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A novel electroactive polymer buoyancy control device for bio-inspired underwater vehicles

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***Abstract*— A novel depth control device has been designed and built. The proof-of-concept device utilizes the principles of electrolysis of water, enhanced by the inclusion of an ionic polymer-metal composite (IPMC) membrane as a medium. The device design incorporates an artificial bladder where the volume of gas generated by electrolysis is controlled by a solenoid valve, thus changing the device's buoyancy. A set of gold electrodes, separated by an IPMC film, is used as a lightweight and compact electrolysis generator. IPMC acts as stable, low power, highly efficient and environmentally friendly gas generator. Experimental results using open-loop control show that the device is capable of controlling its buoyancy efficiently with no noise and low power consumption. Applications for this technology include integration into bio-inspired, unmanned underwater vehicles.**

I. INTRODUCTION

A simple and efficient method for buoyancy control is critical in the design of an autonomous underwater device. The most common method used today to achieve depth control is to utilize a piston-cylinder assembly connected to a servomotor [1]. A cylinder, usually containing air, is compressed and expanded to adjust the volume of the system. This method usually yields reliable results with relatively fast response times. However, it generates noise from the servomotors and due to limitations in scaling the servo motor this method is not feasible for implementation in small devices.

In order to build more efficient buoyancy control devices, researchers have turned to biology for inspiration for the next generation of autonomous underwater vehicles. Mother Nature has evolved many novel and effective depth control mechanisms suitable for a variety of environment.

For example, sperm whales (Fig. 1) achieve buoyancy control by using their spermaceti oil. An adult sperm whale contains about 4 tons of spermaceti oils in their spermaceti organ, which represents approximately 8% of its total mass [2]. The spermaceti oil has a low melting point and its density depends largely on the temperature of the oil. By manipulating the arterial blood flow through the spermaceti organ, the sperm whales can regulate the temperature of the oil and are thus able to control their buoyancy. There have been recent demonstrations of buoyancy control concepts manipulating temperature to change the density of oil [2] or wax [3]. However, the response times are slow (on the order of 10 minutes), and it is inefficient for small devices because a constant power must be supplied to maintain the temperature of the oil while cruising at a certain depth.

Fig. 1. Sperm whale (*Physeter macrocephalus*) using spermaceti organ to float to the surface.

Ray-finned fishes, such as one depicted in Fig. 2, change the buoyancy of their body using a swim bladder [4]. Expansion of the bladder results in increased volume, thus making the body more positively buoyant and vice versa. Inspiration for the artificial bladder presented in this paper comes from these ray-finned fishes.

Fig. 2. Fancy goldfish (*Carassius auratus*) using swim bladder.

In this paper, a buoyancy control device using water electrolysis is explored for the first time. In the past, electrolysis has been utilized for harvesting pure hydrogen gases, which can be used as a clean fuel. For this application electrolysis is used only to generate gases in order to displace water and increase buoyancy.

A novel depth control device using electrolysis has been designed and built. The device design incorporates an artificial bladder where the volume of gas generated by electrolysis is controlled via a solenoid valve, thus changing the device's buoyancy. A set of gold electrodes, separated by

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an Ionic Polymer-Metal Composite (IPMC) film, is used as a lightweight and compact electrolysis generator. IPMCs are an important category of electroactive polymers (EAPs), which have built-in electro-mechanical coupling mechanisms. An IPMC consists of two noble metal electrodes, such as platinum or gold, coated on the surface of an ion exchange membrane, such as Nafion or Flemion [5]. IPMCs are usually used as sensors and actuators in many bio-medical devices [6], bio-inspired robots [7], and bio/micro manipulation systems [8]. In this study, an IPMC is used as an electrolysis generator for the first time.

Use of IPMC as a electrolysis generator is ideal for the following reasons: 1) A conductive membrane between the two metal electrodes provide ionic channels such that the actuation voltage can be kept low; 2) freely-moving Sodium and Calcium ions contained within the membrane [10] facilitate the electrolysis in tap water; 3) porous platinum metal on IPMC [5] acts as a catalyst to enhance the electrolysis process by improving the efficiency and allowing easy release of the generated gas from the surface [9]; 4) platinum electrodes and Nafion membrane are chemically stable in water [9]; 5) IPMC acts as a double-layer capacitor [10] such that even a small DC voltage produces strong electrical fields [11], which help to break down of the water molecules.

The body of the depth control device is made from Acrylonitrile butadiene styrene (ABS) using a Fused Deposition Modeling (FDM) machine. The device contains an on-board electrical circuit with a microcontroller, rechargeable battery, and artificial bladder. The device has a mass of 114 g and a peak power consumption of 1.2 W.

Experimental results using open-loop control show that the device is capable of controlling its buoyancy efficiently with no noise and low power consumption. The response times for sinking and rising are approximately 4.67 s and 180 s, respectively. Applications for this technology include integration into bio-inspired underwater vehicles. Such vehicle will be able to explore the ocean in its natural, unperturbed state. It also has advantages in: easy transport, exploring hard-to-reach areas, and consuming less power. Furthermore, multiple vehicles can collect data in a massively parallel manner due to their small size and efficiency.

The paper is organized as follows: mechanism of buoyancy control in section II, device design in section III, experimental result in section IV, conclusion in section V, and future work in section VI.

II. MECHANISM OF BUOYANCY CONTROL

A. Gas Generation by Water Electrolysis

When an electric current is applied between positively and negatively charged electrodes in ionized water, a chemical reaction occurs, in which pure oxygen and hydrogen gases are produced.

$$2H_2O + 2e^- \rightarrow H_2 + 2OH- \qquad (1)$$

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \qquad (2)$$

$$2H_2O(l) \xrightarrow{current} 2H_2(g) + O_2(g) \qquad (3)$$

Hydrogen gas appears at the cathode electrode (1) and oxygen gas appears at the anode electrode (2). Equation (3) shows the net reaction [12].

Two thin gold plates, each approximately 2 cm × 2 cm, are used as electrodes (Fig. 3). Typically, the two plates are placed 1-2 cm apart to allow the current to travel through the water. Most electrolysis experiments are performed in ionic solutions, which are usually prepared by adding salt, acid, or base. However, adding electrolytes is not feasible in this case because the device must be able to generate gas in regular tap water.

Electrolysis in tap water is much slower because of the limited number of ions present. In order to enhance the electrolysis process, an ion conductive polymer is placed directly in between the electrodes. The polymer used is an ionic polymer-metal composite (IPMC) [13]. IPMCs are well-known type of electroactive polymer that can generate large deformation under a low voltage [14]. In this study, the IPMC is used only as a medium to contain electrolytes and provide channels for ion movement in the electrolysis process. An IPMC about 150 µm thick is manufactured by chemically plating platinum electrodes to both sides of *Nafion*^{TM} [14].

By allowing the current to flow through the electrodes and IPMC, oxygen and hydrogen gases are generated. These gases are collected in a gas chamber, displacing the water in the artificial bladder (see Fig. 5). Because the gas mixture has a much lower density than that of water, the device becomes more positively buoyant. Care must be taken because the mixture contains a proportion such that it can burn instantly when ignited [15].

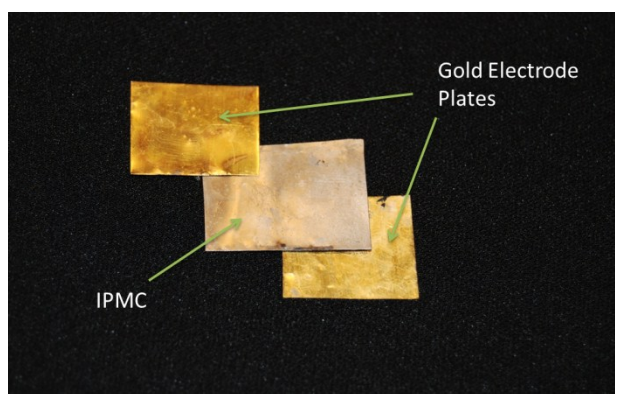

Fig. 3. Gold electrodes and a sample of an ionic polymer-metal composite.

B. Gas Releasing Mechanism by Solenoid Valve

The mechanism to control the release of gas, and thereby depth, uses a two-way solenoid valve (Hargraves Tech. Corp, *Part # 75M06U2.A005S*) This valve is closed in its non-actuated state and is suitable for the size and power constraints of this proof-of-concept design. This particular valve can be opened by applying 6 VDC voltage and has a power consumption and mass of 0.5 W and 5 g, respectively.

When the valve is actuated, the gas formed during electrolysis escapes from the device and water supersedes. As a result, the density of the device increases, causing it to become more negatively buoyant. When the valve is closed, water cannot enter through a bottom opening because the pressure inside the device is equal to that of outside. Thus the device is able to maintain the same depth by having a constant buoyant force. In order to travel up or downwards, gas is either produced or released in a controlled manner.

C. Mathematical Model for Gas Generation

The potential required to drive the electrolytic cell can be calculated by the following equation (At 25 °C, 1 atm, and pH 0) [12]:

$F = Faraday\ constant = 23{,}074 \frac{cal}{volt \cdot g}$
$n = number\ of\ electrons\ transferred = 2,$
$T = temperature,$
$\Delta G = change\ in\ the\ system\ Gibbs\ free\ energy,$
$\Delta H = change\ in\ the\ system\ enthalpy,$
$\Delta S = change\ in\ the\ system\ entropy,$

$$\Delta G = \Delta H - T\Delta S, \quad (4)$$

$$E_{rev} = \frac{\Delta G}{nF}. \quad (5)$$

At standard conditions (25 °C and 1 atm), voltage potential required is 1.23 V [12]. Due to inefficiencies in the electrolysis process, the actual voltage potential needed for decomposition of water is as high as 1.6 V [16]. In our case, the voltage potential is even higher because the pH level of tap water is close to 7. The voltage potential for our electrodes is experimentally found to be 1.88 V. Hydrogen gas generation rate is proportional to the input power whereas the efficiency is inversely related to the input power [16]. In this paper, 5 V is chosen as an actuation voltage to generate gas at a reasonable speed.

III. Device Design

The device consists of three parts: bottom chamber, middle seal, and top chamber. The overall schematic of the device is shown in Fig. 5.

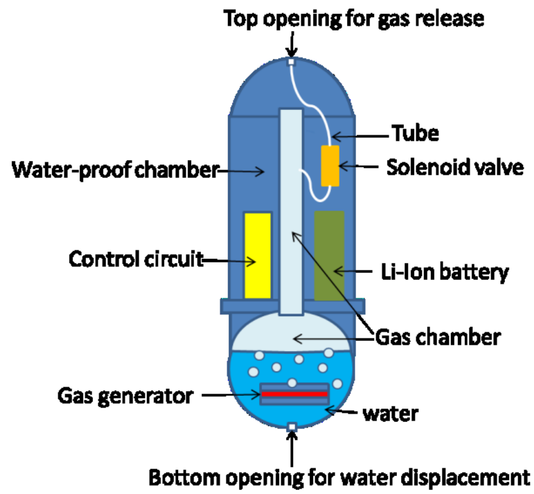

Fig. 5: Schematic of the device.

The parts are drawn using Autodesk Inventor 2010 and printed using a Fused Deposition Modeling (FDM) machine (uPrint Plus by Dimension). The device is approximately 15 cm tall, 6.5 cm in diameter, and has a mass of 114 g.

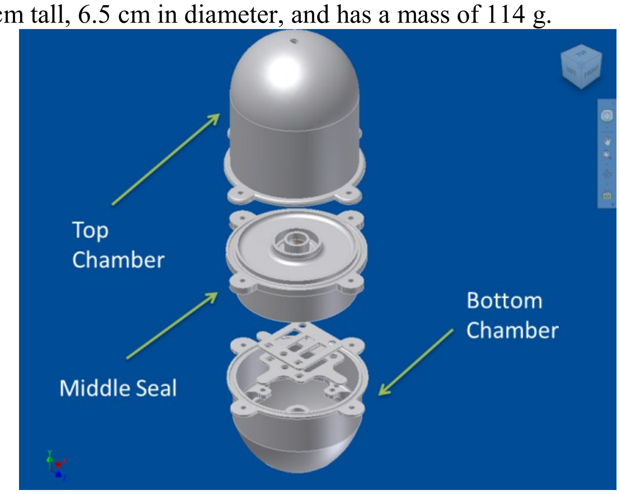

Fig. 6. Computer drawing of the depth control device.

A. Bottom Chamber

The bottom chamber encases the gas generator and holds water (Fig. 7). The water level varies depending on the depth location of the device. When the device is below the surface, the gas generator is submerged under water to ensure that the electrolysis can take place to allow the device to float up.

The bottom chamber also has room to secure up to 8 metal washers such that the device is initially about 80-90% submerged with addition of washers as deadweights.

On the bottom of the chamber, there is a small opening to allow water to enter or escape the device. This opening ensures that the inside and outside pressures are kept equal.

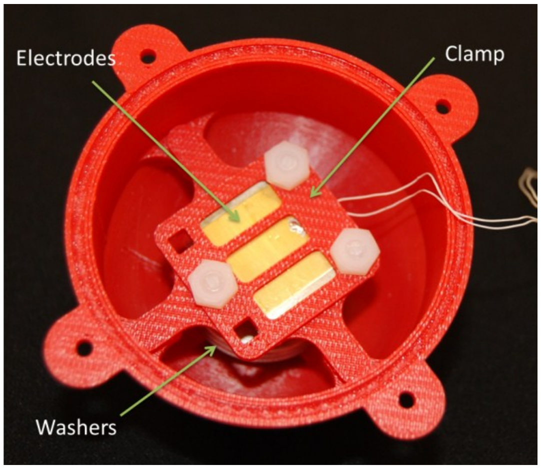

Fig. 7. Bottom Chamber with electrodes assembly (Top View).

B. Middle Seal

The purpose of the middle seal is to provide waterproofing of the electronics in the top chamber (Fig. 8). The bottom inner surface is concaved to direct the gas products to the gas chamber.

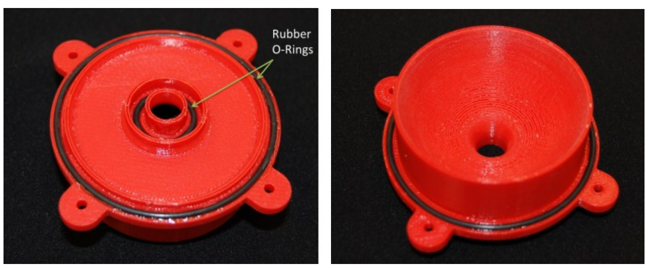

Fig. 8. Middle Seal with rubber O-rings (Left: Top view; Right: Bottom view).

C. Top Chamber

The top chamber is partitioned into a waterproof chamber and a gas chamber. The waterproof chamber contains all the electronics, 7.4 V Li-ion battery and Solenoid valve (Fig. 9). The gas chamber contains a mixture of air and gases produced at the electrodes in the bottom chamber. A tube connects the gas chamber to the device surroundings via solenoid valve.

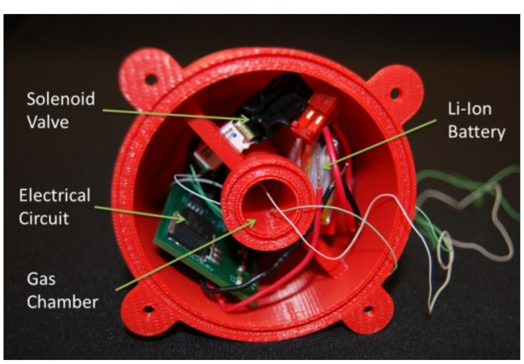

Fig. 9. Top Chamber with electronic components and gas chamber.

D. On-Board Electrical Circuit Design

The on-board circuit provides actuation voltage signals to the electrodes and solenoid valve (Fig. 10). A rechargeable 7.4 V, 400 mAh AA Portal Power Corp Lithium Ion Polymer battery is used as a power source and PIC12F508 microcontroller is used to generate two square wave control signals, S_1 and S_2. A square wave is chosen for simplicity. Since the microcontroller draws only 25 mA, two H-bridge drivers are used to provide up to 2 A peak current output to the electrodes and solenoid valve, which draw up to 500 mA and 80 mA, respectively. Amplitude of the voltage that controls the valve, V_{p1}, is 7.4 V. A voltage regulator sets the amplitude of the voltage applied to the electrodes and microcontroller, V_{p2}, to 5 V. Mass of the circuit and the battery are 11.5 g and 19.1 g, respectively.

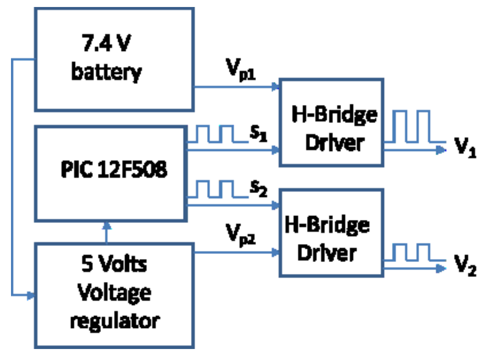

Fig. 10. Circuit schematics.

IV. EXPERIMENTAL RESULT

A. Gas Generation Rate

An experiment is set up to measure the gas generation rate at different voltage levels. Voltages ranging from 2.0 V to 6.0 V at 0.5 V intervals are applied to the electrodes using an Agilent DC Power Supply (Model #E3646A). The hydrogen and oxygen gases generated are collected using water displacement technique with 50 mL graduated cylinder (Fig. 11)

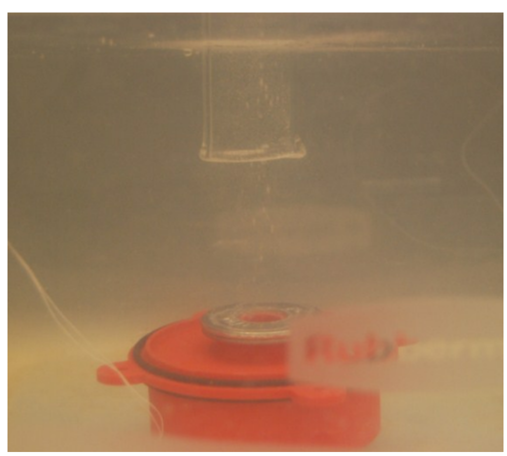

Fig. 11. Gas generation rate experiment set-up; using water displacement technique to collect the gas generated.

A constant voltage is applied for 60 s then the average current and displaced volumes are recorded. Power consumption is calculated as follows:

$$P_{avg} = I_{avg}V \quad (5)$$

The gas generation rate can be found by dividing the displaced volume by 60 s. Gas generation rate vs. power consumption is plotted (Fig. 12) and a least squares regression line is fitted to find a correlation.

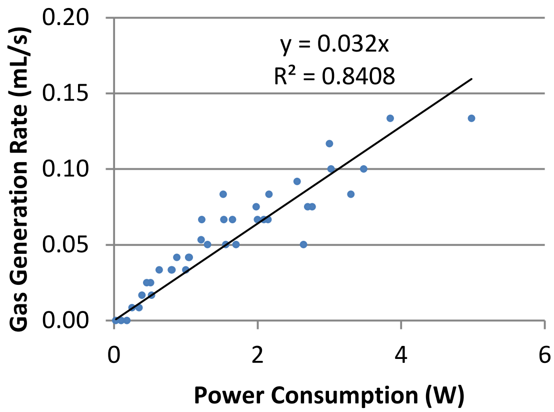

Fig. 12. Gas generation rate vs. power consumption. (R = correlation coefficient)

The results indicate a fairly strong linear relationship between gases generated and power consumption. The proportionality constant is approximately 0.032 mL/J. The on-board circuit is set up such that the output voltage is 5V. However the actual voltage measured across the electrodes is 4 V due to limited capacity of the battery. At this voltage, the average current and power consumption based on 5 trials are 0.3 A and 1.2 W, respectively. The average gas generation rate was 0.048 mL/s. The linear model predicts 0.040 mL/s at this power so the model and the result are in a fair agreement.

B. Diving Test

The depth control device is tested in a water tank (1.5 m wide, 4.7 m long, and 0.9 m deep). The tank is filled with tap water at a room temperature.

A critical mass is when the device is about 95% submerged under water, at which a slight decrease in buoyancy causes the device to sink. The critical mass of the device is experimentally found to be 283 g. Because the mass of the device is 114 g, 169 g of metal washers are added to the bottom chamber as deadweights. This mass is also equal to the payload for this particular device.

The microcontroller in the circuit is programmed such that there is an initial 3-minute delay to allow time for assembly and fastening of the bolts. After the initial delay, the solenoid valve turns on for 12 s to allow gas to escape such that the device will sink to the bottom of the tank. Then the solenoid valve turns off and 5 V is applied to the electrode plates for up to 15 minutes. Gases generated by the electrolysis fill the gas chamber, which displaces the water inside the bottom chamber. Thus, the device becomes more positively buoyant. The time it takes to rises back up to the top is measured. Fig. 13 shows the timing of the control signals.

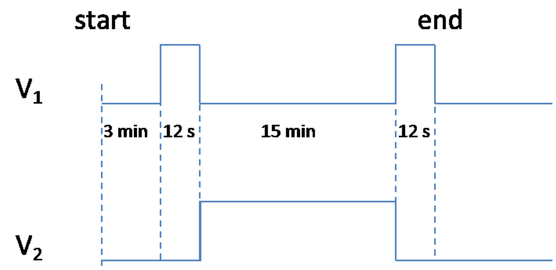

Fig. 13. Timing of the control signals.

It took approximately 4.7 s for the device to sink to the bottom of the tank and 180 s to rise back up to the top. The power consumption for sinking and rising are 0.5 W and 1.2 W, respectively. Fig. 14 shows snapshots of a successful demonstration of the open-loop proof-of-concept depth control device. Also see the supplemental video for a recording of this experiment.

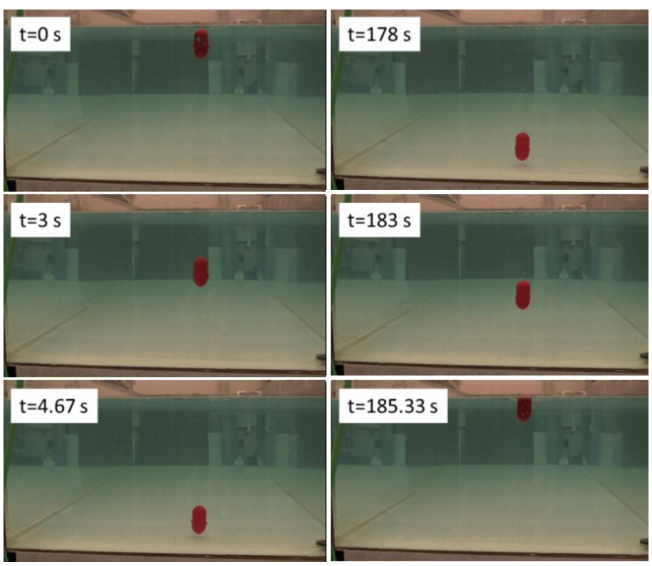

Fig. 14. Snapshots of the device during open-loop testing.

In order to reduce the rising response time, multiple sets of electrodes can be implemented and actuated simultaneously at a higher voltage. To decrease the current rising time by a factor of 1/3 (60 s), a gas generation rate must triple to be at least 0.14 mL/s. This is achievable with two sets of electrodes with approximately 6 V actuation voltages.

V. Conclusion and Future Work

A successful demonstration of a novel buoyancy control system using IPMC electrolysis generator and solenoid valve is presented for the first time. This concept demonstrates significant improvements from the existing devices by having low power consumption, high energy efficiency, and no noise. The device enables untethered depth control in z direction (perpendicular to the surface of water).

This technology can be combined with any free-swimming unmanned underwater vehicle such as one described in [7]. When integrated into a rectilinearly swimming device (x and y directions), an untethered underwater vehicle capable of swimming in x, y, and z directions is possible. The electroactive polymer buoyancy control system is suitable for small devices up to 20 cm long.

In order to improve the results, the device can be redesigned to be smaller and lighter, which would yield quicker response times and higher energy efficiency. Also, a closed-loop system can be created using a pressure sensor and remote control receiver. Finally, a dynamic model of the system can be derived and used with a PID controller to precisely control the depth of the device.

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