Doing the Locomotion...with a Microrobot Powered by a Microbial Fuel Cell

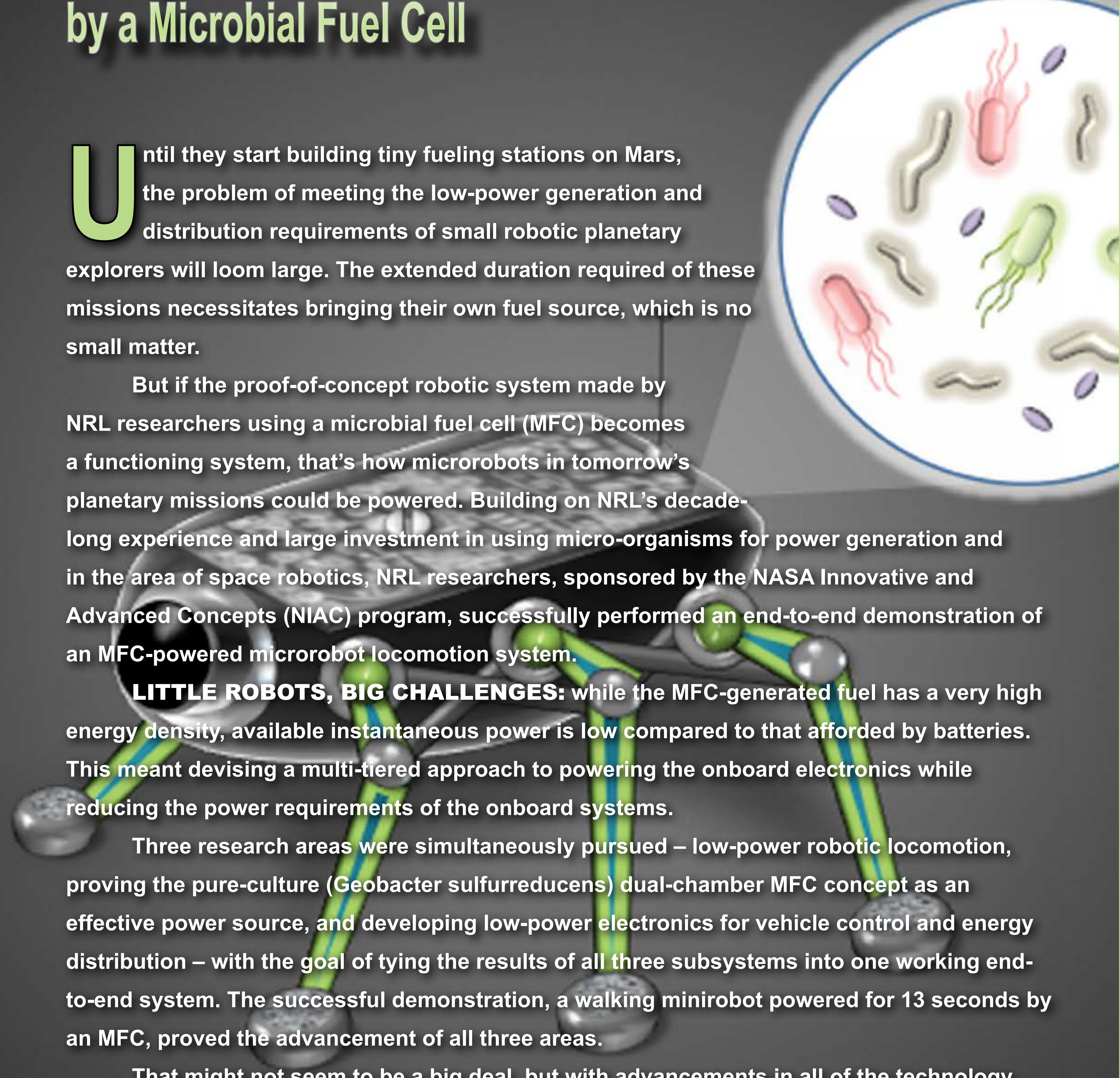
Until they start building tiny fueling stations on Mars, the problem of meeting the low-power generation and distribution requirements of small robotic planetary explorers will loom large. The extended duration required of these missions necessitates bringing their own fuel source, which is no small matter.

But if the proof-of-concept robotic system made by NRL researchers using a microbial fuel cell (MFC) becomes a functioning system, that's how microrobots in tomorrow's planetary missions could be powered. Building on NRL's decade-long experience and large investment in using micro-organisms for power generation and in the area of space robotics, NRL researchers, sponsored by the NASA Innovative and Advanced Concepts (NIAC) program, successfully performed an end-to-end demonstration of an MFC-powered microrobot locomotion system.

LITTLE ROBOTS, BIG CHALLENGES: while the MFC-generated fuel has a very high energy density, available instantaneous power is low compared to that afforded by batteries. This meant devising a multi-tiered approach to powering the onboard electronics while reducing the power requirements of the onboard systems.

Three research areas were simultaneously pursued – low-power robotic locomotion, proving the pure-culture (Geobacter sulfurreducens) dual-chamber MFC concept as an effective power source, and developing low-power electronics for vehicle control and energy distribution – with the goal of tying the results of all three subsystems into one working end-to-end system. The successful demonstration, a walking minirobot powered for 13 seconds by an MFC, proved the advancement of all three areas.

That might not seem to be a big deal, but with advancements in all of the technology areas, the potential is vast. It's one small step for a microrobot, but a giant leap for robot-kind.



The initial concept of the Low Power Microrobotic system, powered by a microbial fuel cell and controlled by a low-power electrical power distribution system. (Credit: K. Reilly, NASA NIAC)

Low Power Microrobotics Utilizing Biologically Inspired Energy Generation

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The Low Power Microrobotics (LPM) project was a multidisciplinary Phase I research effort funded by NASA's Innovative and Advanced Concepts (NIAC) Program to investigate integration of a low-power robotic mobility system with a microbial fuel cell (MFC) power supply. NASA's interest in this topic lies in their goal to create low mass planetary exploration vehicles. In this program, the team successfully performed an end-to-end system demonstration in which an MFC was used to operate a robotic locomotion system.

BACKGROUND

In the past decade, more than $10M has been invested in the development of MFC research at the NRL focusing on generating power and energy using microorganisms. In addition, nearly $30M in research funding has been awarded to space robotics research, including the development of space-qualified actuators, mechanisms, and electronics. Considering the extensive research experience in these areas, a team was assembled at the NRL to investigate low-power microrobotic systems powered by microbial fuel cells (Fig. 1).

The primary investigator (PI) for this program, Dr. Gregory P. Scott, was awarded the NRL's Karles' Fellowship in 2010 to investigate novel space robotics research. Using a portion of this funding, he began investigating technology for maturing small robotic systems, including power generation and distribution. Looking into alternative and innovative technology options for addressing this problem, he turned to MFCs as the primary power generation system owing to their potential to scavenge fuel and oxidants from the environment (Fig. 2). Dr. Leonard Tender, NRL's and the Navy's subject matter expert in MFCs, was brought

FIGURE 1
The Low Power Microrobotics research team, from left to right: Dr. Leonard M. Tender (Code 6930), Dr. Stephen P. Arnold (Code 8242), and Dr. Gregory P. Scott (PI, Code 8231).

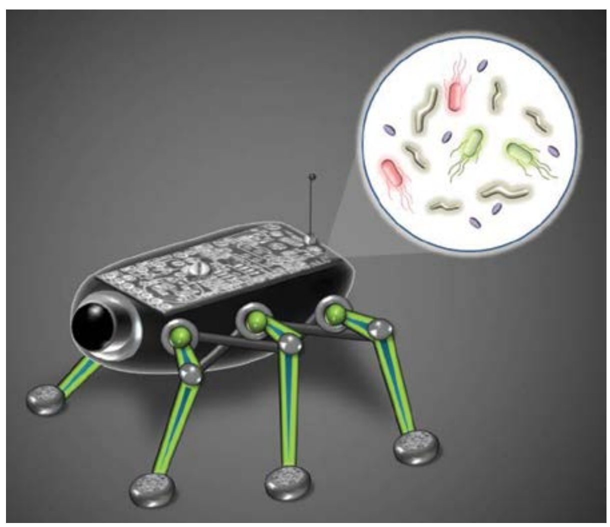

FIGURE 2
The initial concept of the Low Power Microrobotic system, powered by a microbial fuel cell and controlled by a low-power electrical power distribution system. (Credit: K. Reilly, NASA NIAC)

on board to support this aspect of the program. The high energy density of the fuel used in an MFC is one attractive aspect of these systems, yet one significant problem with using an MFC for power generation is their exceptionally low instantaneous power availability compared to batteries. Further discussion with Dr. Stephen Arnold, subject matter expert in spacecraft electronics, led to a consideration of a multitiered approach to powering the onboard electronics, while actively working to reduce the electrical requirements of the onboard components themselves.

Following this initial investigation and using the expertise of this team and others, a research project was awarded by the NASA Innovative and Advanced Concepts Program to investigate low power microrobotic systems using biologically inspired energy generation.

LOW POWER MICROROBOTICS

To achieve the goals set forth in this research project, the project was broken down into three primary research areas:

- low-power mobility systems for robot locomotion on planetary surfaces;
- electronics with low power requirements for core robot control functionality;
- biologically inspired power generation techniques for long duration vehicle lifetime.

The first research area followed the development of the low-power robotic locomotion system. Due to the high power requirements of motors in traditional wheeled/tracked locomotion, nontraditional methodologies were considered to reduce onboard electromechanical hardware for locomotion. Slow-charging spring-loaded hopping locomotion was considered for ground mobility and a gravity-assisted offset "pendulum" system was also investigated. Trade studies and designs were completed, weighing the capability of locomoting a 1-kilogram system while constrained by the power available from the fuel cell and energy storage devices.

The second research area followed the investigation of MFCs. This research area focused on a dual chamber MFC using the microorganism *Geobacter sulfurreducens* as the anode catalyst. This low power generation technology was selected as it would have an exceptionally long lifetime, beneficial for recharging onboard batteries or capacitors for long duration robotic scouting missions. A prototype MFC was fabricated to determine its power density and to demonstrate the ability of an MFC to actuate an electromechanical system. The third research area followed the development of low-power electronics for vehicle control and energy distribution. A power budget was developed based on power output of the MFC and proposed onboard power storage system based around a small super-capacitor. The output requirements of the locomotion actuators and additional onboard sensor systems that would be required for a robotic system were also baselined. A prototype control board with an energy distribution circuit was built and the power consumption was tested while operating a microrobotic system.

Although all three research areas were conducted independently, they were all directly interrelated and relied on constant design iterations and constant collaboration in order to ensure the systems could converge into a demonstrable proof of concept.

EXPERIMENTAL RESULTS

Through the work performed on this study, the technology readiness level of each system was advanced, allowing for an increased understanding of how these systems operate independently, as well as how they could interact together. Experiments showed that the dual-chamber MFC used in this research can produce an effective amount of power (~2 mW at 0.3 V) that could be harnessed by an energy harvesting circuit. Low-power electronics were tuned to charge a supercapacitor and eventually discharge the stored energy to activate an electromechanical system. Two distinct low-power mobility actuators were designed for operation in different environmental conditions, and sized to appropriately be actuated by this system.

In the final experiment, a benthic microbial fuel cell (BMFC) was used as the microbial fuel cell power source operating in a benthic mesocosm (Fig. 3) in the littoral facility of the Laboratory for Autonomous Systems Research (LASR). The BMFC was used instead of the dual-chamber MFC tested earlier in this project due to the inoculation cycle not being ready for use at the time of the final experiment. Although the BMFC

FIGURE 3
Sediment-based microbial fuel cell in the Laboratory for Autonomous Systems Research.

is significantly larger and sits on the sediment/water (benthic interface) at the bottom of marine environments and generates power using microbes naturally residing in marine sediment, the available power was nearly identical to that of the dual-chamber MFC. With an electrical output of 9 mA at 0.35 V, the BMFC was able to charge a 280 mF 3.6 V supercapacitor through the energy harvesting circuit in less than 2 hours. The charged supercapacitor was then discharged to operate the 3 V motor in a small walking robot for 13 seconds. This demonstrated the effective usage of a microbial fuel cell to locomote a robotic system using low-power electronics and an effective power management system (Figs. 4 and 5).

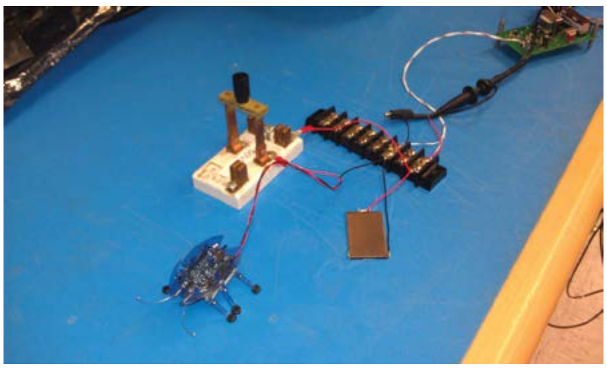

FIGURE 4
The test bench setup for the end-to-end test, including (from left to right) the robotic locomotion system, control switch, supercapacitor, wiring block, and energy harvesting circuit (oscilloscope not shown).

The Low Power Microrobotics project accomplished the following specific successes:

1. Further application and advancement of a dual-chamber, pure-culture microbial fuel cell;
2. Development of an electrical storage and distribution subsystem at low power;
3. Design of efficient mechanisms to be powered from a biological source;
4. Proving the proposed concept through an end-to-end test of the microbial fuel cell to power an electromechanical output system.

With further advances in each technology (such as improving the efficiency of the cathode reaction of the low-volume microbial fuel cell or improving electromechanical efficiency for locomotion systems), a future application of these interdisciplinary areas could include a low-power microrobotic system for low-gravity environments using a microbial fuel cell to generate electricity.

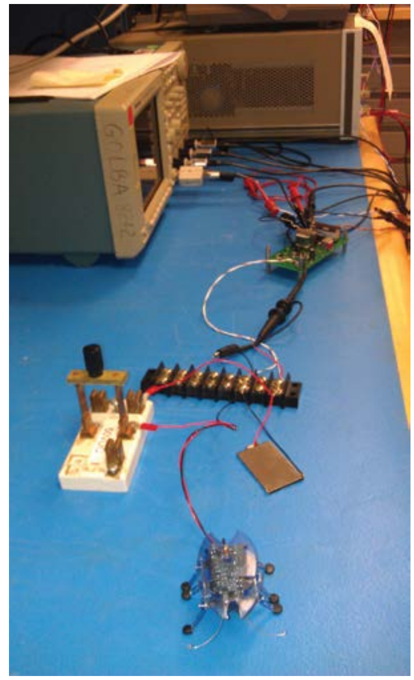

FIGURE 5
The test bench setup for the end-to-end test, including (from bottom to top) the robotic locomotion system, supercapacitor, control switch, energy harvesting circuit, and oscilloscope.

ACKNOWLEDGMENTS

The PI was selected as a NASA Innovative Advanced Concepts Fellow to perform Phase I research on this topic and thanks the NASA Innovative Advanced Concepts Program within the Office of the Chief Technologist for funding this research and helping to extend the state of the art in three key research areas to support low power microrobotics.

[Sponsored by NASA NIAC]

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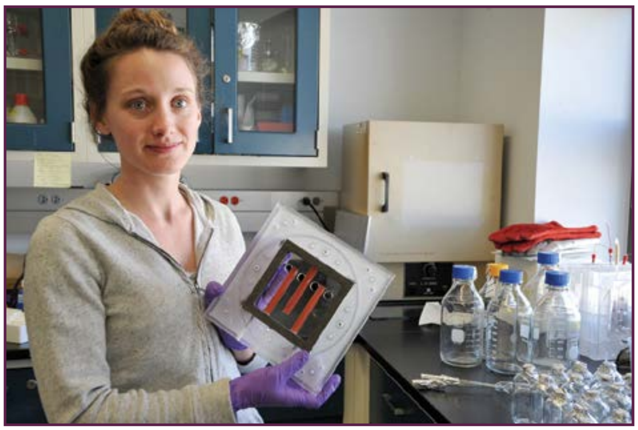
THE AUTHORS

GREGORY P. SCOTT earned his Ph.D. in the field of space robotics with a focus on biologically inspired legged vehicles and their mobility over complex terrain. He joined NRL under the Karles' Fellowship Program in 2010 and is developing a research portfolio to include biologically inspired robotics, vehicle mobility in complex terrain, space robotics, and other related areas. Prior to working with NRL, he completed his Ph.D. research at the Surrey Space Center at the University of Surrey in Guildford, England in 2009. He also earned his M.Sc. in space architecture from the University of Houston and a B.Sc. in aerospace engineering from the Pennsylvania State University. Dr. Scott was selected as a NASA NIAC Fellow and awarded Phase I funding for this Low Power Microrobotics project. For this project, Dr. Scott was responsible for overseeing the locomotion system focus area, including the biologically inspired actuators, as well as overall system development requirements and project management.

LEONARD M. TENDER, a Branch Head and research chemist in the Center for Bio/Molecular Science and Engineering at NRL, is the Department of Defense's leading science and technology expert in the field of bioelectrochemical systems, processes in which microorganisms are used to catalyze electrode reactions. Such processes include anode oxidation of organic matter for alternative power generation and wastewater treatment, and cathode reduction of carbon dioxide into liquid fuels. He earned his B.Sc. in chemistry at MIT and a Ph.D. in chemistry at UNC, Chapel Hill. For the NIAC Phase I project, Dr. Tender was responsible for the microbial fuel cell power generation focus area, including advancements to the fuel cell hardware, and supported the energy harvesting process.

STEPHEN P. ARNOLD is a computer scientist/engineer in the Flight Systems section of the Naval Center for Space Technology (NCST) at the NRL in Washington, DC. Dr. Arnold received his B.Sc. in physics in 1997 from the University of Michigan, his M.Sc. in computer engineering from The George Washington University (GWU) in 2002, and his D.Sc. in computer engineering from GWU in 2010. He has been with NRL since 1997. The Flight Systems section designs, constructs, tests, and integrates space flight electronic circuits, card level designs and chassis in support of NRL payloads and spacecraft busses with specific expertise in space flight processors, memory devices, high speed bus standards, FPGA (field programmable gate array) design, and VHDL (VHSIC Hardware Description Language) coding. He is a two-time winner of the NRL Alan Berman Research Publication Award. He is a longstanding member of the IEEE. For the NIAC Phase I project, Dr. Arnold was responsible for the electronics focus area, including the energy harvesting electronics development and the energy storage capabilities of the power subsystem.

CLARK PERSON received an M.Sc. in electrical engineering from Virginia Tech in 2008 and a B.Sc. in electrical engineering from Washington University in St. Louis in 2001. While studying at the Center for Power Electronics Systems at Virginia Tech, his research focused on multi-element resonant converters and soft-switching techniques in DC/DC converters. Other research interests include GaN power devices and spacecraft charging. He currently works as a power system design engineer in the Spacecraft Engineering Department at the Naval Research Laboratory.



KYLA GREGOIRE is a Ph.D. candidate in the Department of Civil & Environmental Engineering at the University of Maryland. Her research focuses on energy-positive wastewater treatment, including integrated anaerobic digestion-microbial fuel cells (AD-MFCs). She has six years' experience with design of water and sanitation initiatives in Tanzania, Peru, and Haiti, most recently including the design of low-cost AD system for the Partners in Health medical complex in Cange, Haiti. She is mentored by Dr. Leonard Tender at the Naval Research Laboratory and Dr. Stephanie Lansing in the Department of Environmental Science & Technology at the University of Maryland.