter described below.

Wireless communication of data in this sensor network was handled by a range of products under the ANT brand name, from Dynastream Innovations (Cochrane, Alberta, Canada). These were chosen for their low power consumption, built-in analog-to-digital converters with 10-bit resolution, and flexibility of programming through the use of external microcontrollers. Wireless communication was achieved by operating the ANT AT3 sensor units in their built-in shared channel configuration. Operating in this mode, each individual sensor is assigned a unique ID number. The network hub (ANT AP2) sequentially requests a new data message from each sensor unit according to its ID number. When a sensor receives this broadcasted request for data, it responds by sending its newest data message along with its ID number. The messages requesting data by the network hub were sent at a rate of 5 messages per second, so that each of the 5 sensors responds with new data once per second. In the interest of keeping file sizes within practical limits, the data messages were saved by the computer once per minute. The hub receives this wireless data information, and then transmits it to the next ANT wireless component programmed to listen for it; in this case, the next wireless relay unit (ANT AP2). Both the hub and relay units were controlled with an MSP430F2013 microcontroller (Texas Instruments) running custom code programmed in-house. To ensure network reliability, the microcontrollers driving the hub and relay units were given additional code based on the principle of a watchdog timer. For each successful cycle of receiving and transmitting a message, a counter in the program was reset. In case of a communication breakdown, the program would continue to attempt listening for new messages, but the counter is incremented every time the program fails to receive and send a message. When the counter reaches a level representing approximately 1 min of communication cycles, a complete reset of the microcontroller is triggered.

Protecting the sensitive electronic components from water and other environmental damage that may occur in various microalgae cultivation environments was a major design priority. Because of these hazards, enclosures for the sensors and data relay units were designed to be waterproof and physically robust. All electronic components were enclosed in sections of PVC pipe; and at locations where a sensor probe needs to pass through the watertight PVC boundaries; a small hole was created to allow the sensor probe to pass through, which was then sealed with silicone caulk. These methods, applied carefully, create sufficient protection against weather damage and short periods of immersion. A photograph depicting this enclosure design is given in the Supplemental data.

A network of five sensors composed of three pH sensors, one dissolved oxygen sensor, and one temperature sensor was operated in a raceway tank with a capacity of 1600 L at a depth of approximately 18 in., equipped to cultivate a culture of *Scenedesmus dimorphus* in late summer (August–September) using fresh water with a commercial chemical fertilizer as the nutrient source. A schematic of the wireless network is provided in Fig. 1. The length of this experiment was intended to allow sufficient time for a complete growth cycle of the microalgae culture, and to determine the battery life in every network component. Battery conditions and sensor calibration were recorded on 10 separate occasions, and any problems with the operation of the network were recorded and corrected. Calibration was performed by directly reading the sensor output in standard buffer solutions of pH 7 and 10. To avoid confusing the drift performance of the ISFET sensor with