Low Power Microrobotics
Utilizing Biologically Inspired Energy Generation
(6 month review)

Gregory P. Scott (PI)
Leonard Tender
Stephen Arnold

Naval Research Laboratory
The Storyline

• You’re doing what!?
• Who’s doing this?
• What is this all about?
  – The Microbial Fuel Cell
  – Low Power Electronics
  – Bio-inspired Locomotion
• Where are you now?
• What’s next?
Project Overview

- Create Electricity
- Store Energy
- Power Systems
- Put it all together
The Naval Research Lab (NRL)

- **Spacecraft**
  - Developing spacecraft for the DoD since 1960s, 100 launched to date.
  - Developed GPS, 1st full lunar mapping (Clementine), 1st Recon. satellite

- **Robotics**
  - >$30M in research funding towards FREND-related tech.
  - Expanding into micro-vehicle, CubeSat manipulators, etc.

- **MFCs**
  - >$4M in “waste-to-energy” research funding since 2000
  - 1st practical application of an MFC – meteorological buoy
NRL Investigators

• Dr. Gregory P. Scott (PI) – *Space Roboticist*
  - Project Integration
  - Locomotion and Mechanical Sub-Systems

• Dr. Leonard Tender – *Microbial Electro-chemist*
  - Microbial Fuel Cell Development
  - Energy Generation Sub-System

• Dr. Stephen Arnold – *Computer Scientist*
  - Control System Development
  - Electrical Sub-System
Project Breakdown

• Three primary research areas:
  – The Microbial Fuel Cell
  – Low Power Electronics
  – Bio-inspired Locomotion

• Project objective:
  – NOT to have a full working robot!
  – IS to improve capabilities of each individual system, with reliance on every other system
  – IS to link 3 independent sub-systems into a single test system
Project Breakdown

Microbial Fuel Cell Theory

• MFC – fuel cell that uses microbes to generate energy
• High energy density: 14,600 kJ per 1 kg of acetate (sugar)
  - ~11x lithium battery (1,300 kJ/kg)
  - ~10x hydrogen-oxygen fuel cell (1,290 kJ/L H₂ at 2000 psi) {converted}
• Sediment vs. pure culture MFCs
Project Breakdown

Microbial Fuel Cell Development

• Same concept as the NASA-developed hydrogen fuel cell
• Research-grade pure-culture prototype MFC
  – 0.2 L total volume (0.1 L in each chamber)
• Core energy generation:
  – Carbon fiber anode, permeable membrane, carbon fiber cathode
  – All compressed together to minimize separation and improve efficiency
  – Membrane causes high internal resistance which lowers output V
  – *Geobacter sulfurreducens* (DL-1 strain)
    • breaks down biomass (sugar) at anode
    • results in CO$_2$, H$^+$ and e$^-$
Project Breakdown

Microbial Fuel Cell Status

• Prototype MFC built and inoculated
• Output power (single cell):
  – Inoculation period of 2-4 weeks
  – Then ~0.35 V max, ~2 mW continuous output
• Ongoing tests: pure culture *Geobacter* vs. waste water
• Power conditioner to upscale voltage to usable quantity
  – ... onward to the electrical system...

![Graph showing DL-1 MFC (A/m²) vs. Time (hr)]
MFC voltage is very small (~0.35V)
Must be increased to a usable value and stored
Energy storage methods investigated
Energy discharged as needed, once available
Project Breakdown

*Electrical System Development*

- MFC direct output simulated as input to the electrical system
- Key focus area – time to charge and discharge super-capacitor
- Goal – time for charge/discharge to determine movement capability
Project Breakdown

Electrical System Status

• Expected MFC voltage and upcharge circuit to 12V simulated
• Charge/discharge capability of various supercaps simulated
• Locomotion mechanism energy requirements simulated
  – ... onward to the locomotion system...

![Diagram of electrical system components]

- Comparator
  - On: 6V
  - Off: 5V
- Auxiliary Power (12V)
- Motor – Electrical
- Motor – Mechanical
- Motor – Gear Train
Project Breakdown

Locomotion System Theory

• Mechanism design requirements:
  - Vehicle must traverse asteroid terrain (rocky, low gravity)
  - ~1mW electrical input, 12V max step input from super capacitor
  - Minimize moving parts and actuators
  - Low activation cost (mechanical or electrical)

• Focus on biological systems for inspiration

• Considerations:
  - Bi-stable mechanism
  - Single geared motor actuation
  - Offset motor vibration
  - Flagellum-like movement

Asteroid EROS 433 Surface (from NEAR Mission)
Project Breakdown

Locomotion System Development

- Benchmarked hopping mechanism
  - Bi-stable, spring-loaded actuation
  - Actuator slowly builds up mechanical potential energy
  - Mechanism snaps into place at maximum potential
  - Snapping induces hopping motion
  - Single actuator for system simplicity

![Diagram of hopping mechanism](image)
Project Breakdown

Locomotion System Status

- Mechanism designed in CAD
- Motor and gears modeled for system accuracy
- Simulation developed to model mechanism energy requirements

<table>
<thead>
<tr>
<th>Motor Rotation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of Discharging</td>
<td>0.06 s</td>
</tr>
<tr>
<td>Speed of motor</td>
<td>5000 rpm</td>
</tr>
<tr>
<td>Motor Rotations</td>
<td>300 rev</td>
</tr>
<tr>
<td>Gear box Reduction</td>
<td>67 :1</td>
</tr>
<tr>
<td>Worm Wheel Reduction</td>
<td>50 :1</td>
</tr>
<tr>
<td>Number of Teeth of worm wheel rotated</td>
<td>0.090</td>
</tr>
<tr>
<td>Total number of discharges to actuate</td>
<td>217</td>
</tr>
<tr>
<td>Time to charge</td>
<td>180 s</td>
</tr>
<tr>
<td><strong>Total Time to Actuate</strong></td>
<td><strong>651 minutes</strong></td>
</tr>
</tbody>
</table>

Total Time to Actuate: 651 minutes (10.86 hours)
Overall Project Status

• All sub-system developments are progressing well
• Simulation of full system (MFC to electronics to actuator) complete
• Results show significant actuator inefficiencies – some re-development required
• Individual sub-system testing and refinement underway
• Press coverage – Wired, Popular Science, Space.com, ABC local news broadcast, international science radio shows, and more...
Future Work

• Benchmark MFC capabilities
• Complete breadboard electronics (based on MFC)
• Prototype locomotion mechanism
• Test individual sub-systems
• Perform benchtop test of systems working together
• Define approaches to:
  – Improve efficiency, reduce size/volume, and better integrate systems.
• Complete Phase II proposal and final report
Future Work

10-year timeline

2012: Concept developed. Each subsystem concept proofed.

2014: Greatly reduce subsystem magnitude and prototype large-scale working vehicle

2018: Near 1-kg robotic system designed, developed, and prototyped (inclusive of subsystems)

2022: Space-qualified 1-kg robotic system, ready for launch
Conclusions

• The team has been successfully progressing with the project.
• The project is on schedule for a bench-top demonstration of the individual subsystems working in unison for July 2012.
• We are all excited about our success to-date and are looking forward to more in the near future.
Questions

Thank you for your attention!

Are there any questions?
Backup – Motor Sim Results

Capacitor Voltage

Motor Torque

Motor Speed

Motor Position
Energy Storage Technologies

Charge per Unit Volume

Charge per Unit Mass

Volume

Mass

Ceramic

Tantalum

SuperCap

Lithium Coin

Low Charge Losses

High Charge Losses