Bugbots! A Multidisciplinary Design Project for Engineering Students

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Abstract

Rowan University's College of Engineering stresses the importance of a well-rounded undergraduate engineering curriculum, incorporating relevant aspects of all engineering fields as well as promoting teamwork through multidisciplinary group projects. This paper describes a semester-long sophomore-level multidisciplinary engineering design course in which student teams design and create a microbial fuel cell (MFC) that powers a Lego® Mindstorms robot. The project combines mechanical, chemical, civil & environmental, and electrical & computer engineering skills. Students determine how changing certain fuel cell parameters and conditions affect voltage and current, then construct a Lego® Mindstorms robot that will derive its energy from a MFC stack. The project reinforces many concepts from courses early in the curriculum, such as chemistry, biology, and physics. Because of the multidisciplinary nature of the project, contribution and cooperation from all students are important factors in the success of their designs. This paper discusses the course structure, experimental and design aspects of the project, and student response to the project.

Introduction

In 1992, Henry M. Rowan donated $100,000,000 to the then Glassboro State College to establish a unique engineering program in southern New Jersey. What is now Rowan University boasts an innovative College of Engineering comprised of four programs: Chemical, Civil and Environmental, Electrical and Computer, and Mechanical. The College graduated its first class in May 2000 and serves 15 to 35 students per year in each of its four programs for a total of 60 to 125 students per year.

The hallmark of the Rowan engineering program is an emphasis on technical communication and integrated, hands-on design and experimentation, which is realized in the multidisciplinary, project-oriented Engineering Clinic sequence. To better prepare students for entry into a rapidly changing and highly competitive marketplace, engineering design and practice as well as communication and teamwork skills are introduced early in the curriculum. Beginning in the freshman year, all students enroll in Clinics and work with students and faculty from all engineering disciplines on laboratory experiments, real-world design projects, and research projects of increasing complexity. The importance of effective written and oral communication skills, teamwork skills, and technical proficiency is reinforced in the Clinic sequence[1]. In addition, the clinics can be designed to encourage students to address environmentally conscious design and issues related to sustainable development.

In the sophomore year, students from all engineering disciplines work together on semester-long design projects and present results through either written reports (Sophomore Clinic I) or oral presentations (Sophomore Clinic II). Students learn not only the fundamentals of the design process, but also hone their technical communication skills. This paper focuses on Sophomore Clinic I, which is a combined composition and design course team-taught by faculty from the College of Engineering and College of Communication. The course is structured so that students meet twice a week in small (~20 students) 75 minute writing sections, and once a week in a 165 minute engineering design lab.

The objective of the Fall 2001 Sophomore Clinic I project was to design, build and test a semi-autonomous robot that uses power provided by batteries that are charged with a microbial fuel cell. The project was designed to:

- Introduce open-ended design (both product design and experimental design)
- Familiarize students with sustainability concepts and alternative energy sources
- Compel students to work effectively in teams, as much of the work required skills from the various engineering disciplines
- Reinforce core concepts from engineering pre- and co-requisites such as chemistry, physics, and biology

Microbial Fuel Cell Technology

Fuel cell technology and alternative energy sources such as biofuels and photovoltaics are developing technologies that are exciting to students. Microbial fuel cells operate on the same principles as the more widely used (and more powerful) hydrogen fuel cells. Rather than a non-renewable source such as natural gas, however, microbial fuel cells (MFCs) use biomass as the substrate and microorganisms as the catalyst. While MFCs in which various types of subtrates and waste products are converted to energy by a range of microorganisms[2-9], this project focused on yeast as the catalyst and glucose as the primary substrate.

This project was inspired by the University of South Florida's research on the "Gastrobot," a semi-autonomous robot that is self-sustaining[10-12] and educational materials available from the National Centre for Biotechnology at the University of Reading[9,13-15]. This combination of readily available educational kits and supplies (see http://www.ncbe.reading.ac.uk for supplies) and accessible literature (see http://www.eng.usf.edu/~wilkinso/gastrobotics/) that describes cutting edge research made the project feasible yet stimulating for the students.

A microbial fuel cell takes advantage of the metabolic reactions of microbes to generate electricity. Organisms carry out the following respiration reaction

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad (1)$$

to draw energy from food, or carbohydrates[15]. The above reaction can be broken down as shown in (2) and (3), which follows the activity of electrons:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 24H^+ + 24e^- \qquad (2)$$

$6O_2 + 2$

A redox mediator (methylene blue) can traverse the cell membrane and scavenge electrons from intermediates in which the electrons are stored. The mediator can then present these electrons to an electrode, and if an electron sink is provided (potassium ferricyanide), the circuit is completed (see Figure 1). Voltage and current can be monitored using a multimeter. A single microbial fuel cell is capable of producing approximately 0.5 V.

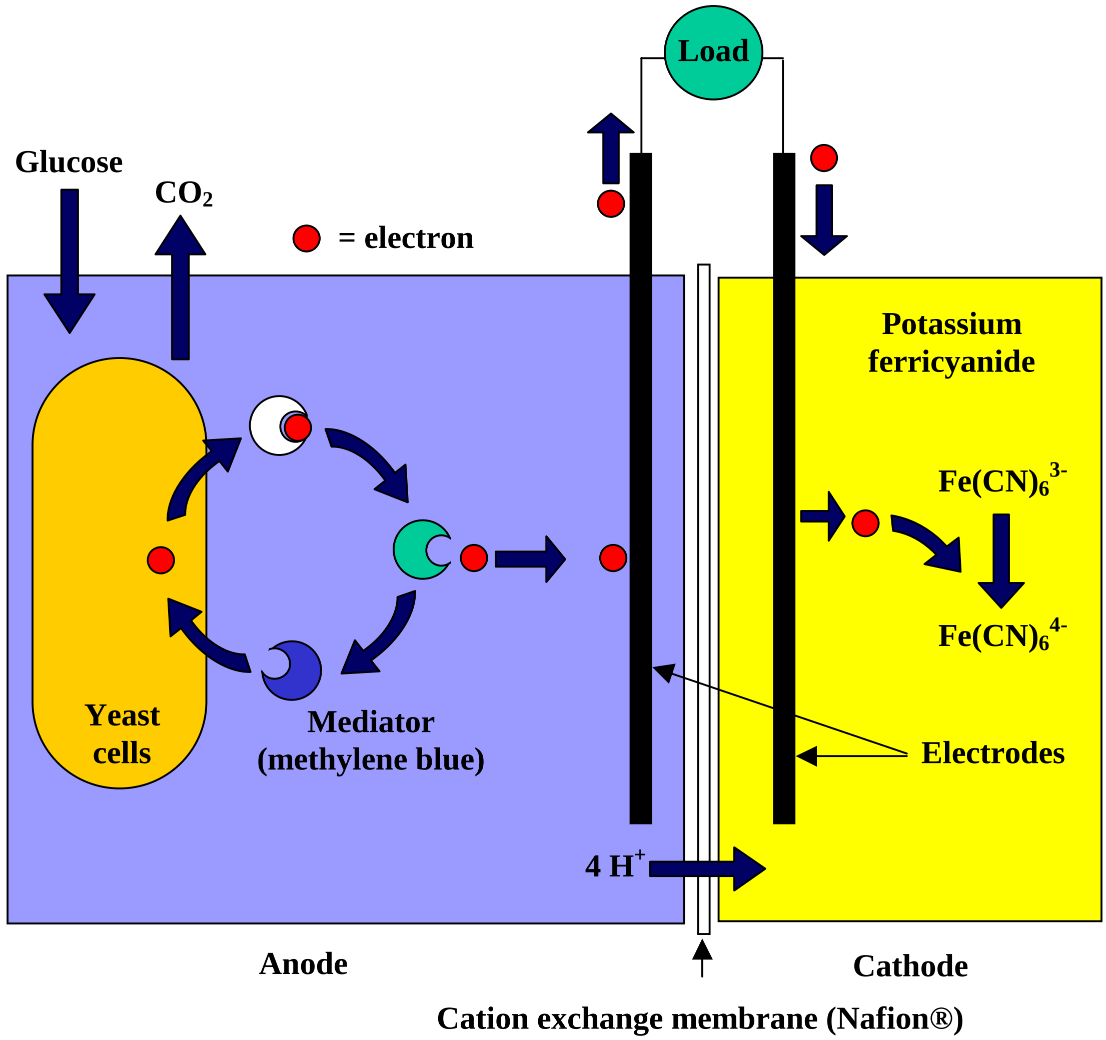

Figure 1: Schematic of a microbial fuel cell. Red dots represent electrons. Adapted from material produced by the National Centre for Biotechnology[4].

Project Organization

Eighteen teams of 5-7 students from all disciplines were divided into subteams—a fuel cell team (2-4 members) and the robot team (2-4 members). The fuel cell subteam drew on the expertise of civil and chemical engineers, whose understanding of microbiology and chemistry were crucial to optimizing the output of the fuel cell. Because of the multidisciplinary nature of the project, contribution and cooperation from all students were important factors in the success of their designs. The fuel cell and robot subteams worked in parallel to develop designs for the fuel cell and robot.

The fuel cell subteams were responsible for accomplishing several objectives:

- Assess the performance of a prototype fuel cell (discharge across a resistor)
- Consult the literature for ways to optimize output of fuel cell (varying fuel cell size, glucose and microbe concentration, glucose feeding schedule, electrode material, etc.)
- Propose 3 designs for a microbial fuel cell stack capable of charging 1 to 6 1.2 volt batteries
- Select one of proposed designs, construct a fuel cell stack, and charge batteries for robot.

Mechanical engineering students contributed to the construction of the fuel cell and Lego robot. Electrical and computer engineering students worked with mechanical engineering students to design a robot that could retrieve a tennis ball from another team's robot, navigate through a maze, and hand off the tennis ball to another robot. This aspect required coordination between the different robot subteams, as the method for passing the ball from one team to another had to be agreed upon. The robot subteams were required to achieve the following:

- Learn the programming language for control of the Lego Mindstorms® robot
- Propose 3 designs for a robot capable of retrieving a tennis ball from another group's robot, navigating through a maze while carrying the ball, and passing the ball to the next group's robot
- Select one of the proposed designs and construct and test a robot capable of carrying out the assigned tasks.

Teams composed of robot and MFC subteams submitted periodic progress reports that addressed safety, project planning, design "brainstorming," and individual responsibilities. Additional deliverables included a midterm design proposal that presented robot and microbial fuel cell designs and a final *Scientific American*-type paper explaining the concepts behind the project and applications for this technology. The project culminated in a final "BugBot Rally," in which the robots were loaded with the batteries charged by the MFCs, and navigated segments of a maze in sequence, with one team's robot passing a tennis ball to another team's robot, and so on.

Fuel Cell Optimization and Construction

Students were given a small prototype fuel cell for initial measurements. A simple microbial fuel cell developed by Bennetto (similar to that pictured in Figure 2) served as a prototype[15]. The kit may be purchased from the University of Reading's National Centre for Biotechnology Education (www.ncbe.reading.ac.uk) for GBP£40.00, or approximately US$57, per set. The kit recommends but does not include all of the following materials:

- Plexiglass fuel cell (30x40x1.8 cm)
- Carbon electrodes
- Cation exchange membrane (Nafion 117 was generously donated by DuPont for this project)
- Rubber gaskets
- 2 leads with crocodile clips
- 0-5 range voltmeter
- Dried baker's yeast, made into a thick slurry in 0.1 M phosphate buffer
- 5 mL methylene blue solution (10 mM)
- 5 mL glucose solution (1 M)
- 10 mL potassium ferricyanide solution (0.02 M)

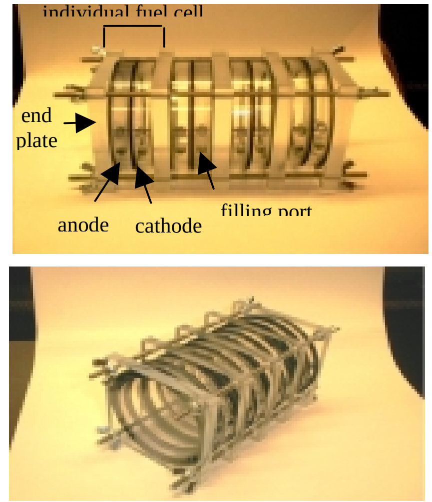

Figure 2: Student fuel cell stack design (side and front view). Stack is composed of 4 fuel cells of ~0.5 V each

Students measured the discharge of the prototype fuel cell over time, and used this information and recommendations from the literature to develop designs that were capable of charging six 1.2 V batteries for use in the robots. From these experiments, students found that a microbial fuel cell is capable of producing approximately ~0.5 V, so a fuel cell stack composed of at least 3 fuel cells was needed to charge a 1.2 V battery. Additionally, students were able to make estimates for approximate glucose addition time to maintain a current sufficient for charging the battery (as glucose was depleted, current and voltage dropped).

Students were given a great degree of freedom in designing the fuel cells. Several constraints were imposed for efficiency, cost, and safety reasons:

- Basic materials of construction were restricted to Plexiglass or PVC pipe, rubber gaskets, and Nafion-117 membrane (cation exchange membrane)
- Yeast was primary organism used and glucose was the primary substrate
- Methylene blue was provided as redox mediator
- Potassium ferricyanide was provided as electron sink (cathode).

From a review of the literature, students found that the fuel cell size and shape were important physical considerations for design, as the size of the fuel cell affected current. Student designs (see Figures 3 and 4) varied considerably, yet all designs were capable of charging at least 2 batteries over the course of one day.

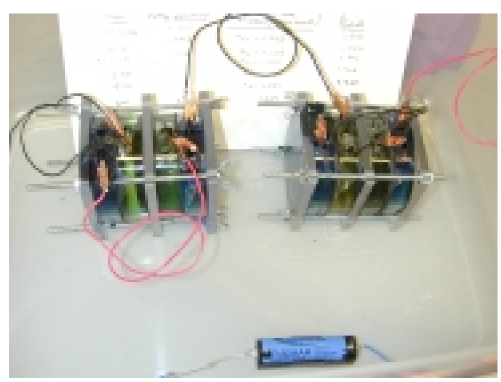

Figure 3: Charging a NiCad battery with a microbial fuel cell

To charge a battery, each group connected their fuel cell stack to a 1.2 V discharged NiCad battery (see Figure 3), and monitored the current over time using a multimeter. When the voltage of the battery reached a steady value of 1.23 V or above, the battery was replaced by another discharged battery. If the fuel cell stack voltage fell below 1.3 V or the current transferred across a resistor fell below a specified level, the fuel cell anode was replenished with fresh glucose and mediator.

Robot designs

Robot designs varied considerably, from a "forklift" design that lifted the ball to a claw design (Figure 5) that grabbed the ball and pulled it behind as the robot navigated through the maze. One design consideration that the robot groups had to address were the effect of the tennis ball's weight on the robot's ability to navigate through the maze. Another design problem that each team had to overcome was setting the sensitivity of the light sensor to recognize the black outlines of the maze and distinguish these from shadows.

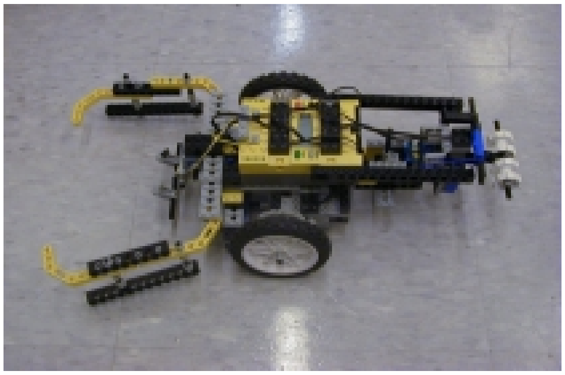

Figure 5: A student design—"The Claw"

Student feedback and concluding remarks

Students were excited about this project, and dedicated many hours outside class to perfecting their designs. Student comments on evaluations for the course include the following (in response to a question regarding the project developing their abilities as an engineering designer):

- It allowed us the freedom to put our own ideas into the project
- I learned to make an initial design, test it, and improve it
- It developed our problem solving skills
- It covered a lot of aspects involved in design, both technical (writing) and experimental/research
- I learned how to weight the advantages and disadvantages of the different designs
- I thought the project was interesting. I would have liked to have more freedom with the chemicals and materials used in the fuel cell
- As far as the different types of engineering, this project was well-balanced
- I learned how to go about organizing projects
- It exposed me to fuel cells, which I didn't know anything about.
- Finally, something cool about being smart!

This project exposed students to multidisciplinary teamwork, project planning, open-ended design, and technical communication skills. Student responses to the project were overall favorable, and this project will be offered next year. Improvements to be made to the course (based on student remarks and faculty experience) include better communication between writing and engineering faculty, allowing more time for students to develop designs, and requiring more coordination between robot and fuel cell subteams.

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BIOGRAPHICAL INFORMATION

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