Centre for Health Technologies
School of Biomedical Engineering
University of Technology Sydney

An Energy Harvesting System Using Biological Fuel Cells for Powering Medical Devices

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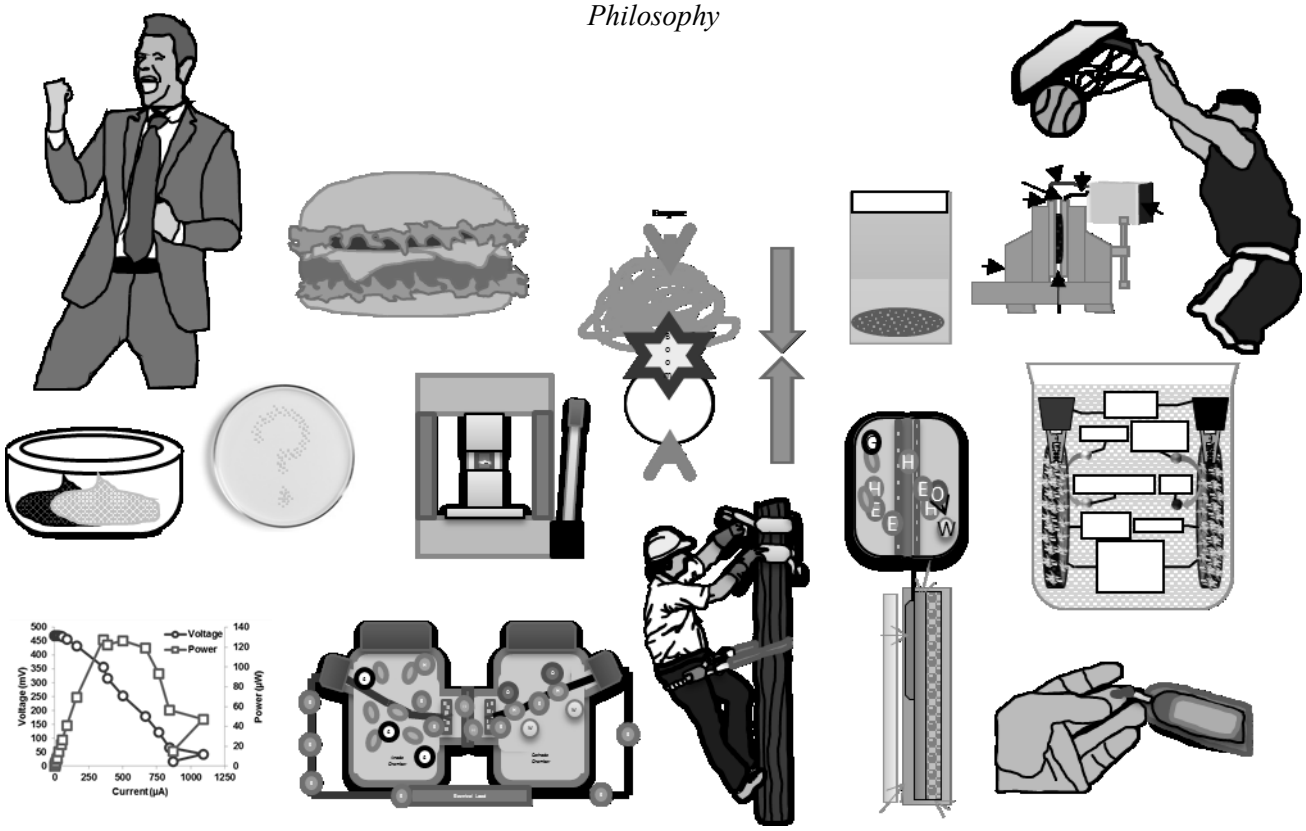
A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy



CERTIFICATE OF AUTHORSHIP

I, Daniel Ninio Roxby, certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

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NOMENCLATURE

AIMD	Active Implantable Medical Device
Ppy	Polypyrrole
SEM	Scanning Electron Microscopy
MWCNT	Multiwalled Carbon Nanotubes
MFC	Microbial Fuel Cell
SCMFC	Single Chamber Microbial Fuel Cell
DCMFC	Dual Chamber Microbial Fuel Cell
BFC	Biofuel Cell
GEBFC	Glucose Enzymatic Biofuel Cell
RAFT	Reversible Addition-Fragmentation Transfer
RVC	Reticulated Vitreous Carbon
PBS	Phosphate Buffer Solution
LBB	Luria Bertani Broth
TSB	Tryptic Soy Broth
LBA	Luria Bertani Agar
TSA	Tryptic Soy Agar
GPC	Gel Permeation Chromatography
NMR	Nuclear Magnetic Resonance
CV	Cyclic Voltammetry / Voltammogram
GOx	Glucose Oxidase
LAC	Laccase
FTIR	Fourier Transform Infrared Spectroscopy
EP	Electropolymerisation
EI	Enzyme Immobilisation
IC	Increased Conductivity
Glut	Glutaraldehyde
DI	Deionised

ABSTRACT

The most common example of an active implantable medical device (AIMD) is the pacemaker. In 2017, Abbott Laboratories said that 'more than 4 million people worldwide have an implanted pacemaker… and an additional 700, 000 patients receive the devices each year.' Other devices also exist, such as neurostimulators and cochlear implants which are implanted at different ages and whose batteries lives differ such that surgical replacement is required. With further technologies being developed and life expectancy rising, the incidence of this problem will increase.

Current wireless charging and energy harvesting solutions are not ideal. Wireless recharging continues to be researched where issues around alignment, power transfer efficiency and skin heating remain. Importantly, patient anxiety for their device's charge remains but at more regular intervals. Peltier cells can harvest heat energy from the body but must be unfeasibly large. Mechanical energy harvesting with piezoelectric, electrostatic and electromagnetic generators has potential, however, require patient movement or require risky attachment to organs.

Biological fuel cells have the potential to power AIMDs from glucose, using bacteria or enzymes to catalyse the capture of electrons. This study outlines methods to improve the power of both microbial fuel cells (MFCs) and glucose enzymatic biofuel cells (GEBFCs) for AIMDs.

Firstly, MFCs are used to find that positioning electrodes can improve the power output by 5 times as well as that fuel cell stirring can improve power by 1.2 times. These findings have implications where a patient can be upright or lying down, and active or sleeping. Internally, bacteria composition was found to be an important factor in power output, where MFCs that use of a mixed culture could provide 10.27 μW of power whereas a single culture could

provide 5.94 μW and that fuel cell stacking could achieve up to 1.6 V and 39 μW. These findings speak to the size of a MFC and that power density is a significant challenge to implantation.

Alternatively, polypyrrole electrodes were developed for a GEBFC. The method involved a novel combination of RAFT and electro-polymerisation to create a polymer which had a high conversion efficiency of 80.9% and uniform polydispersity of 1.034. The disc electrodes were synthesised through a simple compression method, enabling high enzyme loading and suitability for manufacturing. Further improvements using glutaraldehyde crosslinking and high conductivity silver composites lead to harvesting of 451 mV, 128.2 μW and 1.4 mA and ultimately, an actual medical device is powered.

Whilst there is significant potential, there are some areas for future work. MFCs will require significant work in miniaturization whilst also increasing the power output and making them biocompatible. GEBFCs using polypyrrole will likely also require further biocompatibility work as well as improvements in the conductivity and crosslinking of the material, which will help take care of several issues such as porosity, enzyme leaching, enzyme orientation, biofouling and electron transport.