Research Preparation: A Functioning Biodegradable Robot

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Contents

1 Aims and Objectives

Aim:

- To design and test a small, fully biodegradable robot capable of energetic autonomy.

Objectives:

- Research components capable of full biodegradability: actuators, microbial fuel cells, electronics, control systems and chassis.
- Consolidate research by determining the feasibility of use of studied components.
- Decide on types of components to use, based on expected capability and requirements.
- Design a robot that effectively utilises the most viable components.
- Testing of individual subsystems to prove viability of energetic autonomy.
- Build and test prototype.

2 Motivation

The field of robotics has seen vast improvements over the past few decades, with the industrial robot becoming a mainstay of various modern production processes, and our reliance upon autonomous technology for our continued exploration of our solar system set to continue in the foreseeable future. With the increasing prevalence of robotics in our society however, a full consideration of the robot lifespan must become an integral part of the development process. In wake of the damage caused by rampant, uncontrolled production and consumption, sustainability of a production cycle is now heavily considered alongside product cost and lifespan.

Much of modern robotics has yet to account for this issue however, with the materials and electronic components largely lacking in biocompatibility; batteries, actuators and control systems have miniaturised and improved in power and efficiency, but not in sustainability. Elements and manufactured materials present in consumer electronics, such as lead, cadmium, mercury and PVC (to name a few) have all been linked to severe health issues, either through direct contact or indirect consumption. Being inherently imperishable over human timespans, such materials persist in the environment for long periods, working their way into the ecosystem through animal or plant consumption, a process known as bioaccumulation, or contaminating water supplies.[1]

Environmental concerns aside, an arguably more pressing issue is that of finite resources and lengthy production times; elements such as lithium, commonly used in batteries, or palladium, present in hard drives and capacitors, are in limited supply. Though relatively abundant in the earths crust, many rare earth elements (REE) prove difficult to produce in high volumes due to wide dispersion and separation difficulty, a problem set to worsen over time as easily accessible resources dwindle.[2]

Though robotics researchers frequently look to nature for novel, biomimetic solutions to control, sensory and mobility problems, the cyclical processes of life and death that are inherent in biological life are largely overlooked. Nature tends towards homeostasis, reaching a balance between decay and rebirth that avoids depletion of resources within the biosphere through the recycling of biological material. Such a system is highly robust to drastic change in conditions, as proven by resilience to the various mass extinction events that have rocked the planet since the emergence of life.

It is therefore worth considering the concept of robots as synthetic organisms; can we develop autonomous robotic systems tailored to our needs, that insert seamlessly into the ecosystem without upsetting the delicate balance? Such robots would return much of the energy used to produce them back into the biosphere, leaving no trace of their existence behind, much like any biological specimen. To achieve this, a departure from current fabrication material is required. Material used should be biodegradable and biocompatible – that is, degradable in the natural environment and completely non-toxic to biological life.

Though the degradability of biological life sustains the constant renewal of resources within ecosystems, energetic autonomy allows it to flourish. Storing enough energy to allow a robot to function for long periods proves problematic with current battery energy densities, particularly in small scale robotics, where weight becomes a key design consideration. It is therefore desirable for robotic systems to be capable of on-board energy production, reaching a balance between stored energy and expended energy that allows useful tasks to be completed whilst simultaneously generating energy to allow continuous functioning of the robot. On-board energy production is not a novel concept and has long been a staple part of autonomous systems design for remote locations, with solar panels and radioisotope thermoelectric generators proving extremely useful in space exploration roles. However, biocompatible and biodegradable power sources have yet to be fully exploited.

Continued research in this field could give rise to a completely new approach to robotics, in which

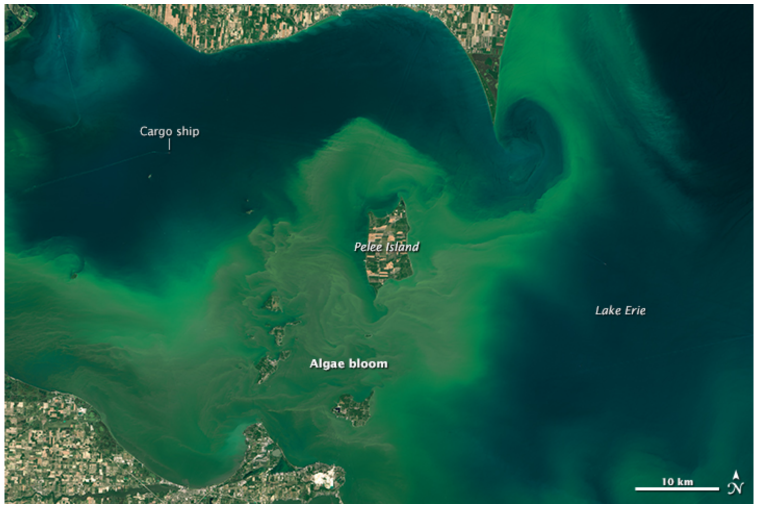

Figure 1: Natural colour satellite image of Lake Erie, demonstrating the scale of algal bloom events.[6]

low-cost robots are released indiscriminately en masse into a task area, with no need for collection upon completion of their mission. Full realisation of this capability still requires significant advances in artificial intelligence and swarm control, yet solutions to current problems can potentially be found, particularly in aquatic environments.

A few applications appear feasible in the short term. Environmental monitoring has become an invaluable tool for quantitative measurement and analysis of human impact on the planet, as well as improving our understanding of complex natural changes. Autonomous gathering of environmental data through large numbers of agents could allow for monitoring at a resolution and scale not previously possible.

The data gathered could be hugely varied, and of use to scientists and environmentalists across a wide range of disciplines. Some examples include: monitoring of ocean acidification, considered a result of increased C02 in the atmosphere; ocean temperature, to further understand the flow of heat energy within the biosphere; variability of ocean currents; monitoring the spread of chemicals after a spill; and water oxygen levels, heavily linked to the health of the local ecosystem.

Beyond simply monitoring the environment, the utility of the robot could be in the act of feeding itself, providing energetic autonomy whilst clearing undesirable material from the surroundings. Microbial fuel cells (hereby MFCs), though relatively low in power output, have proven capable of consuming a wide range of pollutants and undesirable materials to provide energy, including crude oil[3] and algae.[4]

Oil spills often prove difficult to contain, and often involve the dumping of large quantities of dispersants or biological agents into the water, with high risk of entering the food chain of local marine life.[5] The dispersion of high numbers of simple clean-up robots over large areas could provide a means of quickly removing oil from large swathes of the ocean surface (the main point of concentration) without the use of further damaging contaminants.

Algal blooms have become a pressing issue worldwide, both in oceanic and freshwater environments. Often caused by contamination of bodies of water by agriculture and storm run-off, excess nutrients lead to rapid growth of algae, with a range of resulting harmful effects: ocean dead zones, due to depletion of oxygen levels; production of toxins dangerous to humans, either through direct contact or through insertion into the food chain; and other issues relating to fresh water supplies for consumption and industrial use.[1] As with oil spills, the scale of algal bloom events, as highlighted in figure 1, leads to difficulties in containment without further contamination. Robotic agents, dispersed as previously described during a nutrient pollution event, could provide a means of preventing the catastrophic loss of oxygen implicated in the formation of dead zones.

In all the above scenarios, the need for collection of the robotic agents post mission would make any attempt at such solutions difficult (if not impossible) using conventional robotics techniques. As the full potential of robotics is unlocked over the coming century, and automated systems become more ubiquitous, we will likely need to begin considering the sustainability of our creations with as much weighting as their effectiveness in a chosen role.

3 Literature Review

The review of relevant literature that follows will begin by considering the various subsystems required for a simple robot of the kind previously described. A review of previous successful robotic systems will follow, for which literature relevant to both biodegradability and energetic autonomy will be considered.

3.1 Power Sources

Whilst roboticists often draw inspiration from biology, power production has remained largely artificial by design. Photovoltaic (PV) cells have become a staple method for on-board power production, particularly for robots operating in remote environments. Most contemporary interplanetary exploration robots, for example, utilise solar cells as a reliable source of energy, combined with on board batteries to store energy for later use. Rising efficiency and a dramatic reduction in cost has put photovoltaic cells at the forefront of the renewable energy debate[7].[8]

Such cells are not inherently renewable however, and certainly not degradable or biocompatible, containing various toxic compounds harmful to plant and animal life.[9] Though not an issue in the space exploration sphere (currently), their usefulness is limited by their lack of degradability; though in many ways ideal for small-scale robotics, current PV cells will always require collection post-mission, ruling them out as power sources for large swarms of biodegradable robots.

Various work has suggested the possibility of fully biodegradable organic PV cells. Genetic modification of tobacco plants to produce light harvesting chromatophores capable of electron production grants the possibility of low cost, biodegradable solar cells, though the production of a functioning cell has yet to be demonstrated.[10] Development of an organic solar cell using a biodegradable substrate suggests the possibility of solar cells with a high efficiency and biocompatibility.[11] Recent progress has also been made on biophotovoltaic solar cells, generating electricity from sunlight using 3D printed cyanobacteria, with arrays of cells capable of powering small consumer electronics, such, as digital clocks and LEDs.[12]

Microbial fuel cells (MFCs) also offer exciting new possibilities for sustained power production, with current produced by electron transfer interactions between anaerobic micro-organisms and the fuel source. A typical MFC structure is displayed in figure 2. Though MFCs have been developed since the 1960s, the fully biodegradable MFC is a contemporary development, with many of the recent advances originating at the Bristol Robotics Laboratory.

Much progress has been made at the BRL towards reducing the cost of production, and improving the biocompatibility and degradability: natural rubber has proved a suitable replacement for the expensive materials commonly used in fabrication of the ionic exchange membrane;[14] A

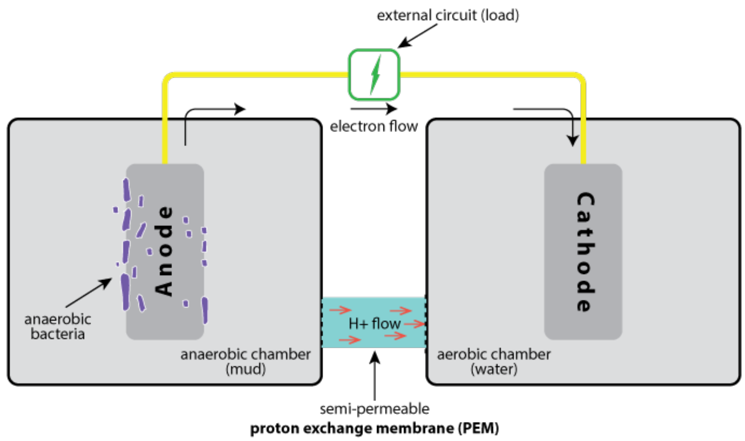

Figure 2: Diagram of typical microbial fuel cell.[13]

biodegradable stack of MFCs was developed, capable of providing sufficent power for a range of applications when combined with a energy harvesting components;[15] A fully biodegradable MFC was developed using very low cost materials, capable of running low power electronic devices intermittently;[16] And an MFC was developed utilising biodegradable 3D printed polylactic acid (PLA) as the frame, demonstrating significant improvements over previous 'soft' designs.[17]

Due to the availability of materials and expertise, a MFC will likely prove to be the most suitable source of power for any robot developed within the scope of this project.

3.2 Actuators

Soft robotics actuators have seen significant research in recent decades, with highly varied mechanisms of action. Actuators that are responsive to heat, light, chemical gradients, pressure and electricity have been developed,[18] though a more considerably narrower subset of these have been developed with biodegradability and biocompatibility as a goal, or an unintended advantage.

Dielectric elastomer actuators provide actuation through couloumb forces, usually consisting of a layer of elastomer materials sandwiched between two electrodes. It has proven possible to fabricate both the elastomer and electrodes from biocompatible materials; latex proves a suitable candidate for the elastomer,[19] and gelatine mixed with an ionic solution provides suitable electrode material.[20]

Ionic polymer actuators instead function based on the movement of ions within a material, and the subsequent swelling caused by this chance in ion density. Much work. In recent years, research at the BRL has produced gelatin-based ionic polymer actuators; when immersed in salt solution, the actuators exhibit slow, but large displacement, though periodic dehydration is required due to material swelling.[21] A lightweight composite consisting of chitosan and carbon nanotubes has also proven capable of significant actuation power, while retaining full biocompatibility, with expected applications in the field of medicine.[22] The composite functions outside of a salt solution, a significant benefit to any robotics applications.

Further mechanisms of actuation provide yet more options. Soft pneumatic actuators have been recently developed using a gelatin-glycerol mix, building on cavity expansion methods commonly used in soft pneumatic actuation. The actuator, when acting as a gripper, was capable of generating forces comparable to polymer actuators.[23] In another recent development, photo-responsive hydrogel actuators have demonstrated slow but repeatable actuation, with potential applications for cardiac muscle support.[24] Electroactive paper has also proven capable of actuation, consisting of a thin layer of thin electrodes on either side of a layer of cellulose (paper).[25]

3.3 Electronics

Though the field of electronics has seen very significant advances in recent decades, with components both reducing in cost and in size dramatically, little consideration has been taken in improving the biodegradability of components in the average consumer product. As outlined in section 2, the toxicity and increasing scarcity of various materials is an issue that can't be ignored.

Organic electronics offer a potential solution to this issue. Though yet reach the level of stability offered by non-organic electronics, the 'soft nature of such components lends them some distinct advantages over their hard counterparts.[26]

The substrate upon which electronic components and circuitry can be fixed, and the barrier layers between them, has seen some interesting solutions, and the use of biocompatible materials, such as paper or synthetic polymers, have proven suitable for the task.[26] Though currently unable to match the robustness of less biocompatible materials, the inherent flexibility of many organic materials offers great advantage over inorganic substrates. Difficulty does arise however in retaining operational capabilities under stress and strain forces however. A combination of paper with nano-materials to create highly robust capacitors[27] has proven the efficacy of paper as a substrate, and when combined with other biodegradable components, grants the possibility of integrated circuits on a paper 'chip'. Biocompatible synthetic polymers also offer solutions, with many now utilised in implantable electronics research.[26]

The transistor forms an integral part of any modern electronic device, and the development of organic transistors has seen great interest. a great body of work has been carried out in the pursuit of organic field-effect transistors, and proven designs have been created using materials such as gelatin and chicken albumen.[28]

It is worth noting that though an understanding of the current limitations of biodegradable electronics is worth having, it is likely that it will not play a large role in a project of this scope.

3.4 Current Implementations

The field of biodegradable, energetically autonomous robotics is a relatively modern development, tied closely with an increasing drive toward soft, biomimetic systems. Though computational autonomy remains the main drive behind much of current robotics research, the desire for fully self sufficient robots will only increase as system adaptability and robustness improves.

Some notable research has begun to explore these possibilites. The 'EcoBot' series of robots, developed at the Bristol Robotics Laboratory from 2002 onward formed a series of successful attempts at demonstrating self-sustainability in a robotic system. EcoBot-I successfully proved the concept of energetic autonomy in robots. By using energy harvested from sugar by an on-board MFC, the robot demonstrated phototaxis; low levels of power from the MFC would allow for pulsed movement towards a light source.[29]

The second iteration in the series, Ecobot-II, further expanded on previous work, demonstrating (for the first time) the use of unrefined fuel, and carrying out various tasks. Intermittently fed on flies and fruit, the robot successfully demonstrated phototaxis, temperature measurement and data transmission, again during pulsed energy discharges. The robot was capable of operating for periods in excess of 11 days, with experimentation halted only due to time constraints.[30]

Research for Ecobot III went a step further; by recycling waste to maximise energy extraction, and excreting unusable waste material, the robot essentially demonstrated a form of artificial digestive system. The robot was capable of self-feeding (within the bounds of the simple experiment

Figure 3: The Row-bot; a single MFC powered energetically autonomous robot. Displayed here with mouth open and closed.[32]

setup), removing the requirement for manual feeding.[31]

The above systems mark important milestones in the development of energetically autonomous robots, yet require large banks of small MFCs for greater power output (the smaller the MFC, the higher the efficiency). The development of small-scale, low power robots therefore requires a different approach. Another BRL development, the 'Row-Bot', demonstrated for the first time the use of single MFC in powering a practical robot, capable of energetic autonomy.[32] Feeding directly from the liquid the device was floating on, the row-bot could successfully feed, digest to charge a capacitor, and moved small distances to provide more fuel.

work carried out in this project will likely form an extension to the work carried out on the 'Row-Bot, with higher focus on the biodegradability and biocompatibility of the components.

4 Risk Register

Risk	Mitigation	Likelihood	Impact	Score
Breakage of fabricated parts	fabricate multiple spares	3	4	12
Difficulty fabricating novel components	Discuss with supervisor in depth the limitations and production times for each component	3	3	9
Delay in procuring required materials	Close discussion with supervisor to organise any required deliveries	2	3	6
Delay caused by safety Considerations (training required, staff presence required etc)	Discuss with supervisor any safety considerations before lab work begins	2	2	4

5 Project Timeline

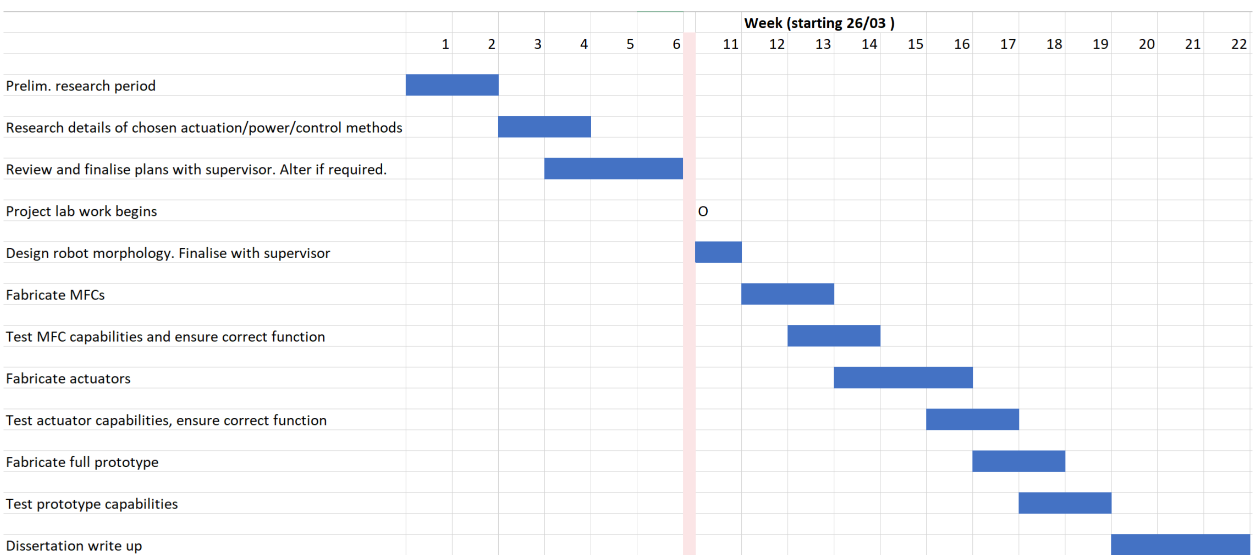

Figure 4: Project gantt chart. Weeks 7-10 omitted due to examination period.

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