Power Considerations for Micro-Autonomous Systems

Brian C. Morgan, Ph.D.
Sensors & Electron Devices Directorate
U.S. Army Research Laboratory - Adelphi, MD
Brian.c.morgan25.civ@mail.mil
Power Considerations for Micro-Autonomous Systems

Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees’/Contractors’ Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.
Outline

• Army Needs & Niche
• Energy & Power Requirements
• Power Source Options
  • Bring energy with you
  • Get more on site
• Suggestions
Enduring Army Problems

• It is burdensome to **carry & sustain** everything
• Soldiers need to be more **survivable**
• There is never enough **power**
• We must operate in **extreme environments**
• **24/7 situational awareness** of actions & intent is key to success
To enhance tactical situational awareness in urban and complex terrain by enabling the autonomous operation of a collaborative ensemble of multifunctional, mobile microsystems

<table>
<thead>
<tr>
<th>Lead &amp; Platform Integration</th>
<th>BAE Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing for Autonomous Operation</td>
<td>Univ. of Pennsylvania</td>
</tr>
<tr>
<td>Microelectronics</td>
<td>Univ. of Michigan</td>
</tr>
<tr>
<td>Microsystem Mechanics</td>
<td>Univ. of Maryland</td>
</tr>
</tbody>
</table>
Autonomous Robot Landscape

Biology

MAST Goal

Size / Maturity

1g 1kg 1000kg

Autonomy
Energy & Power Needs
Representative Platform: DFS/UMD MicroQuad

Weight Breakdown (Total = 77.4g)

- Battery
- Frame
- Motors & Rotors
- Misc
- Electronics

Power Breakdown (Total = ~12W)

- Motors (hover)
- Comms
- Processor
- Control

*Numbers courtesy of Dr. Joe Conroy, ARL/UMD

Power for mobility dominates over sensors & Comms; especially for aerial platforms (~10:1)
Non-Ragone Plot

Specific Power of Source (W/g) vs Endurance (Hours)

NOTE: When necessary, power source estimated as 25% of body weight
If 25% of biological systems were “power source,” some systems dramatically break the mold!

NOTE: When necessary, power source estimated as 25% of body weight
Option 1:
Bring what you need
COTS Rechargeable Batteries (<150Whr/kg)


- Typically <$10
- Available down to ~1g
COTS Primary Batteries

Plenty of energy (300-400 Whr/kg); Power Density limited (typically <100 W/kg)

COTS Rechargeable Batteries (<150 Whr/kg)

U10004 – 15g
~300 Whr/kg; 25 W/kg

UHE-ER14505 – 18g
~400 Whr/kg; 17 W/kg
Emerging Batteries: Secondary used as a Primary

- **Typical Li-S problem:** performance degrades with cycling
  - Commercial electronics care; MAST does not!

  ![Diagram](SionPower.com/technology.html)

  - **Lithium-Sulfur:** promising rechargeable technology
    - Up to 350 Wh/kg at 60 W/kg
    - Project >200 Wh/kg @ 800 W/kg

- **COTS Rechargeable Batteries (<150 Whr/kg)**

- **Primary Batteries**
Thermo-Photovoltaics

Photonic Crystals Predicted to Double System Efficiency

Thermal Radiation to Electricity via a PV cell
Micro-Thermo-Photovoltaics

GaInAsSb PV diodes

1D PhC emitter

low-power MPPT

micro channel

Silicon MEMs reactor

POC: Ivan Celanovic
Micro-Thermo-Photovoltaics

1st Order Calculations for a hypothetical <25g, 5W propane-fueled “system”

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor &amp; TPV Cells</td>
<td>5-8g</td>
<td>5-20%</td>
</tr>
<tr>
<td>Packaging</td>
<td>.5-1g</td>
<td>--</td>
</tr>
<tr>
<td>Heat sink</td>
<td>3-5g</td>
<td>--</td>
</tr>
<tr>
<td>Pumps, Power Elec</td>
<td>.5-1g</td>
<td>1W, 90%</td>
</tr>
<tr>
<td>Fuel to Tank Ratio</td>
<td>2:1 to 10:1</td>
<td>--</td>
</tr>
</tbody>
</table>

COTS Rechargeable Batteries (<150 Whr/kg)
Option 2:
Get more energy on site
Solar Photovoltaics

1000 W/m²
~20% Efficient
~80% Fill Factor
~65 g/m²

Ideal Outdoor Solar

>1 W/g

Specific Power of Source (W/g)

Endurance (Hours)

2um GaAs
1um metal routing
25um Kapton backing
Solar Photovoltaics

Ideal Outdoor Solar

- ~20% Efficient
- ~80% Fill Factor
- ~65 g/m²

Indoor Solar

- Specific Power of Source (W/g): <.03 W/g
- Endurance (Hours): 1-10

Great...in the right conditions
*Surface area constraints

25um Kapton backing
1um metal routing
2um GaAs

\[ .1 - 10 \text{W/m}^2 \]
Power Beaming

Pro’s:*
>20% Net Efficiency
Scalable to kW & km
800 W/kg (receivers)

Con’s:
Line of sight
Safety & reflections

Demonstrated 60W over 2m at 40-50% efficiency (~60cm coils)

*Kurs et al, Science, 2007

*Nugent & Kare, SPIE DSS, 2011
Suggestions
Use Less Power

Improved understanding of aeromechanics

Appropriate vehicle & scale

Roll / Crawl if possible!!

NOTE: When necessary, power source estimated as 25% of body weight
Match Needs to Use

Some Missions Do Not Need Continuous Flight

- **COTS**
  - 200g LiPo
  - Single 26min flight
  - ~2X* Capacity

- **Hybrid**
  - 150g Primary
  - 50g LiPo
  - 8 flights (6 min each, 30 min re-charges)

Assume:
- LiPo = 150 Wh/kg @ 1.5 W/g
- Primary = 350 Wh/kg @ 0.1 W/g

Some Missions Do Not Need Continuous Flight
Embrace Cooperation

Knowledge vs. Mission Speed

- Single Platform
  - 2-3 Knowledge
  - 2-D, Indoors

- Homogeneous Team
  - 3-5 Knowledge
  - 2.5D, Indoor & outdoor

- Heterogeneous Team
  - 5-10 Knowledge
  - 3-D feature rich environments (caves, rubble)

- 3-D with Persistent surveillance
  - 10+ Knowledge

Environmental Complexity
Biology will likely win for a while… but military utility is not far off
END
Representative Platforms:
DynaRoACH from UC Berkeley

Current dynaRoach 1.0 (24 grams)
- measured COT at cruise: 5 J/kg-m = 120 mW
- cruise speed: 1 m/sec (flat ground)
- total power for cruise: 600 mW
- range: 1.8 km
- max power density 10 W/kg (900 mW, 1000 sec)

(Hoover et al BioRob 2010)

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
<th>Power</th>
<th>COT Cruise</th>
<th>Speed</th>
<th>Total Power for Cruise</th>
<th>Range</th>
<th>Max Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>3 grams</td>
<td>0.24/0.6 W</td>
<td>2 J/kg-m</td>
<td>40 mW</td>
<td>130 mW</td>
<td>25 km</td>
<td>150 W/kg</td>
</tr>
<tr>
<td>structure</td>
<td>17 grams</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>1.5 grams</td>
<td>0.3 W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiPo Battery</td>
<td>2.5 grams</td>
<td>1100 J</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hypothetical dynaRoach 2.0 (10 grams)
- COT at cruise: 2 J/kg-m = 40 mW
- cruise speed: 2 m/sec (flat ground)
- total power for cruise: 130 mW
- range: 25 km
- max power density 150 W/kg (3000 mW, 500 sec)

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
<th>Power</th>
<th>COT Cruise</th>
<th>Speed</th>
<th>Total Power for Cruise</th>
<th>Range</th>
<th>Max Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>1.7 grams</td>
<td>0.6/1.5 watts</td>
<td>2 J/kg-m</td>
<td>40 mW</td>
<td>130 mW</td>
<td>25 km</td>
<td>150 W/kg</td>
</tr>
<tr>
<td>proposed structure</td>
<td>3.2 grams</td>
<td>1600 J</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>goal:</td>
<td>3.6 grams</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>1.5 grams</td>
<td>50 mW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Micro-Thermo-Photovoltaics

- GaInAsSb PV diodes
- 1D PhC emitter
- low-power MPPT
- micro channel
- Silicon MEMs reactor
Representative Platforms: DynaRoACH from UC Berkeley

Acoustic/thermal \rightarrow Mission Sensors \rightarrow Interface Electronics \rightarrow Camera, 802.15.4 radio, 40 MIPS CPU, gyros, accelerometers

Power Supply

LiPo Battery

Example: 220 mA-hr, 5.3 grams

90 mA @ 40 MIPS
30 mA @ 10 MIPS

100 mW (25 mA) cruise
900 mW (240 mA) max

Drive Motors

Legs

Steering actuators

Cruise w/o camera and reduced CPU clock: 55 mA (~ 4 hours range)

<table>
<thead>
<tr>
<th>Motor</th>
<th>LiPo Battery</th>
<th>Structure</th>
<th>CPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 grams</td>
<td>2.5 grams</td>
<td>17 grams</td>
<td>1.5 grams</td>
</tr>
<tr>
<td>0.24/0.6 W</td>
<td>1200 s</td>
<td></td>
<td>0.3 W</td>
</tr>
</tbody>
</table>

*Ron Fearing, “Power & Energy for Small Robotic Systems,” 2010 Army Science Conference*
*Bubble size = Power Handling (W)