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Digital fabrication of a novel bio-actuator for bio-robotic art and design

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Abstract

We describe the design, fabrication and testing of a biologically-driven actuator which serves as a proof-or-concept "artificial heartbeat" for future use within bio-robotic art and design. The actuator employs live biological material, both as a source of power and means of actuation. Pneumatic pressure generated by the action of the yeast Saccharomyces cerevisiae causes a diaphragm to distend. Movement of the diaphragm is regulated by a purpose-built control valve. When the diaphragm is fully distended, the valve opens to release pressure, returning the actuator to its state of rest in readiness for the next actuation cycle.

The control valve employs a temperature-responsive NiTi "artificial muscle" which is activated when heated electrically using power generated by microbial fuel cells. In an alternative embodiment, the NiTi valve is powered by solar energy via photovoltaic panels. Results are presented showing the performance of devices powered by both energy sources.

The structure of the bio-actuator is fabricated by 3D printing and rapid tooling techniques.

Bio-actuation may be employed for such functions as shape-change, pumping and propulsion. Possible applications for the physical principles described in this paper range from energy autonomous robotics and artificial life to artworks which creatively exploit robotic and bio-technology.

Introduction

There is a growing interest in interdisciplinary research that connects the arts and scientific communities. Creative collaboration between the complementary disciplines of art, design, science and engineering can often result in outcomes that are innovative and highly original. In this paper we present outcomes from an interdisciplinary collaboration between research specialists in art, design and robotics that set out to explore ways in which live biological materials might be exploited to bring about movement or shape changes in physical objects. A result of our creative collaboration is a novel, biologically-driven actuator: an "artificial heartbeat". This proof-of-concept device exploits live biological materials both as a source of electrical power and means of actuation, enabling it to exhibit a "pulsating" action which can be considered analogous to the heartbeat of a living organism.

We begin by introducing the creative context for the project: the field of bio-robotic art and design. We will then introduce the key technologies which are exploited in the design of the bio-actuator: microbial fuel cells, artificial muscle materials and 3D printing. Finally we will describe the design of the bio-actuator, and report results of experiments investigating its performance.

Bio-robotic art and design

Creative artists and designers are increasingly seeking to engage with developments in the scientific fields of bio-technology and robotics.

For example, within his artistic practice, the performance artist Stelarc has worn a robotic "Third Hand" controlled by electrical signals from his abdominal and leg muscles. He has also had an "Extra Ear" surgically constructed on his forearm that includes an implanted microphone connected to the internet [1, 2]. The artist Arthur Elsenaar has developed a novel form of technological performance: "Artificial Facial Expression", in which the muscles of the human face are controlled using purpose-built electronic hardware and software. This allows the face to exhibit movements and expressions not normally possible, and also to be controlled from anywhere in the world via the internet [3]. Design researchers based at the Interaction Research Studio, Goldsmiths, University of London undertook a research project, "Material Beliefs", which involved collaboration between designers and engineers working in fields of biomedical and cybernetic technologies. As part of the project, designers James Auger and Jimmy Loizeau created "Carnivorous Domestic Entertainment Robots" – speculative design proposals for a series of domestic robotic devices that could potentially be powered by microbial fuel cells, which generate electricity by breaking down and digesting organic material [4].

The prototype bio-actuator described in the present paper is not intended to be a finished bio-robotic artwork or design product. Rather it is our intention to demonstrate physical principles which may be exploited in future applications ranging from bio-robotic art and design to energy autonomous robotics and artificial life. We will now introduce the key technologies employed within the prototype bio-actuator.

Microbial Fuel Cells

Microbial Fuel Cells (MFCs) are bio-electrochemical transducers that convert bio-chemical energy directly into electricity, through the metabolic activity of live microorganisms (Figure 1). The origins of the technology date back to the 18^{th} century and Luigi Galvani's famous work on "animal electricity" [5]. Galvani demonstrated for the very first time that it is possible to get electrons to flow through biological matter by passing electrical current through frog legs. In 1911, Michael C. Potter demonstrated the very first MFC, working with *Saccharomyces cerevisiae* (baker's yeast) or *Escherichia coli* [6]. The principle of operation of MFCs lies with the ability of live microbes to digest organic substrates inside an electrochemical cell. An MFC typically comprises two half-cells separated by an ion-selective membrane. In one half-cell, micro-organisms living in a liquid broth are fed an organic substrate. The metabolic activity of the microbes produces electrons which are transferred to the anode electrode. An external electric circuit allows the electrons to flow from the anode to the cathode. At the anode, cations such as protons leak into the liquid and pass through the membrane to reach the cathode half-cell. At the cathode, the incoming electrons and protons react with an oxidising agent (ferricyanide, water or O_2), to complete the reactions and close the circuit.

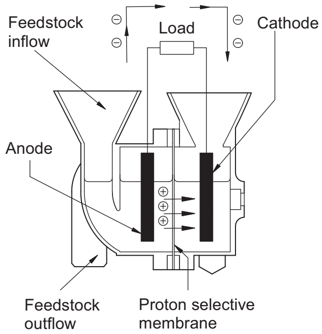

Figure 1. Microbial fuel cell.

Artificial Muscle Materials.

Materials which exhibit movement or changes in shape when externally stimulated have been described as "artificial muscles". Two classes of artificial muscle materials are shape memory alloys and electroactive polymers. Shape memory alloys are metallic alloys, typically composed of nickel and titanium. Wires, fibres and helical springs formed from NiTi shape memory alloy materials can be stretched out of shape at room temperature, but when heated above the material's transition temperature by the application of electric current, they will contract, generating significant force [7]. Electroactive polymer materials (EAPs) include dielectric elastomers and ionic polymer metal composites. Dielectric elastomers contract in thickness and expand in area with the application of a high voltage, whilst ionic polymer metal composites bend when stimulated by a relatively low voltage [8,9].

Researchers have demonstrated that electroactive polymer-based artificial muscles can be powered by electrical energy from microbial fuel cells. In a previous study it has been shown that an EAP-based sphincter, stirrer and cilia-like mechanisms have been powered by the MFCs of the EcoBot series of energy-autonomous robots [10]. In [11] Bowers et al. demonstrate an EAP-based peristaltic pumping tube intended for future use in the fluid circulation system of the EcoBot.

For the prototype bio-actuator described in this paper, we chose to use a NiTi fibre actuator (Biometal Fibre BMF100, Toki Corporation, Japan). This was because we found this type of contractile fibre actuator to be readily available and easy to incorporate into the bio-actuator design without the need for any special processing. In addition, the relatively low operating voltage (2.5 volts for 48 mm fibre length) meant it would be feasible to power the NiTi actuator with the electrical energy generated by MFCs and stored in a capacitor bank.

3D printing.

3D printing technologies enable physical objects to be fabricated directly from computer aided design data through the layer-by-layer deposition of material. The 3D printing process employed in the fabrication of the bio-actuator is photopolymer jetting (Objet Geometries, Israel) in which a liquid photopolymer resin is deposited by inkjet printing and immediately cured by ultraviolet light [12]. 3D printing is employed to fabricate the rigid components of the bioactuator and also to make the moulds used to cast flexible components in silicone elastomer material.

Bio-actuator design and characterisation.

The design of the bio-actuator is illustrated in Figure 2. The bio-actuator comprises a pressure inlet, a diaphragm fabricated from soft silicone elastomer, a magnetic switch, a "smart" control valve incorporating a NiTi fibre actuator, and an outlet.

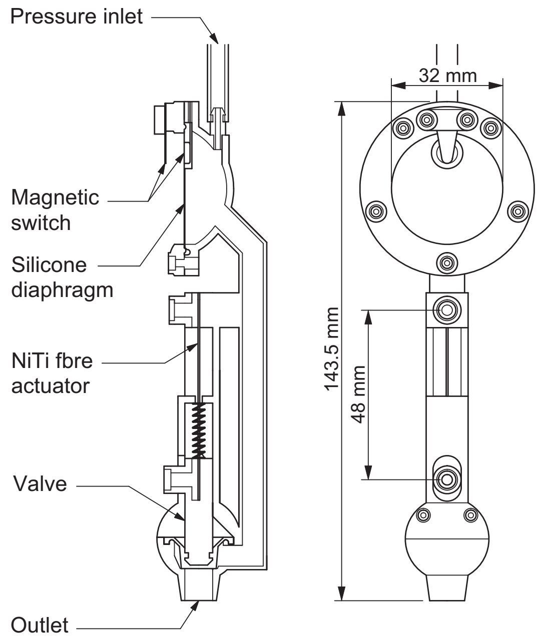

Figure 2. Bio-actuator design.

The sequence of operation is illustrated in Figure 4. Pnuematic pressure, generated by the metabolic action of live yeast *Saccharomyces cerevisiae,* enters the bio-actuator through the pressure inlet. This causes the diaphragm to distend. When the diaphragm is fully distended, the magnetic switch closes (Figure 4 a). This allows electricity, generated by MFCs and stored in a capacitor bank, to flow through the NiTi fibre actuator, heating it and causing it to contract, opening the valve. Pneumatic pressure is released through the outlet of the bioactuator (Figure 4 b). The magnetic switch remains closed long enough to allow the bio-actuator to fully exhaust, returning the diaphragm to its state of rest in readiness for the next cycle of actuation.

Figure 3. Bio-actuator 3D printed working prototype.

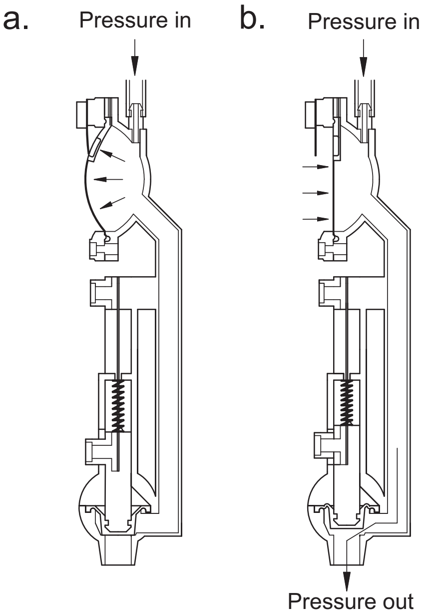

Figure 4. Bio-actuator sequence of operation.

In order to characterise the physical performance of the bio-actuator, two tests were carried out. The first test, a static test, investigated the relationship between the pressure inside the bio-actuator and the deflection of the diaphragm. Pneumatic pressure was applied using air from a syringe. A digital manometer was used to measure the internal pressure within the bio-actuator, and a digital vernier gauge was used to measure the deflection of the diaphragm. The results of this test are shown in Figure 4. Readings of pressure and deflection were recorded up to a maximum pressure of 25 mBar, when the corresponding value for deflection of the diaphragm was approximately 6.5 mm (Figure 5).

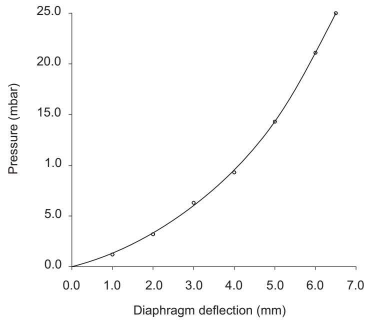

Figure 5. Pressure vs. diaphragm deflection.

The second test was a dynamic test, in which pneumatic pressure was applied using a computer-controlled syringe driver, (flow rate of 210 ml/minute). Pressure within the bio-actuator was recorded using a high-speed pressure transducer (sample rate 10 milliseconds) attached to a data logger. Electrical power for the NiTi-actuated valve was provided by a bench power supply set to 2.5 volts. Results for the dynamic pressure test are presented in Figure 6. which shows four consecutive actuation cycles. In each cycle, pneumatic pressure within the bio-actuator increases up to a maximum value (approximately 21 mBar), at which point the valve opens and pressure is released. Pressure drops to approximately 0.5 mBar before the valve closes and the next actuation cycle begins.

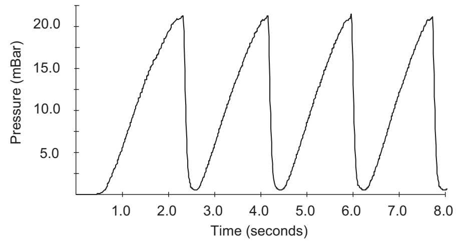

Figure 6. Pressure vs. time.

Experiments in bio-actuation

Experiments were carried out to investigate the feasibility of using live micro-organisms to generate the pneumatic pressure that is necessary for actuation, and to provide the electrical power that is required to operate the NiTi-actuated valve.

The experimental set up is shown in Figure 7. Electrical energy generated by a stack of 48 small-scale (6.25 ml/unit) MFCs is stored in a bank of electrolytic capacitors, with a total capacitance of 0.408 Farad. The MFCs were inoculated with mixed cultures of micro-organisms that are commonly found in sludge and they were fed on neat wastewater (primary effluent supplied by Wessex Water). These MFCs form the power source of EcoBot-III and have been in operation for the last 4 years. A mixture of 7 g dried yeast *Saccharomyces cerevisiae*, approx. 8 g of sugar and 200 ml water at 36 degrees Celsius is placed in a bioreactor vessel. Carbon dioxide gas generated by the metabolic action of the yeast is collected in a balloon. When the MFC energy was accumulated to a threshold of 2.5 volts in the capacitor bank, and when the balloon has inflated, a valve is opened in order to allow the gas which has been collected in the balloon to flow through the bio-actuator, causing it to operate.

Results

It took 55 minutes to charge the 0.408 Farad capacitor bank to 2.5 volts. This was found to have provided enough electricity for 12 consecutive actuations, after which the voltage of the capacitor bank had dropped to 1.55 volts. It then took 14 minutes and 30 seconds to charge the capacitor bank back up to 2.5 volts.

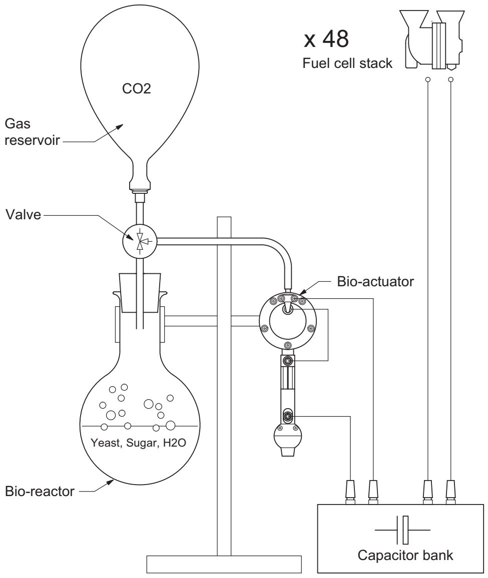

Figure 7. Bio-actuation experiment

For the purposes of comparison, we also investigated the performance of a photovoltaic panel (Solarbotics Ltd SCC3766 Monocrystalline solar cell, 37 x 66 mm) to generate the electrical energy that is required to power the NiTi fibre actuator. Outdoors, on a moderately sunny day in June, it took 1 minute 22 seconds to charge the same capacitor bank up to 2.5 volts.

It took 30 minutes for the yeast to inflate the balloon with carbon dioxide to approximately 85 mm diameter. This was found to provide enough gas pressure for more than 30 consecutive actuations.

Discussion

In this paper we have presented the design, fabrication and testing of a novel bio-actuator, which for the first time exploits the action of live micro-organisms, both as a source of electrical power and a means of actuation. The bio-actuator exhibits a self-regulating, pulsating action which is in some ways analogous to the heartbeat of a living organism.

The physical principles demonstrated by the bio-actuator may in the future be applied within the field of bio-robotic art and design. There is also potential for further development, leading to functional applications in energy autonomous robotics and unconventional computing. It is envisaged that within bio-robotic art and design, the bio-actuator could serve as an artificial heartbeat for a cyborg-like machine or *biological automaton*. Furthermore, in the case of energy autonomous robotics, the bio-actuator could function as a biologically-driven diaphragm pump, for fluid circulation in an application such as the EcoBot. Finally, for the field of unconventional computing, the bio-actuator could potentially function as an oscillator or “clock” for biologically-driven logic circuits.

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