

The Dawn of Biodegradable Robots

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Robotics is a field that is not normally associated with green technology or sustainability. Robots are generally constructed using materials that are non-biodegradable, toxic and expensive. These factors can limit the potential uses that an artificial agent might have, especially if operation is required outside and away from where humans live. Things are further complicated when considering the robot's power supply. In most cases, batteries are used that will inevitably run out and require recharging from charging stations. Imagine then, an environmentally friendly robot, one that can safely roam a targeted area whether that is within agricultural fields, rain forests or remote jungles. Movement would not be random but with a preset purpose built-in perhaps to identify pests, clean up human-made waste and generate electricity from it, or simply monitor/sense environmental conditions.

When designing such a robot it is important to consider that the natural environment is a well-balanced and closed system where new organisms are born, live and die. The materials that make up the dead are then recycled within that same ecosystem. Could a biodegradable robot fit into such a system and be developed with the capability of consuming other robots at the end of their life? These are areas that we at the University of the West of England (UWE) and the University of Bristol have been investigating through a Leverhulme Trust funded project to develop biodegradable robots.

Based at the Bristol BioEnergy Centre within the Bristol Robotics Laboratory, this line of work has focused on three overlapping areas, a) the robots source of power in the form of microbial fuel cells, i.e., the robot's stomach, (b) the robot's mechanism for movement, i.e., artificial muscles, (c) the biodegradability of the materials. In addition we also looked at whether power could be produced from the consumption of its own parts, i.e., could a robot muscle be fed to the robot stomach!

Microbial fuel cells (MFCs) even when made out of conventional materials are a very promising green technology. MFCs have been described as 'bio-batteries' but this term is not wholly correct because batteries start life with a set amount of reactants. Once the reactants are depleted the battery will cease to operate until recharged at a human-made charging station. A fuel cell on the other hand will carry on producing power for as long as it is being fed with a fuel. For MFCs, that fuel can be any liquid containing organic matter, e.g., wastewater, urine or agricultural runoff. As with a conventional battery, a MFC consists of a negative (anode) and a positive (cathode) electrode. Bacteria grow on the anode and breakdown organic matter in the wastewater releasing electrons and protons. The movement of the electrons and protons to the cathode equates to the production of electricity. Making the technology even more attractive is that the production of electricity comes as a direct consequence of the removal of organic pollutants—the more power produced the cleaner the liquid becomes. This process is never-ending providing the bacteria are continuously fed; we have MFCs in our lab that have been running now for eight years!

Quite rightly there has been considerable interest in the technology from wastewater treatment companies as well, in addition to the robotics application. Before investigating biodegradable robots, Prof. Ieropoulos developed the EcoBot series of robots. Using MFCs as the sole source of power, four robots were constructed over a ten-year period. Each new embodiment moved closer to total autonomy such that EcoBot's III and IV could move towards a food source when their 'on-board' bacteria were hungry and even expel waste when depleted. The EcoBots were a wonderful demonstration of utilizing bacterial power for a useful purpose, however the MFCs aboard the robots were built from conventional plastics and materials.

The first step in developing biodegradable MFCs was the identification of alternative and functional 'green' materials to replace the commonly used components. In conventional MFCs, a proton exchange membrane (PEM) is often used to separate the electrodes while allowing for the movement of protons from anode to cathode. Not only are PEMs expensive but they can inhibit microbial metabolism and more importantly for

our project, they are not biodegradable. In order to find biodegradable replacements, the focus moved to porous materials, ones dense enough to isolate the electrodes but of a porosity that would enable proton transfer. A range of diverse and in some cases unconventional materials were trialed; these included paper, gelatin, alginate and even fruit (specifically kiwi fruit). Perhaps the most unusual material investigated was natural rubber from condoms!

The motivation for using natural rubber was that it was also proving to be a viable material for the biodegradable artificial muscles. In the early stages of the experiment the MFCs with condom membranes produced no electrical current whatsoever. This was because the material was so impermeable that even protons could not pass through, which is perhaps expected given the original purpose of the material.

After a number of weeks and to our surprise, the MFCs began generating a working voltage which continued to increase over the ensuing months. After almost a year the MFCs with 'condom' membranes were outperforming those with conventional PEMs. What was enabling the production of bio-electricity? Biodegradation. Microbes were eating into the natural rubber and creating channels and pores that enabled the flow of protons. Impressively over time, areas of the rubber were completely degraded but the accumulation of microorganisms (biofilm) formed a natural patching that ensured the electrodes remained isolated from one another. The formation of such biofilms on conventional PEMs can inhibit performance but with the rubber separators, their presence boosted performance.

Next we looked at developing alternative electrode materials and our list of ingredients included egg yolk, gelatin, graphite and lanolin. During all of our experiments we ensured the materials were both biodegradable and non-toxic using microbiological techniques and through composting studies at the Bristol Botanic Gardens.

The next step was to develop stacks or multiples of biodegradable MFCs in order to maximize power output. For the individual MFCs in the stack we used natural rubber from laboratory gloves, egg-based electrodes and 3D printed MFCs chassis using biodegradable plastic (polylactic acid). The completed MFCs are shown in Figure 1 and when fed with natural waste (e.g., urine) the stack of 40 MFCs in a series/parallel electrical configuration produced over 3 volts and a power density of 4 Watts/m³



Figure 1. Biodegradable Microbial Fuel Cells

For the artificial muscles we focused on biodegradable electroactive polymers, materials that change in size or shape when stimulated by an electric field. In other words, these materials transduce electrical energy into mechanical energy. In general, there are two categories, i) materials that actuate through the movement of ions and, ii) those that respond to electrons. In both cases biodegradable materials were successfully used as viable replacements to the conventional versions. Natural rubber, being very compliant, proved to be an excellent dielectric elastomer actuator. Gelatin demonstrated actuation through the movement of Na⁺ ions in the gel and in solution, as shown in the figure below.

Now with moving parts and a source of power we looked at whether a biodegradable robot might be able to gain energy by consuming the parts of another. To achieve this, gelatin muscles were 'fed' to MFCs. Fuel cells fed with the 'robot muscle' exhibited a doubling in power as the bacteria consumed the material.

There is clearly more work to be done before biodegradable robots are a thing of the present, but our preliminary findings suggest that it may not be long before such robots are helping protect the environment. They could be sent to remote or sensitive areas to collect data, even tapping into natural resources to obtain their energy, e.g., muddy puddles, sediments or pests like flies or mosquitos. As long as this fuel is continuously supplied the robots will be able to keep working and therefore accruing data. We envisage a built-in mechanism that initiates biodegradation once the robot's 'time has come' or its mission is complete. For example, the release from an internal compartment of a specific microorganism to consume the robot or an inert chemical that renders the robot chassis consumable. In comparison to drones, the biodegradable ground robots, while not covering as much area, could continue operating for longer. Perhaps further down the line, biodegradable drones may even be achievable!



Figure 2. Biodegradable Artificial Muscles

Another role is deployment in areas where human-made waste has accrued such as oil spills or nuclear waste. There have been reports of bacteria that can eat up crude oil in spills and even nuclear waste. Imagine then sending robots to infected areas, loaded with these bacteria that clean the problem as the robot glides over the surface until the area is uncontaminated. Once the all-clear has been broadcast, there need not be any further human intervention, i.e., to remove the device, because the robot can be left to degrade harmlessly into the environment.